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Sustainable Cooling Solutions for Greenhouses under Humid Tropical Climate: A Preliminary Study of a Ground-to-Air Heat Exchanger Cooling System

Nemli Tropikal İklimde Sera İçin Sürdürülebilir Soğutma Çözümleri: Topraktan-Havaya Isı Değiştirici Soğutma Sisteminin Ön Çalışması

Ayorinde Abd-Qudus ASIRU [1]
Mobolaji Oluyimika OMOBOWALE [1]
Timothy Denen AKPENPUUN [2]
Yahaya MIJINYAWA [1]
Misbaudeen Aderemi ADESANYA [3]

[1]: University of Ibadan, Faculty of Technology, Department of Agricultural and Environmental Engineering, Ibadan, Nigeria
[2]: University of Ilorin, Department of Agricultural and Biosystems Engineering, Ilorin, Nigeria
[3]: University of Prince Edward Island, Faculty of Sustainable Design Engineering, Future Urban and Energy Lab for Sustainability, Charlottetown, Canada

ABSTRACT

Greenhouse agriculture in humid tropical regions faces significant challenges due to excessive heat and humidity, which compromise crop productivity and necessitate energy-efficient cooling solutions. This study evaluates the performance of a ground-to-air heat exchanger (GAHE) for greenhouse cooling under the humid tropical climate of Ibadan, Nigeria. The GAHE system, comprising underground PVC pipes at 1 m and 2 m depths, was designed. Experimental trials measured inlet and outlet temperatures over 35 days, revealing that the 2 m depth achieved a mean cooling of 2.99 ± 1.01 °C, with maximum reductions of 4.45 °C. In contrast, the 1 m depth provided negligible cooling (0.06 ± 0.43°C) and occasionally increased air temperature due to soil heat absorption. Results demonstrate that deeper installation leverages stable subsurface temperatures, mitigating daytime thermal fluctuations and solar influence. The findings align with prior studies emphasising depth-dependent efficiency and validate GAHE's potential as a low-energy cooling strategy in tropical greenhouses. This study concludes that GAHE systems installed at 2 m depth offer a sustainable and practical solution for greenhouse temperature control in humid tropics.

Keywords: Earth-Air heat exchanger, Greenhouse cooling, Ground-to-air heat exchanger

ÖZ

Nemli tropikal bölgelerde sera tarımı, aşırı ısı ve nem nedeniyle önemli zorluklarla karşı karşıyadır. Bu durum, ürün verimliliğini azaltmakta ve enerji açısından verimli soğutma çözümlerini gerekli kılmaktadır. Bu çalışma, Nijerya'nın Ibadan şehrindeki nemli tropikal iklim koşullarında, seralarda soğutma amacıyla kullanılan topraktan-havaya ısı değiştiricisinin (GAHE) performansını değerlendirmektedir. GAHE sistemi, 1 m ve 2 m derinliklerde yerleştirilmiş yer altı PVC borularından oluşacak şekilde tasarlanmıştır. 35 gün süren deneysel çalışmalarda, giriş ve çıkış sıcaklıkları ölçülmüştür. Bulgulara göre, 2 m derinlikte ortalama 2,99 ± 1,01 °C'lik bir soğutma sağlanmış ve maksimum 4,45 °C'lik sıcaklık düşüşleri gözlemlenmiştir. Buna karşılık, 1 m derinlikteki sistem neredeyse hiç soğutma sağlamamış (0,06 ± 0,43 °C) ve toprak ısısı nedeniyle zaman zaman hava sıcaklığını artırmıştır. Sonuçlar, daha derin kurulumların kararlı yer altı sıcaklıklarından faydalandığını, gündüz ısı dalgalanmalarını ve güneş etkisini azalttığını göstermektedir. Bulgular, önceki çalışmalarla tutarlıdır ve derinliğe bağlı verimliliğin önemini vurgulayarak GAHE sisteminin tropikal seralar için düşük enerjili bir soğutma stratejisi olarak potansiyelini doğrulamaktadır. Bu çalışma, 2 m derinliğe kurulan GAHE sistemlerinin nemli tropik bölgelerde sera sıcaklık kontrolü için sürdürülebilir ve uygulanabilir bir çözüm sunduğu sonucuna varmaktadır.

Anahtar Kelimeler: Yer-Hava ısı değiştirici, Sera soğutma, Yerden-havaya ısı değiştirici

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Corresponding author / Sorumlu Yazar: Ayorinde Abd-Qudus ASIRU
E-mail: ayorinde.asiru@gmail.com
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Introduction

The global agricultural sector faces unprecedented challenges in the 21st century, driven by population growth, urbanisation, and climate change. As the demand for food security intensifies, controlled-environment agriculture (CEA) systems, particularly greenhouses, have emerged as critical tools for enhancing crop productivity, optimising resource use, and mitigating climate-related risks (Adesanya et al., 2022; Yakub et al., 2024;). However, the efficacy of greenhouse systems is highly dependent on their ability to maintain optimal micro-climatic conditions, especially in regions characterised by extreme environmental stressors (Akpenpuun & Mijinyawa, 2020). A humid tropical climate, with its persistently high temperatures, elevated humidity levels, and intense solar radiation, presents unique challenges for greenhouse operators. Excessive heat accumulation within these structures can lead to thermal stress in crops, reduced yields, and increased susceptibility to pests and diseases (Akpenpuun et al., 2023). Consequently, developing sustainable and energy-efficient cooling solutions tailored to these regions has become a pressing priority for agricultural researchers and engineers.

Cooling is a considerable challenge to greenhouse agriculture under tropical conditions as the abundance of solar radiation results in high temperature during the day and this high temperature within the greenhouse has several detrimental effects on the crops within the greenhouse as it has been recorded to result in loss of plant stem strength, reduction in flower size, delayed flowering, and reduced fruit set in crops (Nayak et al., 2016).

As such, in tropical regions, cooling is a necessity to mitigate against the high-temperature regime within the greenhouse under tropical conditions. Although there have been extensive studies of greenhouse climates, there still exists the need to develop an environmentally friendly and resource-efficient cooling system for greenhouses in the humid tropics. Earlier studies have shown that conventional cooling methods, such as the use of a fan and pad cooling system, are unsatisfactory for humid tropical environments (Arbel et al., 2003). The most common method of cooling greenhouses in tropical and subtropical regions is the use of a fan and pad cooling system, however, they are both resource-intensive and inefficient (Pakari & Ghani, 2019). The efficiency of any evaporative cooling system such as a fan and pad system of cooling is dependent on bringing air tempera-ture down to the wet bulb temperature of the air and increasing the humidity of the air, however, under humid tropical conditions, the relative humidity of the air is al-ready high thereby limiting the amount of cooling which can be achieved by evapora-tive cooling under this climatic condition. The practical use of an evaporative cooling system under humid conditions is limited by the fact that there exists a relatively small temperature difference between the wet bulb and dry bulb temperature (Duan et al., 2012). As such, the use of an evaporative cooling system is neither practical nor sufficient to improve greenhouse productivity under tropical and subtropical conditions (Kumar et al., 2009). It is, therefore, necessary that concerted efforts are made to address this challenge so that the benefits associated with the use of the greenhouse can be realised. The use of thermal energy storage systems has been identified as a potential solution to the problem, as it can potentially lead to a reduction in greenhouse gas emissions and increase operational efficiency of greenhouses (Adesanya et al., 2024).

The near-constant thermal energy of the soil could provide adequate storage for the extraction of heat from greenhouses (Nayak et al., 2016). A system of using the earth's subsurface warmth to raise or lower the temperature of the air passing through a heat exchanger is known as a ground-to-air heat exchanger (GAHE or EAHE). The EAHE is made up of a system of underground pipes. To guarantee the best possible heat transmission between the air and soil, an appropriate fan circulates air inside the underground pipes at a predetermined flow rate. The EAHE's primary benefits includes: (1) easy de-sign and straightforward installation; (2) adaptability to various soil types; (3) use of air as the working fluid; (4) low maintenance costs; and (5) a clean and eco-friendly system free of combustion and pollutant emissions (Bordoloi et al., 2018; Bughio et al., 2022; Castro et al., 2024; Koshlak 2025; Mohammadi & Jahang-ir, 2024; Sakhri et al. 2020; Yue et al., 2024; Zhang, 2020).

Ground-to-air heat exchanger (GAHE) systems represent a compelling yet under-studied solution for greenhouse cooling in tropical climates. GAHEs leverage the earth’s subsurface thermal inertia, where soil temperatures at depths of 2–4 meters remain relatively stable and cooler than ambient air in tropical regions. By circulating greenhouse air through buried pipes, GAHEs facilitate heat exchange between the warm air and the cooler soil, thereby reducing the temperature and humidity of the air before reintroducing it into the greenhouse. This passive cooling mechanism requires minimal energy input, relying primarily on low-power fans or natural convection, and avoids the humidity-related drawbacks of evaporative methods.

GAHE systems have demonstrated success in temperate climates for space heating and cooling in buildings, with studies reporting temperature reductions of 5–15°C depending on soil properties and system design (Koshlak 2025; Mongkon et al., 2014; Sakhri et al., 2020). However, their application in humid tropical greenhouses remains

poorly explored. The feasibility of GAHEs in such regions hinges on several factors: the thermal conductivity of local soils, groundwater table fluctuations, pipe material and configuration, and the dynamic interplay between heat exchange rates and humidity control.

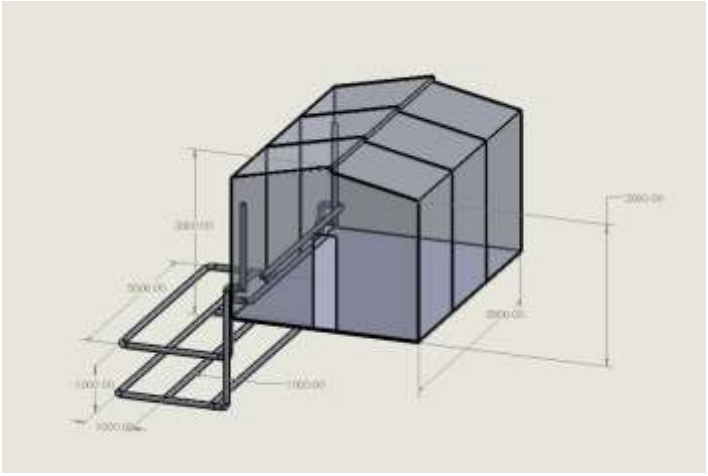
There is limited research into the effectiveness of the use of ground heat exchangers in the cooling of greenhouses under tropical conditions. This study, therefore, seeks to develop a ground-to-air heat exchanger for cooling greenhouses under the humid tropical conditions of Ibadan, Nigeria.

Methods

Design and Performance Evaluation of Ground Heat Exchanger

The design and performance evaluation of the ground heat exchanger was carried out in line with the methodology of Mongkon et al. (2014). Figure 1 shows the schematic diagram of the system integrated into a greenhouse.

Figure 1.
Schematic diagram of the greenhouse with a ground heat exchange



For the design of the ground-to-air heat exchanger, the following assumptions and greenhouse parameters were used

i. The air temperature within the greenhouse is set at 30 °C.
ii. Greenhouse length is 5.8 m
iii. Greenhouse width is 4 m
iv. The greenhouse height at the eave is 3 m
v. The greenhouse height at the ridge is 3.5 m
vi. The specific heat capacity of the air $C_p\ is\ 1006\ J/(kg.K)$
vii. The specific heat capacity of the PVC pipe is 0.19 w/m^2K

$$\text{Greenhouse Floor area} = \text{Greenhouse length} \times \text{Greenhouse width}$$

$$\text{Floor area} = 5.8 \times 4 = 23.2\ m^2$$

$$\text{Greenhouse Volume} = \text{Volume of the Rectangular Section} + \text{Volume of Triangular Section}$$

$$\text{Greenhouse Volume} = 5.8 \times 4 \times 3 + 0.5 \times 4 \times 0.5 \times 5.8$$

$$\text{Greenhouse Volume} = 75.4\ m^3$$

For a temperature rise of less than 4 °C above the ambient air temperature, the airflow rate should be between 0.04 and 0.05 m^3/s per m^2 of floor area (FAO, 2011). Therefore, the required airflow rate is

$$\text{Airflow rate} = 0.05 \times 23.2$$

$$\text{Airflow rate} = 1.16 m^3/s$$

For the design of an earth-air heat exchanger, the mass flow rate of air must be specified and determined by the equation (Mongkon et al., 2014)

$$\text{Mass Flow Rate } \dot{m}_{air} = \rho_{air} \frac{\pi D^2}{4} \times v_{air}$$

Where

ρ_{air} at 30 °C = 1.297

D = 101.6 mm = 0.1016m

v_{air} = 1.16 m/s

$$\dot{m}_{air} = 1.297 \times \frac{3.142 \times 0.1016^2}{4} \times 1.16$$

$$\dot{m}_{air} = 0.01222\ kg/s$$

The convective heat transfer during the mass flow of air was determined by the equation (Kumar et al., 2009).

$$h = \frac{N_u K}{D}$$

where

N_u is the Nusselt number, if the airflow is laminar, $N_u = 3.66$

If airflow is turbulent $N_u = \frac{\frac{\xi}{8}(Re-1000)Pr}{1+12.7\sqrt{\frac{\xi}{8}}(Pr^{\frac{2}{3}}-1)}$

$\xi = (1.82 \log Re - 1.64)^{-2}$ If Reynold's number < 5×10^6

K: specific heat capacity of the pipe

D: Diameter of the pipe in m

The Reynold's number for the airflow is calculated from

$$Re = \frac{\rho v D}{\mu}$$

The kinematic viscosity of air at a specific temperature is calculated from

$$\mu = \mu_0 \left(\frac{T}{T_o}\right)^{1.5} \left(\frac{T+S}{T_o+S}\right) = 1.716 \times 10^{-5} \left(\frac{300.15}{273.15}\right)^{1.5} \left(\frac{300.15+110}{273.15+110}\right)$$

$$\mu = 1.716 \times 10^{-5} \times 1.1518 \times 1.0704 = 0.000021156$$

$$\mu = 2.1156 \times 10^{-5}$$

Substituting kinematic viscosity into the formula for Reynold's number

$$Re = \frac{\rho v D}{\mu} = \frac{1.297 \times 1.16 \times 0.1016}{2.1156 \times 10^{-5}}$$

$$Re = 7225.222$$

Since Reynold's number is greater than 2300, the flow is turbulent. Therefore, the friction factor is determined by the equation

$$\xi = (1.82 \log Re - 1.64)^{-2} = (1.82 \log 7225.222 - 1.64)^{-2}$$

$$\xi = 0.0345$$

The Nusselt number is given by

$$N_u = \frac{\frac{\xi}{8}(Re - 1000)Pr}{1 + 12.7\sqrt{\frac{\xi}{8}}\,(Pr^{\frac{2}{3}} - 1)}$$

$$N_u = \frac{\frac{0.0345}{8}(7225.22 - 1000)0.71}{1 + 12.7\sqrt{\frac{0.0345}{8}}\,(0.71^{\frac{2}{3}} - 1)}$$

$$N_u = 22.868$$

Therefore, the convective heat transfer

$$h = \frac{N_u K}{D} = \frac{22.868 \times 0.19}{0.1016}$$

$$h = 42.7649$$

For an EAHE, optimal efficiency of the system is recommended at 80% (De Paepe & Janssens, 2003) and calculated from the formulae

$$\epsilon = 1 - e^{-NTU}$$
$$0.8 = 1 - e^{-NTU}$$
$$NTU = 1.61$$
$$NTU = \frac{hA}{\dot{m}C_{air}}$$
$$1.61 = \frac{42.7649 \times A}{0.012 \times 1006}$$
$$A = 4.5448\ m$$

Note that

$$A = \pi D L$$
$$4.5448 = 3.142 \times 0.1016 \times L$$
$$L = 14.2368\ m$$

The required length of the pipe for the EAHE system is 14.24m.

Sizing of blower

For a ground-to-air heat exchanger used in the greenhouse, the greenhouse needs to attain an air exchange of every two to every five minutes, cumulating in twelve to thirty air exchanges per hour (Schiller & Plinke, 2016).

1 m^3 = 35.3147 ft^3

$$\text{Greenhouse Volume} = 75.4 \times 35.3147$$

$$\text{Greenhouse Volume} = 2{,}661.92\ ft^3$$

For an air exchange every five minutes

$$\text{Fan Size} = \frac{\text{Greenhouse Volume}}{\text{No of Air Exchange Required}}$$

$$\text{Fan Size} = \frac{2661.92}{5} = 532.38\ CFM$$

Installation of the Ground heat exchanger

The ground heat exchanger was installed at two depths, 1m and 2m depth in the soil to evaluate the performance. Each layer was independent of the other and therefore fully operational. Figure 2 – 4 shows the installation of the heat exchanger.

Results

Figure 3 shows the inlet and outlet temperatures of the ground-to-air heat exchanger at an operating depth of two metres. The results indicate that outlet temperature is lower than the inlet temperature at the heat exchanger, signifying that cooling is taking place. Figure 4 shows the temperature difference between the inlet and the outlet, indicating the change in temperature between the two points. The minimum temperature difference is a reduction of 0.4 °C, while the maximum cooling of 4.45 °C was achieved. Overall, the mean cooling achieved was 2.989 ± 1.0149 °C. This shows that at a 2m depth of operation a ground heat exchanger under the humid tropical conditions provides a 2.989 ± 1.0149 °C cooling under the dry season conditions.

Figure 2.
Heat exchanger installation at 1.0 m



Figure 3.
Heat Exchanger installation at 2.0 m



Figure 4.
Heat exchanger incorporated with the greenhouse



Evaluation of the Ground Heat Exchanger (GHE)

To evaluate the cooling from the ground to air heat exchanger, k-type thermocouples were installed at the inlet and the outlet of the system within the greenhouse. The inlet temperature and the outlet temperature of the cooling system were recorded at every five-minute interval between 9 am and 5 pm. This was aggregated to determine the mean cooling per day from December 05 2023, to January 09 2024. The mean cooling was calculated from the difference between the inlet temperature and the outlet temperature of the heat exchanger.

Figure 5 shows the inlet and outlet temperatures at the ground-to-air heat exchanger operating at a 1m depth. The overlapping nature of the graph indicates that the inlet temperature and the outlet temperature are quite similar as such the degree of cooling achieved at the 1m depth is typically unsatisfactory.

Figure 5.
Inlet and outlet temperature at 2m of operation



Figure 6 presents the difference in the temperature between the inlet and the outlet of the ground-to-air heat exchange at the 1 m depth. At this depth, the maximum cooling achieved was a 0.95 °C while the minimum was -0.76 °C. the negative sign indicates that the outlet air was hotter than the inlet air as such the air gained additional heat energy while passing through the heat exchanger. The mean change in temperature recorded was 0.058 ± 0.432 °C.

Figure 6
Degree of cooling achieved at 2m depth

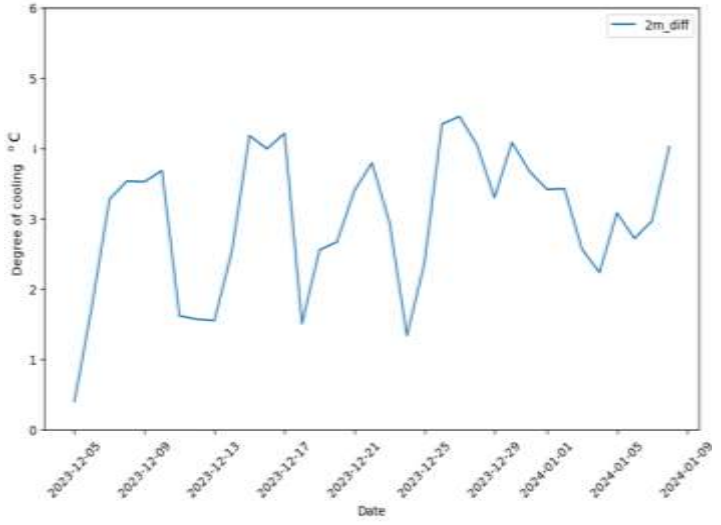


Figure 7 shows the inlet and outlet temperatures at the ground-to-air heat exchanger operating at a 1m depth. The overlapping nature of the graph indicates that the inlet temperature and the outlet temperature are quite similar as such the degree of cooling achieved at the 1m depth is typically unsatisfactory.

Figure 8 presents the difference in the temperature between the inlet and the outlet of the ground-to-air heat exchange at the 1 m depth. At this depth, the maximum

cooling achieved was a 0.95 °C while the minimum was -0.76 °C. the negative sign indicates that the outlet air was hotter than the inlet air as such the air gained additional heat energy while passing through the heat exchanger. The mean change in temperature recorded was 0.058 ± 0.432 °C.

This graph shows that on average at the 1m depth, cooling and heating of the inlet air takes place. As such on some days of operation, there was an increase in the temperature of the air at the outlet of the heat exchange. This indicates that the temperature of the air entering the ground was lesser than the temperature of the soil at the 1 m depth thereby allowing the heating of the air by the ground. For the humid tropical region, the heat of air by the ground-to-air heat exchanger is an unwanted effect as the temperature within the greenhouse in this region is already high enough to necessitate the cooling of the greenhouse.

Figure 7.
Inlet and outlet temperature at 1m depth of operation

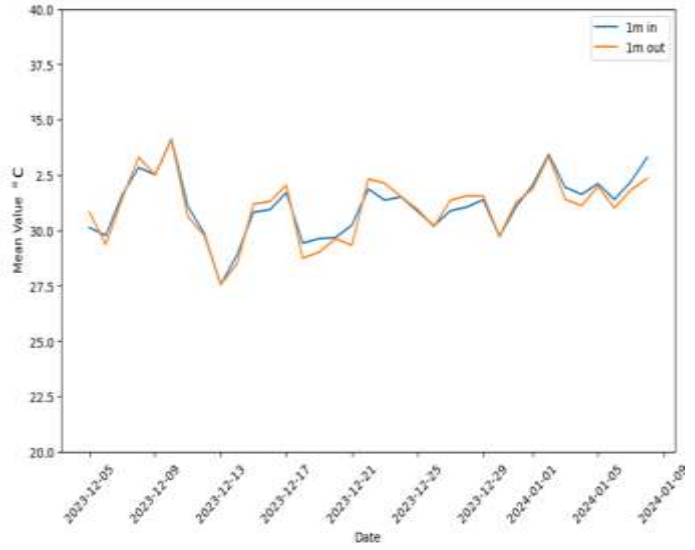
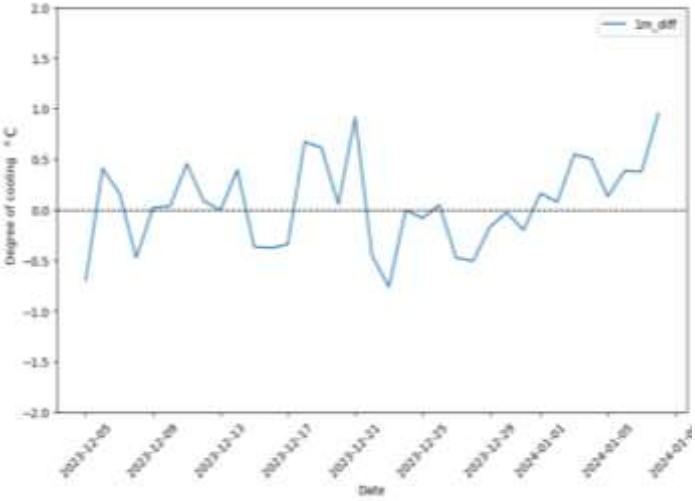


Figure 81.
Temperature difference in the inlet and the outlet of the 1m depth EAHE



Discussion

Although several experimental investigations of the effect of depth on the performance of EAHE have been carried out, the conclusions differ, with some concluding that performance at 1 m depth of operation is satisfactory and adequate (Schiller & Plinke, 2016) while others at deeper depths conclude that the performance at between 2 and 3 m operation is satisfactory (Diaz-Hernandez et al., 2020). The results from this study highlight the differences between the performance of the earth-to-air heat exchanger when operated at two different depths. While the result of the 2 m depth of operation aligns with the result of the study of Nayak et al. (2016), their result established an average of 3 - 4 °C cooling in the temperature of a greenhouse while using the earth air heat exchanger for greenhouse cooling under summer conditions.

The heat exchanger at 1 meter depth shows efficient heat transfer but appears to be more influenced by daily temperature fluctuations compared to the system at 2 meters depth. The higher temperatures at 1 meter depth suggest it may be more suitable for applications requiring higher operational temperatures. The results obtained at the 1 m depth of operation contradict the conclusion of previous research which concluded that although the ground temperature varies minimally at beyond 4m (Bharadwaj & Bansal, 1981), satisfactory performance can be obtained at 1 m depth of operation as long as the ground temperature is lower than 30 °C (Sanusi et al., 2013). Under the humid tropical conditions of Ibadan, Nigeria, the variability observed is not atypical, as the result agrees with previous research, which has established that the EAHE can behave as both a cooler and a heater based on the soil temperature (Diaz-Hernandez et al., 2020; Koshlak, 2025).

The overall temperature values are higher at the 1-meter depth compared to the 2-meter depth. This is due to less soil insulation and more direct influence from ambient air temperature at the shallower depth. This would indicate that the more stable ground temperature experienced at the two metre depth of operation plays a significant role in the cooling process, thereby providing more consistent cooling than is obtainable at the one metre depth of operation, where the effects of the solar insolation on the soil are still noticeable.

The trend of temperature rising and then declining is similar, suggesting a consistent pattern of heat absorption and release during the day at both depths of operation. This would indicate that at both the one metre depth of operation and the two metre depth of operation, the behaviour of the soil as a temperature absorbing mass is consistent with only minor environmental influence on the

one metre depth of operation, thereby resulting in a higher temperature at the outlet than is obtainable at the outlet of the two metre depth of operation.

Results from this study indicate that the performance of a ground heat exchanger is dependent on the depth of installation. For consistent and more stable temperature control, a deeper installation at a depth of 2 m performs better.

Conclusion

Results from this study indicate that the performance of a ground heat exchanger is dependent on the depth of installation. For consistent and more stable temperature control, a deeper installation at a depth of 2 m performs better. The result of this study indicates that a ground-to-air heat exchanger offers a promise for the cooling of a greenhouse under the humid tropical conditions of Ibadan, Nigeria. However, the depth of operation of the heat exchanger is crucial, as operating such a heat exchanger at 1 m depth limits the amount of cooling achieved while at a deeper depth of 2 m better cooling performance is obtained.

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