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Evaluating the Thermal Performance and Environmental Impact of Agricultural Greenhouses Using Earth-to-Air Heat Exchanger: An Experimental Study

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Abstract: The thermal performance and environmental impact of agricultural greenhouses (GH) connected to earth-to-air heat exchanger (EAHE) systems depend on the ambient temperature, soil temperature, EAHE system, and greenhouse specifications. The impact of an EAHE system on the temperature and humidity of a GH microclimate, as well as its effects on CO_2 emissions and heating energy consumption, are determined experimentally. Two scaled-down models of agricultural GHs ($2 \times 1.4 \times 1.4$ m^3) were developed. Each GH was equipped with a heater. A spiral EAHE system was integrated into only one of the GHs. The temperature differences in the microclimate range from 3.5 °C to 7.5 °C, with the microclimates of GH + EAHE and GH being quite similar. In summary, the EAHE system helped to reduce the hourly energy consumption of the heating system by more than 40%. It also reduced emissions to the environment by more than 100 g (CO_2)/hour. The EAHE coefficient of performance (COP) for the cooling mode has a higher average value than that for the heating mode. The closed-loop performed better in cooling mode, while the open-loop performed better in heating mode. When the difference between the set temperature in the heater and the air outlet temperature of the EAHE system is smaller, the heater performs better in reducing energy consumption and CO_2 emissions of the heater. The $COP_{heating}$ range is between 0 and 3.4 and the $COP_{cooling}$ range is between 0.5 and 7.3. The energy consumption ranges between 0 and 1.41 kWh and the CO_2 emissions are between 0 and 359.55 g. Thus, using EAHE in agricultural greenhouses improves thermal performance and reduces environmental impact, providing an overall benefit in terms of energy consumption and environmental sustainability.

Keywords: greenhouse; earth-to-air heat exchanger; CO_2 emissions; energy consumption; environmental impact; sustainability

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1. Introduction

The creation of favorable climatic conditions in greenhouses (GHs) affects product quality and production costs [1]. Heating and cooling of GHs are among the most energy-intensive activities in sheltered cultivation, accounting for more than 30% of the GHs' overall costs [2]. It is also important to reduce GH gas emissions and energy consumption [3–5]. Ghiat et al. [6] used carbon capture for storage or utilization in the concept of energy, water, and food nexus to reduce gas emissions. The supplied chain achieved negative CO_2 emissions of 24.6 kg/m^2.year of cultivated land. In China, the GH non-CO_2 emission increased by 34% from 1980 to 2018, and it is expected to increase by another 33% to 1153 MtCO_2-eq per year by 2060 [7]. The most effective measures to reduce emissions include feed additives, improvements in feed quality, slow-release fertilizers, and improved water management for rice fields and uplands [7,8]. To reduce energy consumption, Badji et al. [9] emphasize the importance of good GH design to create a suitable environment, and climate control and management strategy. While Nematchoua et al. [10] recommend the increased use of new techniques.

Due to high energy costs, few GH owners can afford to use additional heating systems [11]. The use of low-cost or alternative, heating systems is therefore of paramount importance in controlling the indoor climate of GHs [12–14]. Many passive systems are used to reduce energy consumption. The earth-to-air heat exchanger (EAHE) system is said to be a good option for controlling the internal GH environment where the earth can be used as a heat source/sink [15]. The EAHE system has a satisfactory outlet air temperature even over a longer time [16]. The next studies show that the design of the EAHE system affects its performance. The results of the computational fluid dynamics model (CFD) were validated with experimental measurements and found that 152.4 mm is the best diameter for the EAHE tube for overall performance, while 50.8 mm is best for thermal performance [17]. A 3D modeling study CFD examined the effects of moist air on a multi-tubular EAHE system. It showed the effects of condensation inside the EAHE tube on the uniform distribution of airflow [18]. This condensation reduced the thermal output of the EAHE by 7.9%. The shape of the U, Z, and L tubes was used to structure the EAHE multi-tube system. The L structure is optimal because it provides the highest heat transfer and the lowest pressure drop [18]. The air in the GH microclimate should also be refreshed to eliminate moisture that is harmful to plants [19]. Refreshing the GH depends on the season, and ventilation is carried out by exchanging indoor air with outdoor air. During the winter season, high humidity (>80–90%) and excessive condensation cause rot on plant leaves, stem rot, and plant infection problems. For example: in tomatoes, problems with leaf mold occur when humidity is above 80%. In contrast, problems with infections are minor when humidity is below 70% [20]. On the other hand, it is necessary to maintain the recommended temperature for healthy plants. For this purpose, the heat requirement increases when the ventilation rate is increased during the winter season. Therefore, it is important to choose a ventilation rate that keeps the humidity below the level of plant damage and maintains the temperature in the recommended range. GH ventilation typically requires 2 to 3 air changes per hour [21]. While in summer, the large heat load of solar radiation through the GH glazing increases the air temperature of the GH compared to the outside air temperature. For this reason, ventilation of the GH is required, generally allowing air changes of at least 60 per hour [21]. In addition, the spring and autumn periods are volatile, so no special conditions are required to maintain ventilation rates [21]. According to the literature, there are a large number of crops with similar optimal temperature ranges, e.g., cucumber, bell pepper, eggplant, beans, zucchini, melon, etc., all characterized by an optimal temperature between 24–30 °C during the day and 15–20 °C at night [22,23].

1.1. Earth-to-Air Heat Exchanger (EAHE) Test Studies

The application of the EAHE system in GHs is widespread. However, the COP values and energy consumption differ depending on the conditions related to the design of the EAHE system, soil type, the structure of the GH, and the climate zone, among others.

In Delhi-India, the annual maximum heating/cooling potential of EAHE, in the $8.58 \times 4 \times 2.5$ m^3 microclimate of GH, the maximum value of heating potential was 11.55 MJ and the cooling potential was 18.87 MJ. These values are reached on typical days in January and June [14]. Regarding the performance of the integrated system in Tehran-Iran, the results show that the integrated evaporation system with an EAHE system reduces water consumption by 17% to 49%, with the reduced percentage depending on environmental conditions from climate 1 (with cold or very cold winters and hot and dry or mild summers) to climate 4 (with cool or mild winters and very hot and humid summers) [24]. In another study on a 24 m^2 $\times$ 3 m GH located in Iran, Mahdavi et al. [25] explain that the energy and exergy efficiency depends on the length of the EAHE pipes, using 39 m for their system. The pipes are installed at a depth of 1 m, with temperature variations at this depth ranging from 22 to 28 °C. The system used is a horizontal serpentine EAHE, which has a larger footprint. In Bologna-Italy, the soil temperature at shallow depth is 16 °C. Barbaresi et al. [26] installed 12 EAHE systems in a vertical spiral shape (total length 60 m, installation depth 2 m), which serve as backup for the main GH heating system (24 × 8 × 12.7 m^3) during the winter season. The vertical spiral form occupies a smaller area. They state that the EAHE helps reduce energy consumption by 10 to 30%. They also believe their system can reduce gas emissions by 8 to 28% [26]. However, they explain that there is little literature on the energy consumption of GHs.

There are many studies in the literature on the application of the EAHE system in GHs for different regions and conditions. However, few studies have been conducted to give an idea of the dependence on climate, EAHE design, and GH design. An experimental study was conducted in In Izmir, Turkey, in the summer of 2009–2011 on the use of a horizontal EAHE system in a cooling greenhouse. The experimental study showed that the total cooling demand was between 0 and 10 kWh. The total thermal energy consumption was 5.84 kWh/day, and the total energy consumption for electricity was 584 kWh, with a COP of 6.3 [27]. For the same system, after seven years of data acquisition, Ozgener et al. [28] declare that the maximum heat output was set at 12 kW. In different regions of Iran, from climate 1 (with cold or very cold winters and hot and dry or mild summers) to climate 4 (with cool or mild winters and very hot and humid summers), an integrated system with an evaporative cooling system and an EAHE was used in a GH with a size of more than 1600 m^3, where the EAHE system was installed at a depth of 2 m. The average soil temperature was 21 °C. In the month of February, the amount of heat generated by the heating system in the absence of plants was more than 33.3 kWh/m^2 per month [24].

Harjunowibowo et al. [29] installed a thick insulated foam layer around the soil of the EAHE to reduce heat loss. They used this system in heating/cooling a 142.87 m^3 greenhouse, in Loughborough, UK. Measurements show that $COP_{heating}$ ranged between 1.48 and 2.97 and $COP_{cooling}$ ranged between 1.20 and 3.45. The 150 m^3 GH studied by Benli [30] was realized in Elazig, Turkey. Vertical and horizontal EAHEs were used in this greenhouse. In the experiments, the operational performances of the different system designs and the soil temperature field in the heating mode were evaluated. The results from COP are in the range of 2.7 to 3.3 and 2.9 to 3.5 for the horizontal and vertical EAHE systems, respectively. Each of the studies abovementioned has different operational and environmental conditions.

1.2. Study Objectives

In this study, we aim to show the difference between using an open and a closed-loop EAHE system in a reduced-scale GH. This experimental condition is different from the abovementioned studies. We also investigate the effects of a spiral EAHE system on the current GH, where the system is 29 m long and installed at a depth of 3 m at a soil temperature of 13 °C. The microclimate GH (2 × 1.4 × 1.4 m^3) was studied in terms of reducing energy consumption and CO_2 emissions. The paper refers to the experience gained in the western border region of Europe during the winter season. The difference between the set temperature in the heater and the air outlet temperature of the EAHE system was studied to achieve the lowest energy consumption and CO_2 emission of the heater.

To conduct this study, two scaled-down models of agricultural GHs were placed next to the building of the Department of Electromechanical Engineering, University of Beira Interior (Portugal) in February 2020. Each GH was equipped with a heating device. A spiral EAHE system was integrated into only one of the GHs.

Figure 1 shows how the GH + EAHE were connected, namely in the closed-loop (a) and in the open-loop (b). The study was divided into two parts. In the first part, the heaters were turned off. In the second part, they were switched on.

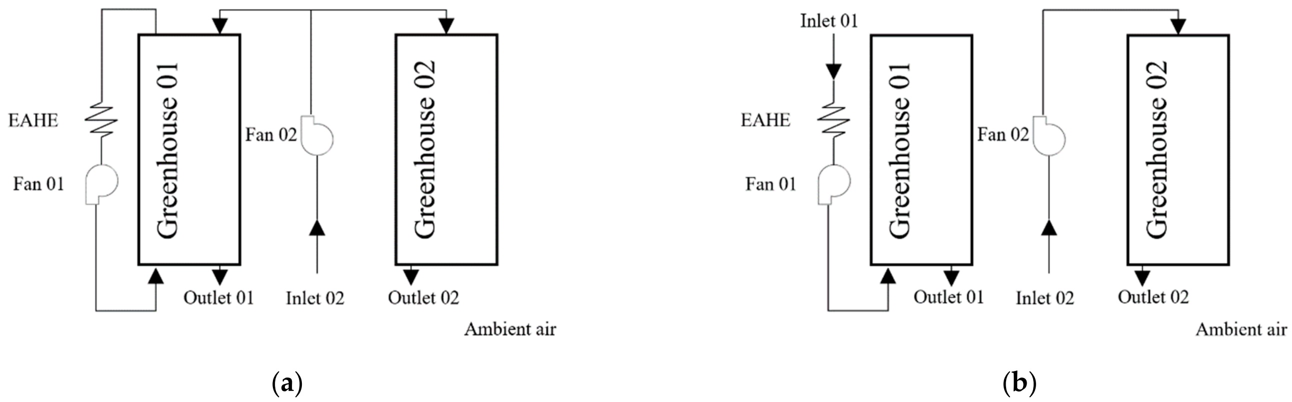


Figure 1. Layouts of GH + EAHE with the reference GH. (**a**) Closed-loop schematics. (**b**) Open-loop schematics.

2. Experimental Setup

The experimental setup was developed in parts through teamwork [31,32]. The choice of the geographic location of the experimental setup was influenced by several factors, such as soil properties (a soil sample from the EAHE site contains 20% gravel, 59% sand, and 21% silt/clay, with a predominance of silt composition in the site) [15], ease of excavation, proximity to a power point, and distance from heat sources that could interfere with heat exchange. The experience was made in February 2020 near the Electromechanics Building of Beira Interior University.

The design of the EAHE system was chosen as a spiral, vertical loop shape. This design requires less space than the horizontal serpentine design [33], due to lack of space, especially in urban areas, or due to geological aspects, such as rocky soils. The layout of the EAHE system is shown in Figures 2 and 3.

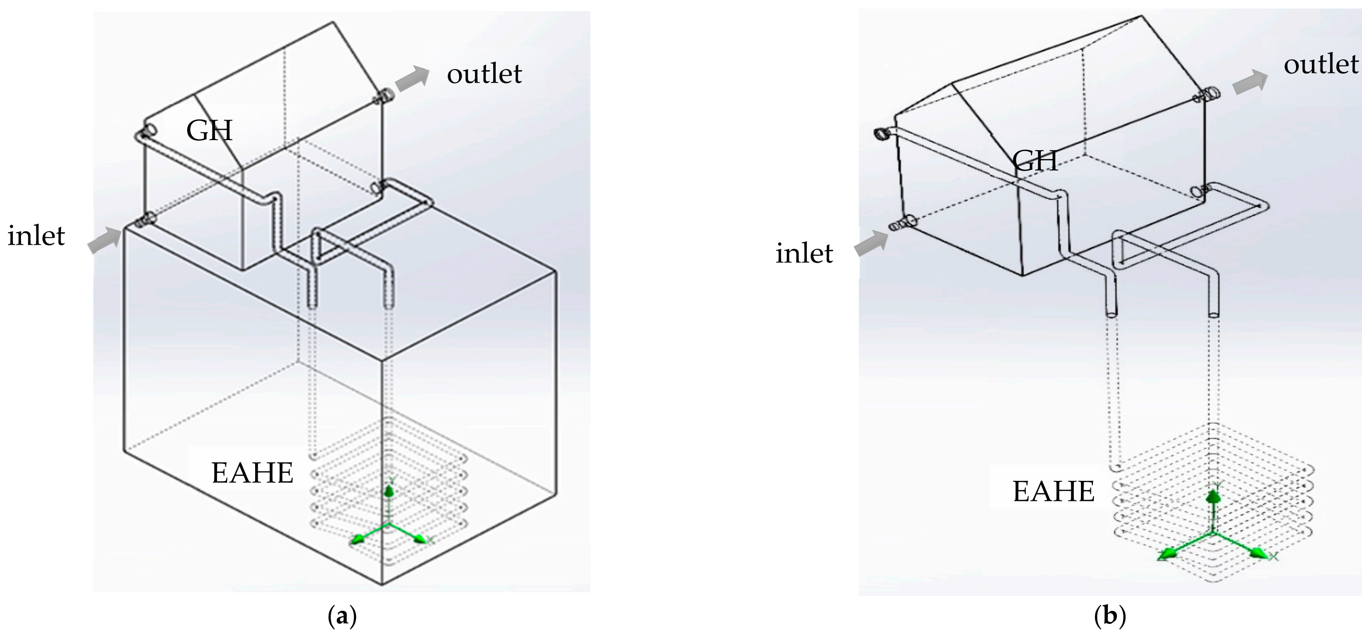
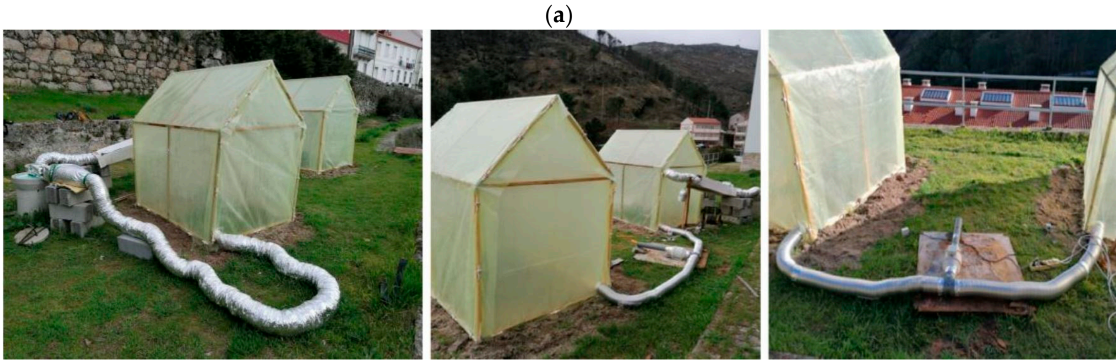


Figure 2. Path of the air exchange in the two models. (**a**) Closed-loop schematics. (**b**) Open-loop schematics.

From Figure 1, it can be seen that there are two fans. In the closed loop, Fan 1 is responsible for blowing the air that comes from the GH to EAHE to GH again (Figure 2a), and Fan 2 is responsible for the air change of both GHs with the ambient air. While in the open loop, Fan 1 is responsible for blowing the air from the ambient to EAHE to GH (Figure 2b), and Fan 2 is responsible for the air change of the second greenhouse.

(**a**)



(**b**)

Figure 3. Details of the two scaled-down models. (**a**) Open-loop photographs. (**b**) Closed-loop photographs.

The airflow was measured with the Testo 416 anemometer positioned inside the PVC pipe with the telescopic anemometer probe inserted in the geometric center of the flow cross-section, at a distance of about 30 cm from the fan outlet. A previous calibration process allows us to use this velocity to evaluate the mean integrated velocity in that section. Several measurements were performed. The average value was used to calculate the number of air changes in the inner volume of the greenhouse (see Table 1).

Table 1. Main characteristics and technical specifications of the equipment used in the experimental setup.

Element	Technical Specification
EAHE—earth air heat exchanger	Configuration: spiral, vertical shape (open-loop ∣ closed-loop) Pipe of PVC (Polyvinyl chloride): density 1380 (kg.m^{-3}). Specific heat Capacity 900 (J.kg^{-1}.K^{-1}). Thermal conductivity 0.16 (W.m^{-1}.K^{-1}) Pipe length: 29 (m) External diameter: 0.075 (m) Pipe thickness: 0.0015 (m) Piping depth: 3 (m) Distance between pipes: 0.15 (m) Inlet/outlet air temperature sensors position are 3.20 (m), 24.77 (m)
GH- greenhouse	Materials: fir-wooden bars with a square profile of 30 × 30 mm section, assembled with steel joinery, screws, and anchored into the ground up to about 20 cm with six steel tubes with a 35 × 35 mm^2 profile. Greenhouse volume is 2 × 1.4 × 1.4 m^3 with extra triangle volume (0.5 × 1.4) x 0.7 × 2 (m^3) = 5 m^3 Distance between greenhouses is 3 m 0.1 mm-thick Polyethylene film was cut, stretched, and fixed to the structure using VD tubes (PVC rigid tubes applied in electrical installations), cut in segments of 7 cm length, and screws.

Table 1. *Cont.*

Element	Technical Specification
Fan for air extraction	Voltage: 230 V Power: 120 W (EAHE) Volumetric flow rate: 60, 15 and 5 (m^3 h^{-1}) (GH) Volumetric flow rate: (1, 3 or 12 air change) ×5 (m^3 h^{-1}) S&P brand, model TD-800/200 Single-phase, two-speed motor fed with 230 V voltage Maximum volumetric flow rate without pressure losses is 1000 (m^3 h^{-1}). S&P model TD-250/100 T fan Single-phase, two-speed motor Max. volumetric flow rate without pressure drop: 240 $m^3.h^{-1}$ (Maximum electrical power: 24 W).
Fan Heaters	Ceramic fan heater Digital thermostat Maximum power of 1800 W IP21 protection index
Power and energy consumption readers	E2 Classic Electricity Monitor
Anemometer	Testo 416 anemometer
Temperature and RH data loggers	Data logger PCE-T 1200 (PCE instruments) Data logger EL-USB-2 (Lascar Electronics)

The materials used are fir wood piles with a square profile of 30 × 30 mm cross-section, connected with steel joints and screws, and anchored in the ground 20 cm deep with six steel pipes with a square profile of 35 × 35 mm. The structure was covered with a 0.1 mm thick polyethylene film. It was carefully cut, stretched, and fixed to the structure with VD pipes (rigid PVC pipes used in electrical installations) cut into segments of 7 cm and screws (Table 1).

To neglect the rounded condition and obtain a better comparative study, the two GHs were built with the same design and rounded by the same condition.

Figure 3a shows the two scaled-down models of the agricultural GHs in the separate construction (open-loop). Figure 3b shows how the two scaled-down models of agricultural GHs share the fan for air exchange (closed-loop).

3. Uncertainty Analysis

In the present study, measurements of temperature, airflow, power, and energy consumption were subject to uncertainty due to the limited accuracy of the instruments previously presented (see Table 2).

Table 2. Accuracy of the equipment used in the experimental setup.

Instrument	Range	Resolution	Accuracy
Lascar EL-USB-2 data logger	−35 °C to +80 °C 0% to 100% RH	0.5 °C 0.5% RH	±0.5 °C ±2.25% RH
PCE-T 1200 data logger	−50.0 °C to +999.9 °C	0.1 °C	±(0.4% + 0.5 °C)
Efergy e2 classic monitor	110 V to 600 V 50 mA to 90 A	-	±10%
Testo 416 anemometer	0.6 $m.s^{-1}$ to 40 $m.s^{-1}$.	0.1 $m.s^{-1}$	±(0.2 $m.s^{-1}$ + 1.5%)

4. Tests Description and Data Analysis

Ten tests were performed during the experimental study. Their descriptions are mentioned in Table 3. The tests were realized to highlight the outlet air affections of the EAHE system on the studied microclimates, its energy consumption, and CO_2 emissions.

Table 3. Tests table, with 24 h duration for each experience, where tests A considered the heating OFF, and tests B considered the heating ON.

Test (n°)	T_{set} (°C)	Air Changes (h^{-1})	Air Flow Rate in EAHE ($m^3.h^{-1}$)	EAHE Fan Electrical Power (W)	EAHE Loop
A1	-	1	60	48	Close
A2	-	3	60	48	Close
A3	**-**	**3**	**15**	**62**	**Open**
A4	**-**	**12**	**60**	**48**	**Open**
B1	18	3	60	48	Close
B2	**18**	**3**	**15**	**62**	**Open**
B3	20	3	60	48	Close
B4	15	3	60	48	Close
B5	**15**	**3**	**15**	**62**	**Open**
B6	**15**	**12**	**60**	**48**	**Open**

There are three types of affections on the air temperature and humidity of the GH + EAHE microclimate, which are:

(i) the outlet air of the EAHE system,
(ii) the microclimate air change by the outside air,
(iii) the heater device.

While only the two last types are affecting the GH microclimate.

The study is divided into two series, in the A series the heater devices are OFF, and in the B series, the heater devices are ON.

During series A and B, the air in the microclimate of the GHs was exchanged by the outside air once, three times, or twelve times, as shown in Table 3. The air exchange was performed in both greenhouses (GH and GH + EAHE) with the same volume flow.

Two different fans were used, one in the EAHE circuit and the other one in the air renovation circuit. To regulate the airflow rate fed by these fans the inlet section was reduced using cardboard restrictors previously calibrated with the Testo 416 anemometer.

Whenever the tests were performed in a closed loop (normal text style in Table 3), the power consumed by the fan in the EAHE circuit was at a constant value of 48 W. This happened also when in open-loop the airflow rate was set at 60 m^3/h, because it was the maximum value available in the system (when no cardboard restrictions were used). However, for open-loop (bold text style in Table 3) and 15 m^3/h airflow rate, the power rose at 62 W, due to the pressure loss imposed by the section restrictors.

The coefficient of performance COP is calculated according to Equation (1), where $\dot{Q}$ is the heating/cooling capacity of EAHE, given by Equation (2), $\dot{P}$ is the EAHE fan energy input [34].

$$\text{COP} = \frac{\dot{Q}}{\dot{P}} \tag{1}$$

$$\dot{Q} = \frac{n}{3600} V \cdot \rho \cdot C_p (T_{out} - T_{in}) \tag{2}$$

with,

C_p is the specific heat capacity of air ($J.kg^{-1}.K^{-1}$);
$\Delta T = (T_{out} - T_{in})$ is the EAHE inlet/outlet temperature difference (°C);
ρ is the air density ($kg.m^{-3}$);
n is the number of air changes per hour;
V is the volume of each greenhouse (m^3).

$$\dot{P} = I \cdot U \tag{3}$$

with,

I is the electrical current used by the fan (A).

U is the fan supply voltage (V).

The uncertainty values related to $\dot{Q}$, $\dot{P}$, and COP were found as 2.50%, 2.64%, and 3.64%, respectively.

5. Results and Discussion

Table 4 shows the calculated EAHE COP (The highest values of Open/Closed loop are in bold text style). It shows that the open loop in heating mode has a better COP. While the closed-loop in cooling mode has a better COP. However, the average temperature of the exhaust air of the EAHE system is 13 °C.

Table 4. Relation between Open/Closed loops and maximum $COP_{heating}/_{cooling}$.

$COP_{heating}$	Closed loop	A1	A2	B1	B3	B4
		1.6	1.3	**1.3**	0	0.9
	Open loop	A3	A4	B2	B5	B6
		0.5	**3.4**	0.4	**0.2**	**1.1**
$COP_{cooling}$	Closed loop	A1	A2	B1	B3	B4
		3.2	2.7	**3.2**	**2.8**	**3.2**
	Open loop	A3	A4	B2	B5	B6
		0.5	**7.3**	0.5	0.6	3

Figure 4 shows the variations in temperature and humidity inside and outside the greenhouses. The figure shows that as the air temperature decreases, the humidity increases, and at less than 15 °C drives to the humidity exceeds the levels already mentioned as harmful to plants (>80–90%) [20]. The differences between the GH and GH + EAHE microclimates range from 2.5 C to 5 C in air temperatures, and the differences in relative humidity vary from 8% to 12%. GH + EAHE microclimates' relative humidity is lower compared to GH. The increase in humidity at night is due to the decrease in temperature, which leads to increased condensation. However, in A3 and A4, the air temperature at night was warmer than in GH + EAHE. In addition, the air temperature was cooler during the day. It must be emphasized that the GHs with microclimates at reduced scale are only used to study the differences that occur when the EAHE system is used, and the design isn't the same as industrial GH.

Figure 5 shows the heaters with different set temperatures, where T_{set} = 18 °C in B1 and B2, T_{set} = 20 °C in B3, and T_{set} = 15 °C in B4, B5, and B6. However, GH and GH + EAHE are quite similar, the differences in air temperatures in the microclimates are between 3.5 °C and 7.5 °C.

Figure 6 shows the differences in relative humidity variations in the microclimates of the GHs. The highest values are measured at night in the GH + EAHE and range from 8.5% to 37.5%. We suspect that these values are due to condensation, and these measurements are consistent with the work of Qi et al. [18].

In Figure 7 it can be observed that the energy consumption becomes lower when the difference between the set temperature of the heater and the outlet air temperature of the EAHE system is smaller (outlet temperature ≈ soil temperature). However, if the difference is large enough, the EAHE system works as a pre-cooler and makes the heater consume more energy (B3: T_{set} = 20 °C and T_{out} = 13 °C).

More energy consumption equals more CO_2 emissions. For the average CO_2 content abroad in the combustion of fuels, the Portuguese value of the base carbon was taken from a publication of the International Energy Agency [35]. It follows:

$$\frac{m_{CO_2}}{E} = 0.255(\text{kgCO}_2/\text{kWh}) = 255(\text{gCO}_2/\text{kWh}) \rightarrow m_{CO_2} = 255 \cdot E \quad (4)$$

Figure 4. GHs air temperature/humidity variation during the experiences periods (heater device: Off).

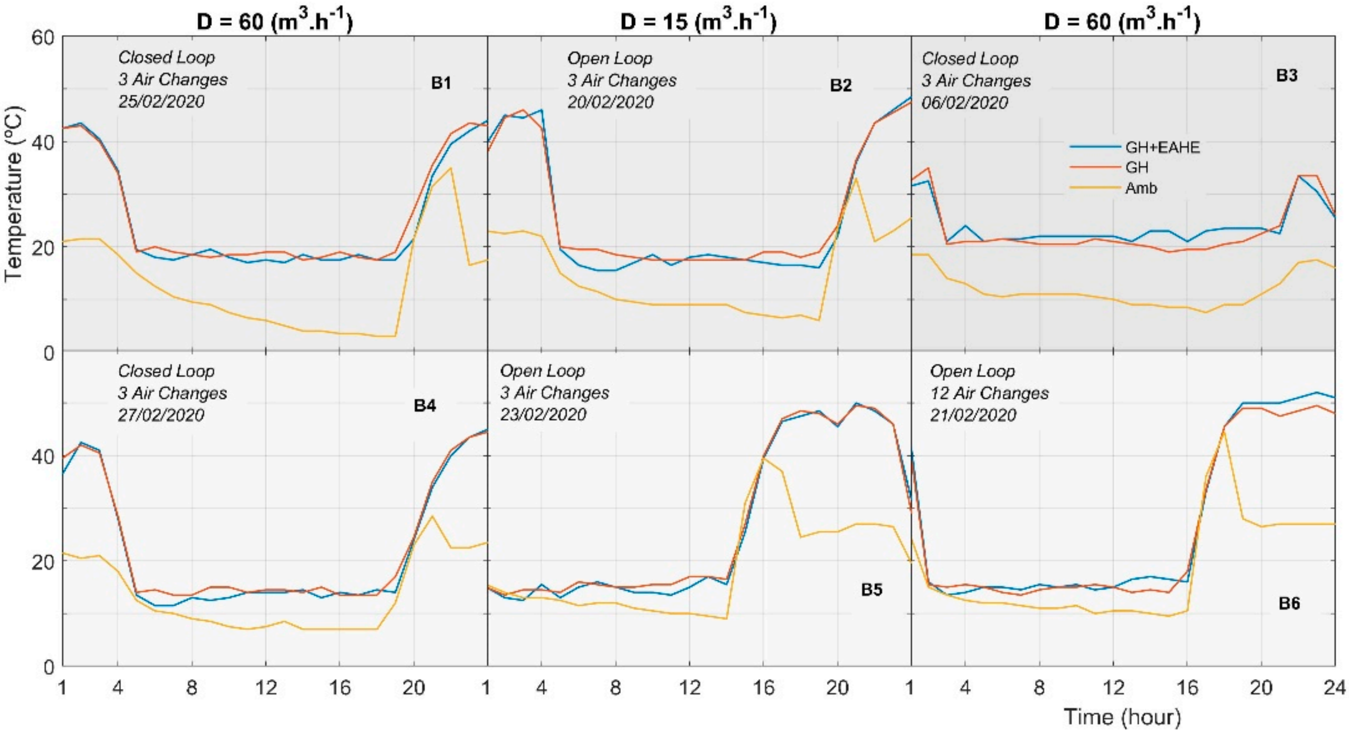


Figure 5. GHs air temperature variation during the experience's periods (heater device: On).

The measurements show that the highest CO_2 emissions belong to the B1 experience, where the value in the GH reached 359.55 g at 07:00 am. The B1 experience was conducted on a relatively cold day, where the outdoor temperature dropped to 3 °C (at 07:00) and the average temperature was 13 °C. The heater consumed 1.41 kWh of energy to maintain the air temperature at 18 °C in the GH. However, the energy consumption in the GH + EAHE greenhouse was 1.23 kWh with 313.65 g (CO_2) emissions.

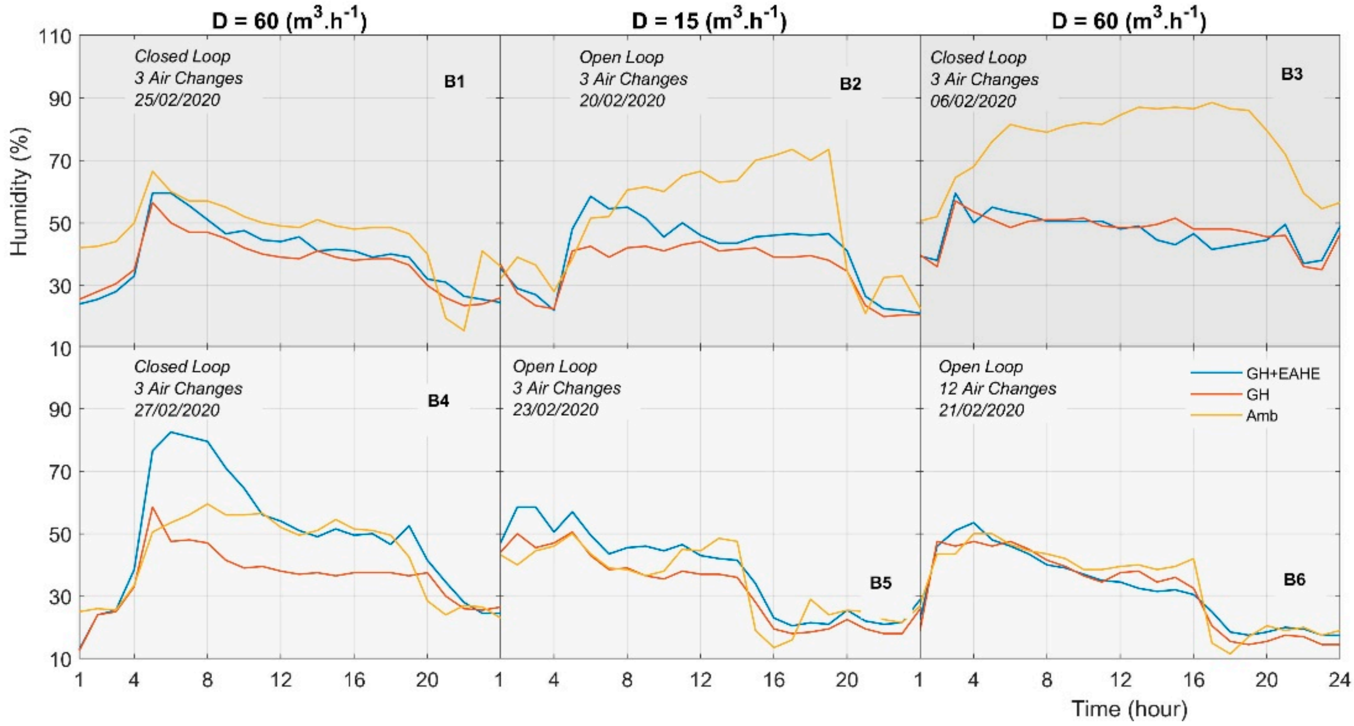


Figure 6. GHs air humidity variation during the experiences periods (heater device: On).

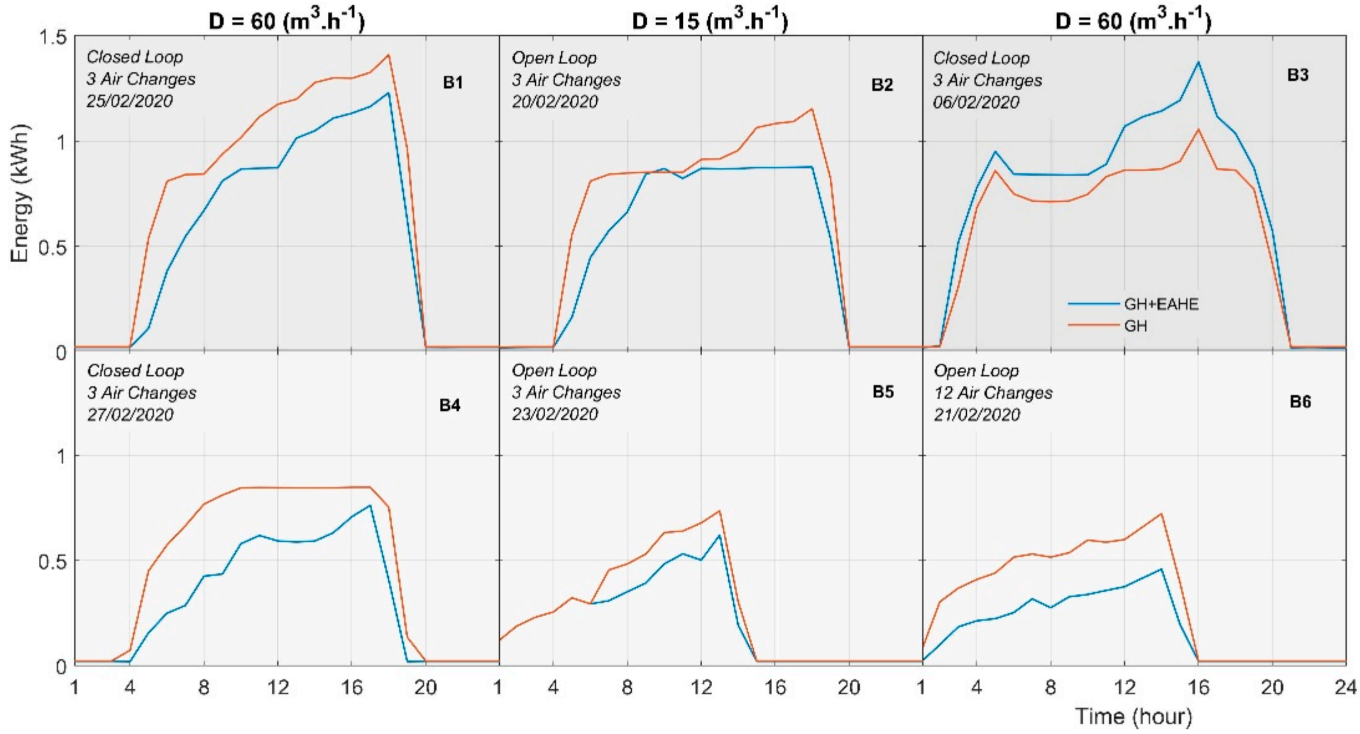


Figure 7. Energy consumption.

Even though the thermal performance was not significantly improved, 12.8% of gas emissions were reduced on a typical cold day (B1). Figure 7 shows that B4 has the largest decrease in energy consumption in GH + EAHE compared to GH, 44.7%. In this case study, the environmental parameters that could affect the improvement of thermal performance and the reduction of CO_2 emissions and energy consumption are indoor/outdoor temperature and humidity. Table 5 shows the novelty of the current study compared to the data in the literature.

Table 5. Parameter from literature.

Parameter	Ozgener et al. [28]	Tahery et al. [24]	Harjunowibowo et al. [29]	Benli [30]	Current Study
Location, Climate	Izmir, Turkey	Iran	Loughborough, UK	Elazig, Turkey	Covilhã, Portugal
GH size (m^3)	-	1600	142.87	150	5
EAHE Length (m)	47 Horizontal Closed loop	40 Horizontal Open loop	60 Vertical serpentine	246 Horizontal serpentine	29 Vertical spiral
Soil temperature (°C)	25	21	17	12	13
$COP_{Cooling}$ or	10	-	1.2	[2.9, 3.5]	[0.5, 7.3]
$COP_{Heating}$ or	6.3	-	2.1		[0, 3.4]
Heating supply (MJ/m^2)	-	119 44	-	-	-
Cooling supply (MJ/m^2)	-	212 160	-	-	-

The EAHE system and the greenhouse used in the current study are not industrial, which can be seen as a limitation. The small greenhouses had no windows. In addition, the EAHE system used in our study occupied 1 m^3 of soil volume under 3 m. This study focused on the thermal performance of GH + EAHE and the environmental impact achieved in the western border region of Europe during the winter season. The results obtained can be sized to other GH and EAHE systems. The feasibility of the test was demonstrated by the sustainability of the EAHE system, which can be used as a pre-cooler in summer and a preheater in winter.

6. Conclusions

- In this case study, where the temperature at 3 m depth is 13 °C, the vertical spiral tube is the shape of the EAHE system with a length of 29 m, the size of the greenhouse is $2 \times 1.4 \times 1.4$ m^3, February is the month of experience with specific variations in ambient temperature (from 29.5 to 4 °C) and ambient humidity (from 88.5 to 11.5%), the conclusion can be formulated as follows.
- The GH + EAHE open loop is the better option in heating mode. In cooling mode, the closed-loop is better.
- In this case study, the EAHE system reduced energy consumption for maintaining the temperature of the microclimate in the GH + EAHE by more than 40%. Gas emissions were also reduced by more than 10%.
- It is better to use a lower temperature difference between the set temperature in the heater and the outlet air temperature of the EAHE system, to avoid the EAHE system doing the opposite of what we used it for, resulting in higher energy consumption and more CO_2 emissions.
- On cold days, the heater operating time is more than 19 h, for example, B3. For this reason, the use of the EAHE system is recommended in terms of reducing energy consumption and CO_2 emissions.

Although the EAHE system reduces the heating energy consumption, the humidity measurements for GH + EAHE are higher than for GH. Further research is needed to control relative humidity. In future work, a dehumidification (DH) system will be installed in the EAHE system entrance, and the results of this study will be used to conduct the new research. Based on the GH models, the effects of EAHE + DH performance on temperature and humidity distribution in GHs will be studied.

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Nomenclature

Amb	Ambient
C_p	Specific heat capacity of air ($J.kg^{-1}.K^{-1}$)
CFD	Computational Fluid Dynamic
COP	Coefficient of Performance
D	Dimension
EAHE	Earth-to-air heat exchanger
GH	Greenhouse
I	Electrical current used by the fan (A).
in/out	EAHE inlet/outlet
m	Mass of CO_2 emissions (g)
n	Number of air changes per hour
$\dot{P}$	EAHE fan energy input
$\dot{Q}$	Heating/cooling capacity of EAHE
ρ	Air density ($kg.m^{-3}$)
T	Temperature (°C)
U	Fan supply voltage (V).
V	Greenhouse volume (m^3)

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