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Microclimate Fluctuations and Temperature Modelling of Naturally Ventilated Greenhouse Nurseries in Tropical Region

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Abstract

Wood production from industrial plantations in Indonesia has increased from 18.8 to 49.6 million m³ (2015–2022). This requires an increase in the supply of seedlings in terms of both quantity and quality. Generally, seedling production involves the use of seeds and cuttings in greenhouses, followed by their relocation outdoors once they are nearly ready for planting. The success of greenhouse seedling production is often hampered by challenges related to temperature increases beyond the tolerance limits of the seedlings, which disrupts their growth. This study aims to identify temperature fluctuations inside greenhouses where Eucalyptus seeds are grown as a source for the pulp and paper industry and to develop a heat transfer model suitable for the conditions of these greenhouses. Climate conditions inside and outside the greenhouses were measured using automatic weather stations at 30-min intervals over five months. The developed heat transfer model explains how external climate changes affect the temperature inside the greenhouse. Based on the greenhouse conditions, differences in temperature between the floor and roof can be disregarded, resulting in a simpler heat transfer model. This model yields a coefficient of determination (R^2) of 0.9051 and a root mean square error (RMSE) of 1.31°C. Temperature fluctuations inside the greenhouse are relatively more stable, with an average temperature 0.1°C lower and humidity 2.9% higher than those outside. A limitation of the model is its inability to accurately predict extreme outdoor temperatures. Therefore, this model requires further development, including considering the possibility of changes in heat transfer parameter values at more extreme temperatures.

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1. Introduction

The demand for wood as a raw material in the pulp and paper industry has increased. This is in line with data from Statistics Indonesia (Indonesia. Badan Pusat Statistik, 2023), which reported that roundwood production increased from 18.8 million m³ in 2015 to 49.6 million m³ in 2022. Indonesia

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ranks 8th globally in pulp production and 6th in paper production (Indonesian Pulp and Paper Industry Directory, 2019). Generally, seedling production for the pulp and paper industry involves the use of seeds and cuttings in greenhouses, followed by transplanting them outdoors once they are nearly ready for planting.

Greenhouses can protect plants from unfavorable environmental conditions, such as excessively low air temperatures, high rainfall, and strong winds (Suhardiyanto, 2022). Therefore, the use of greenhouses, which can disrupt agricultural productivity, is becoming increasingly important in response to climate change. This is further supported by evidence that climate change affects rainfall variability (Mohamed et al., 2022), whereas global warming increases rainfall intensity (Weber et al., 2018). Greenhouses were originally developed in subtropical climates to protect plants from low air temperatures during winter. In contrast, Indonesia has a humid tropical climate characterized by high solar radiation and rainfall intensity. Consequently, greenhouse designs in Indonesia differ from those in subtropical regions. The interaction between greenhouses and external climatic parameters results in the formation of a distinct internal microclimate, known as the greenhouse effect.

According to Bot (1983), the greenhouse effect is caused by restricted air movement due to the enclosed structure of the greenhouse, resulting in higher air temperatures inside than outside. Excessively high temperatures may hinder plant growth, highlighting the need to investigate thermal conditions within greenhouses. Plants subjected to extreme temperatures may experience reduced productivity, from the reproductive phase to fruit development, as well as disruptions in their phenological growth (Chaibi et al., 2022; Rabbi et al., 2019). The internal temperature is a critical factor that influences both optimal plant development and productive efficiency (Dimitropoulou et al., 2023)

Air temperature in greenhouses can be analyzed using a heat transfer model under unsteady-state conditions, which assumes that the air temperature is not constant but varies over time (Suhardiyanto, 2022). Constructing a physical model is particularly challenging because of the nonlinear and complex nature of greenhouses. This type of model primarily relies on thermodynamic principles, as well as heat and mass transfer processes. Consequently, parameters, such as solar radiation, and variables associated with thermal and mass exchanges, must be estimated with high accuracy (Choab et al., 2019; López-Cruz et al., 2018; Su & Xu, 2017). Most heat balance models are highly complex and challenging to develop because of the intricate parameters and computations; in contrast, commercial software tools tend to be cost-prohibitive for most designers (Ma et al., 2022).

A similar model has been developed for tropical climates by Suhardiyanto et al. (2007), considering variations in air temperature and solar radiation incidence angle within the greenhouse. Based on the study by Suhardiyariyanto et al. (2007), the daily total radiation values on sunny days (June 24, 26 , and30,ne 2006were 5.677m2, 5.3,m2 and 5.529 Wh/, respectivelym2. Meanwhile, on cloudy days (June 21–23, 2006), the daily total radiation values were 5.028, 4.616, and 4.692 Wh/m2, respectively. Air temperature inside based on study by Suhardiyanto et al. (2007) ranged 21 – 38 °C on sunny day and

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21 – 36 °C on cloudy day. However, the model is relatively complex as it also requires parameters such as roof temperature, floor temperature, and soil temperature, thus necessitating numerous sensors and advanced programming to solve the equations simultaneously. Therefore, simplification of the model is necessary to improve its practicality while still maintaining the ability to accurately predict air temperature inside the greenhouse. Unlike previous models that rely on multiple temperature and climate inputs, this study proposes a simplified approach requiring fewer parameters while maintaining predictive accuracy. Air humidity is not predicted here because this study refers to Suhardiyanto et al., (2007) which has good result without modelling the humidity. The simplification is justified because the model targets temperature prediction, where radiative and convective processes dominate, while humidity effects are indirect and secondary under natural ventilation. This study aims to identify temperature fluctuations inside greenhouses where Eucalyptus seeds are grown as a source of pulp and paper industry and to develop a heat transfer model suitable for the conditions of these greenhouses.

2. Material and Methods

2.1 Date and Location

The research was conducted from July 2024 to July 2025 at Jalan Carang Pulang, Cikarawang, Dramaga, Bogor (6°32'55.5" S, 106°43'56.0" E). The greenhouse condition is shown in Figure 1. The greenhouse was constructed with a northwest–northeast orientation, measuring 8 meters in length, 4 meters in width, and 4.2 meters in roof height. It was equipped with a fiberglass roof featuring slopes of 17° and 8°, a 70% shade net (paranet) installed beneath the roof, and 200-micron insect screens on the walls (see Figure 2 and Figure 3).

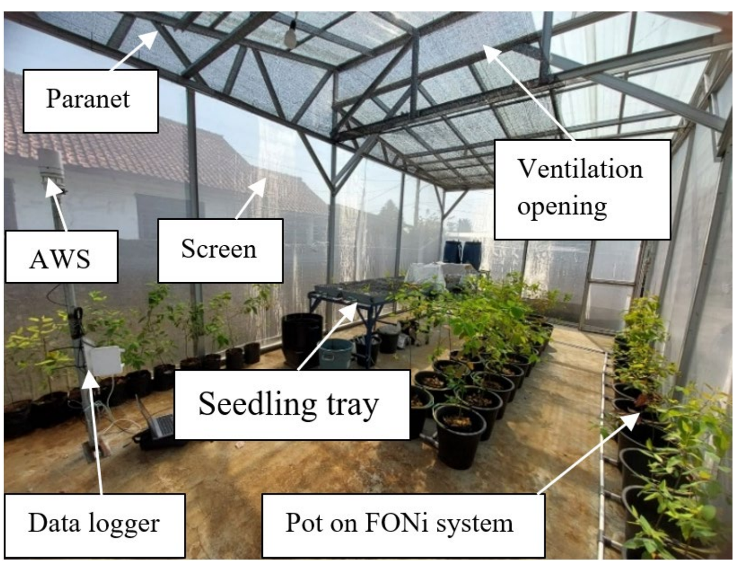

Figure 1. Greenhouse condition (10th October 2024).

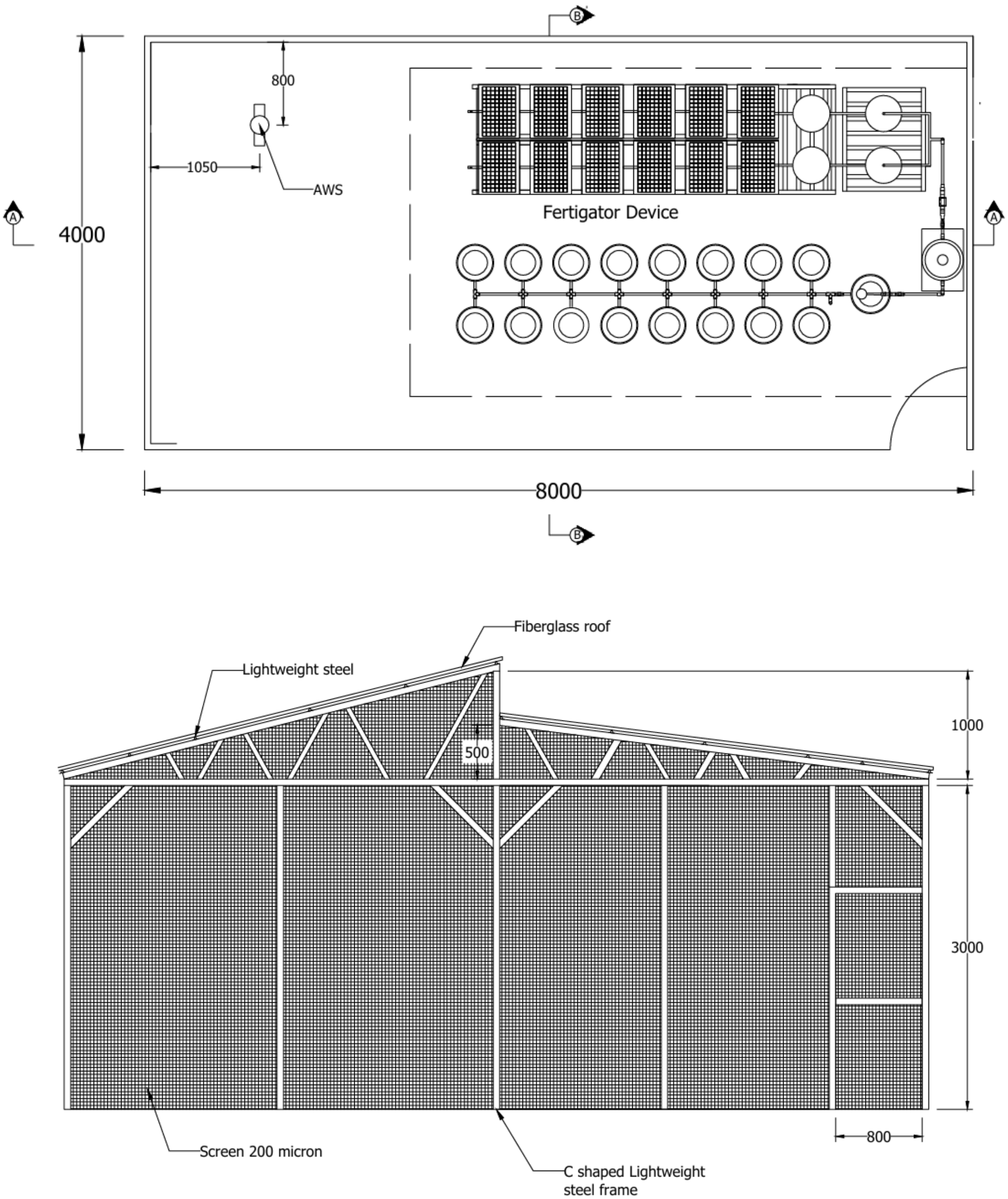

Figure 2. Floor plan and front view of the greenhouse.

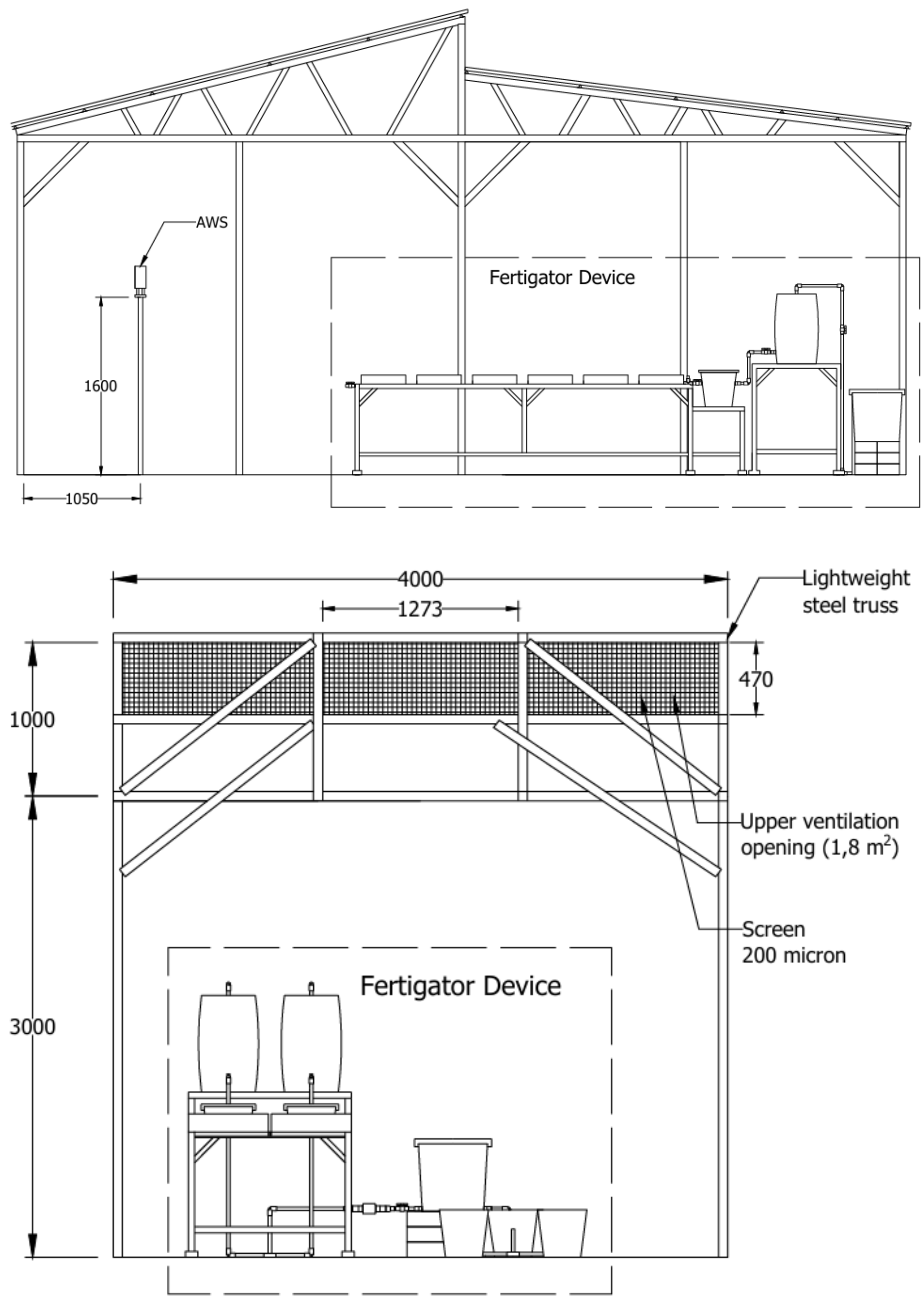

Figure 3. Section A-A and section B-B ofthe greenhouse.

According to Suhardiyanto (2022), the greenhouse shown in Figure 1 is classified as a Semi-Monitor type. This type is characterized by a roof design with unequal slopes and a ventilation opening between the two roof sections. Greenhouses are typically designed using only natural ventilation without any other cooling method. Natural ventilation is a fundamental approach that is widely adopted to manage the microclimate within greenhouses (Ghani et al., 2019; Ghoulem et al., 2019; Gruda et al., 2019; Taki et al., 2018).

2.2 Tools

An automatic weather station (AWS) was installed both outside and inside the greenhouse (see Figure 4). The AWS used inside the greenhouse was a Meter brand ATMOS 41, with data collected using a ZL6 data logger of the same brand. Outside the greenhouse, an Ecowitt WS6006 AWS was installed 20 m to the northeast of the indoor AWS. During the data collection period, the greenhouse was used for eucalyptus seedling cultivation and was equipped with seedling trays and pots installed in an evapotranspirative irrigation system named Fertigator Otomatis Nirdaya (unpowered automatic fertigation), known as FONi (Muharomah et al., 2024).

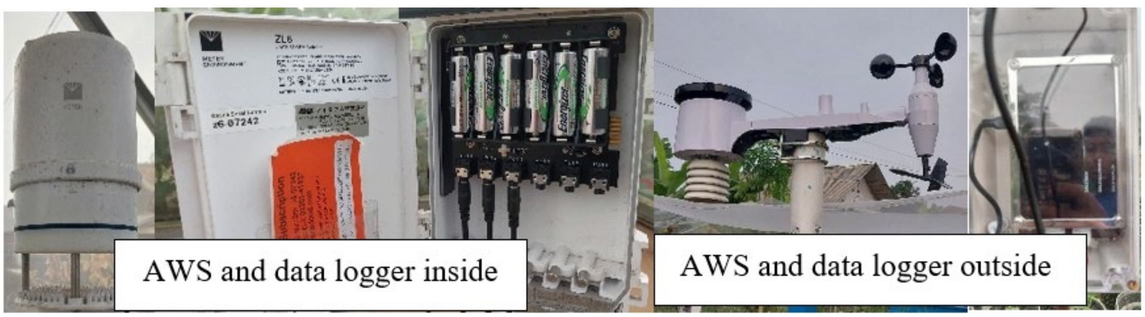

Figure 4. AWS and data loggers used in this study.

2.3 Microclimate Parameters

To characterize the greenhouse microclimate and develop a temperature prediction model, several environmental parameters were continuously measured both inside and outside the greenhouse during a five-month observation period. Data were measured using an ECOWITT WS6006 outside and an ATMOS41 outside, which was installed at a height of approximately 1.6 m above ground level, corresponding to the crop canopy zone. These sensors recorded data at 30-min intervals and were collected every 2 weeks using a laptop. A summary of the microclimate parameters is presented in Table 1.

Table 1 Microclimate parameters symbol and instrument used

Parameter	Symbol	Instrument
Air temperature inside greenhouse	T_{in}	ATMOS 41
Air temperature inside greenhouse	T_{out}	Ecowitt WS6006
Global solar radiation on a horizontal surface (outside)	I_o	Ecowitt WS6006
Relative humidity inside greenhouse	-	ATMOS 41
Relative humidity outside greenhouse	-	Ecowitt WS6006

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2.4 Data Analysis

To estimate evapotranspiration, the Hargreaves model was employed. This model requires only air temperature and solar radiation parameters; however, it demonstrates high accuracy compared with the FAO standard model (Penman–Monteith). A study by Arif et al. (2020), who used weather data from Bogor City in 2017 and 2018, reported R^2 values of 0.99 and 1, respectively, with root mean squared error (RMSE) values of 0.418 and 0.357, respectively. These findings are supported by Adlan et al. (2021), who showed that the Hargreaves model was the most comparable to the Penman–Monteith method based on R^2, RMSE, MAE, COVARIANCE, and LOG values using weather data from Aceh for the period 2010–2019. The Hargreaves method is presented in Equation 1 (Wu, 1997).

$$ETo = 0{,}0135(T_{mean} + 17{,}78)R_s\left(\frac{238{,}8}{595{,}5-0{,}55T_{mean}}\right) \quad (1)$$

Where ETo is the potential evapotranspiration (mm/day), T_{mean} is the mean air temperature (°C), R_s is the total solar radiation (MJ/m²/day).

The heat balance of the air inside the greenhouse is expressed by Equation 2 (Suhardiyanto et al., 2007)

$$c_a \times I \times \frac{dT_{in}}{dt} = h_i \times r \times (T_c - T_{in}) + h_f \times \left(T_f - T_{in}\right) + h_v \times (T_{out} - T_{in}) + Q_{st} \times \tau \times I_o \times K \quad (2)$$

where c_a is the volumetric specific heat of air inside the greenhouse (= 1000 J/m³/K), I is the average height of the greenhouse (= 3.3 m), h_i is the convective heat transfer coefficient from the roof to the air (W/m²/°C), r is the ratio of roof area to floor area, T_c is the roof temperature (°C), T_{in} is the air temperature inside the greenhouse (°C), h_f is the convective heat transfer coefficient from the floor to the air (= 7 W/m²/°C), T_f is the floor temperature (°C), h_v is the convective heat transfer coefficient due to ventilation-induced airflow (= 3 W/m²·°C), T_{out} is the outside air temperature (°C), Q_{st} is the sensible heat absorbed by the plants (= 0.3), τ is the transmissivity of the greenhouse covering material (= 0.6), I_o is the global solar radiation on a horizontal surface (W/m²), and K is the cosine of the solar incidence angle.

The assumptions used, according to Suhardiyanto et al. (2007), include a constant h_v throughout the simulation. Additionally, the mass of air inside the greenhouse is not considered, and the airflow within the greenhouse is assumed to be uniform in the horizontal direction. In this study, the model was simplified by assuming that the roof and floor temperatures are equal to the air temperature, thereby eliminating heat transfer from the roof and floor surfaces. Consequently, by assuming $T_c = T_{in} = T_f$, Equation 2 can be rewritten as:

$$\frac{dT_{in}}{dt} = \frac{h_v \times (T_{out}-T_{in}) + Q_{st} \times \tau \times I_o \times K}{c_a \times I} \quad (3)$$

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By considering $\frac{dT_{in}}{dt} = f(t, T_{in})$, equation 3 can be resolved by Runge-Kutta 4th order (RK4) with equation 4 to equation 8 (for n = 0, 1, 2, 3, …)

$$k_1 = f(t_n,\ T_{in,n}) \tag{4}$$

$$k_2 = f(t_n + \frac{h}{2}, T_{in,n} + \frac{h}{2} \cdot k_1) \tag{5}$$

$$k_3 = f(t_n + \frac{h}{2}, T_{in,n} + \frac{h}{2} \cdot k_2) \tag{6}$$

$$k_4 = f(t_n + h, T_{in,n} + h \cdot k_3) \tag{7}$$

$$T_{in,n+1} = T_{in,n} + \frac{h}{6}(k_1 + 2k_2 + 2k_3 + k_4) \tag{8}$$

where h is timestep (s), k_1 is the slope at the beginning of the interval, using T_{in} (Euler's method); k_2 is the slope at the midpoint of the interval using T_{in} and k_1; k_3 is the slope at the midpoint using T_{in} and k_2; k_4 is the slope at the end of interval using T_{in} and k_3.

The coefficient values for c_a, h_v , Q_{st}, τ and the variable K refer to Suhardiyanto et al. (2007). Temperature was calculated at 30-minute intervals, consistent with the data interval from the AWS. The inputs for Equation 3 included T_{in} (at 00:00, as the initial condition), along with T_{out}, and I_o.

After solving using RK4, the coefficients in Equation 3 were calibrated using the Solver tool in Microsoft Excel with the objective is to maximize the cofficient of determination (R^2) by changing Q_{st}, which the result is Q_{st} = 0. For validation, the coefficient root mean squared error (RMSE) were calculated by comparing the modeled T_{in} values with the measured T_{in} from the AWS.

3. Results and Discussion

3.1 Climate Fluctuations

The data used in this study were collected from July 17, 2024, to December 15, 2024. The average air temperature inside the greenhouse was 27.3 °C, with a maximum of 36.3 °C and a minimum of 20.7 °C. The average relative humidity was 78.4%. The daily air temperature and relative humidity inside the greenhouse are presented in Figure 5a, whereas those outside the greenhouse are shown in Figure 5ab.

The average air temperature outside the greenhouse was 27.4 °C, with a maximum of 36.3 °C and a minimum of 20.7 °C, while the average relative humidity was 77.5%. During this period, the air inside the greenhouse was cooler and more humid than outside. Moreover, based on Figures 5a and 5b, the highest average air temperature inside the greenhouse occurred on July 27, 2024, at 29.2 °C, while outside the greenhouse it occurred on October 26, 2025, at 29.5 °C. These results contradict the findings of Arif et al., (2008), who reported that air temperature inside greenhouses is generally higher than outside.

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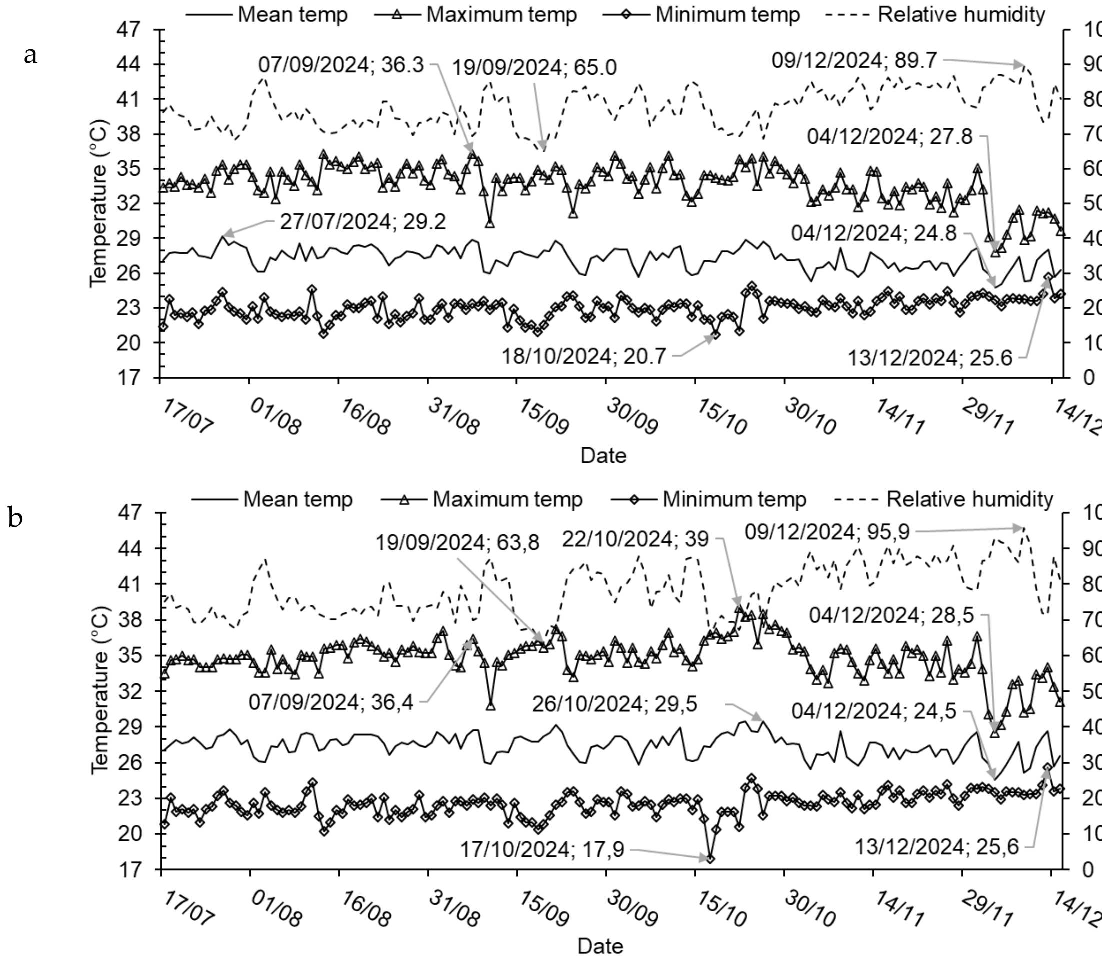
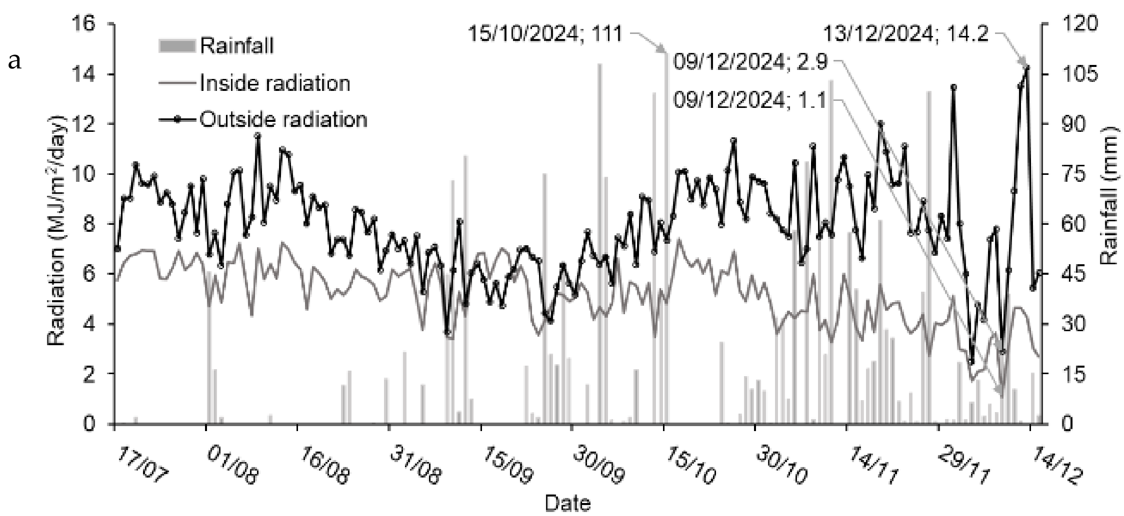


Figure 5. Air temperature and relative humidity inside (a) and outside (b) greenhouse



b

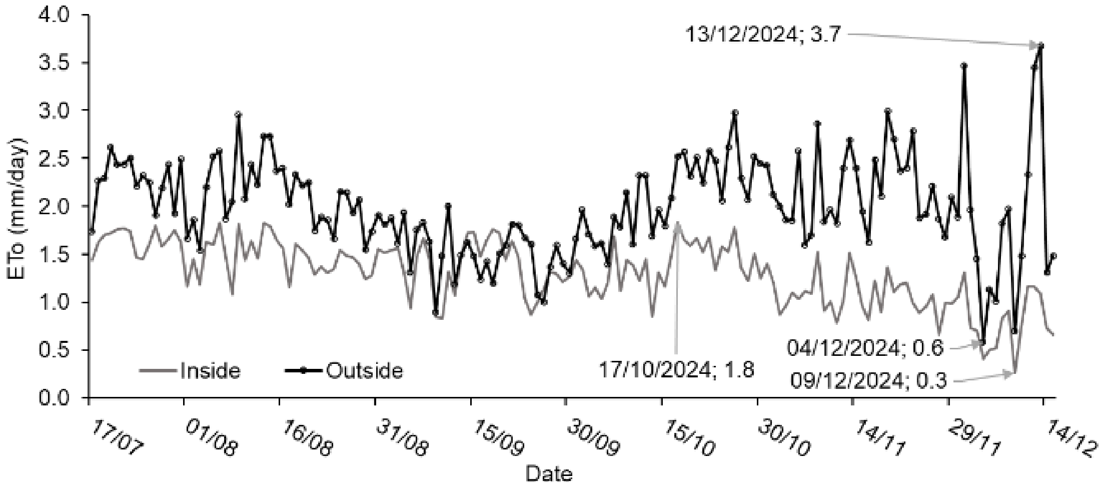


Figure 6. Radiation and rainfall (a) and potential evapotranspiration (b).

According to Ngugi et al., (2003) the optimal temperature range for photosynthesis in several eucalyptus varieties is between 21 °C and 33 °C. However, as shown in Figure 1, the maximum air temperature frequently exceeded 33 °C, particularly from July to October. The greenhouse maintained relatively high humidity levels, which are sufficient for eucalyptus seedling growth, because Farhan (2023) reported that the misting system set point for eucalyptus nurseries is at 70% relative humidity. In fact, excluding nighttime hours (6:00 p.m. to 6:00 a.m.), the average relative humidity inside the greenhouse still reached 70%.

The daily air temperature and relative humidity outside the greenhouse are shown in Figure 5b. The maximum outdoor temperature recorded in this study was higher than that reported by Arif et al. (2020) who found that the maximum outdoor air temperature in Bogor in 2018 was 36.4 °C, with an average temperature of 26.2 °C. Wati et al. (2015) analyzing climate data from 1975 to 2012 based on BMKG Jawa Barat records (located within a 1.43 km radius of the study site), reported an average temperature of 25.1 °C for the July–December period. Meanwhile, the relative humidity reported by Arif et al. (2020) for the year 2018 was 82.7%, and that reported by Wati et al. (2015) for the period from July to December was 82.3%.

Because the greenhouse had a roof and shading net (paranet), solar radiation inside the greenhouse was lower than that outside, as shown in Figure 6a. The highest solar radiation outside the greenhouse occurred on December 13, 2024, reaching 14.2 MJ/m²/day. Meanwhile, the highest radiation inside the greenhouse occurred on a different date, October 17, 2024, with a value of 7.2 MJ/m²/day. The lowest radiation values for both inside and outside the greenhouse occurred on the same date, December 9, 2024, with 2.5 MJ/m²/day outside and 1.1 MJ/m²/day inside.

The average solar radiation inside the greenhouse was 5.2 MJ/m²/day, while outside it was 7.9 MJ/m²/day. The average radiation outside the greenhouse was lower than the findings of Arif et

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al. (2020), who reported an average of 12.1 MJ/m²/day in 2018. This relatively low radiation in the present study is likely due to frequent rainfall, with a total rainfall of 2,039 mm across 82 rainy days. Observations also showed that in November and December, many days were overcast without rainfall, which further reduced radiation levels.

Radiation outside the greenhouse fluctuated, with an overall decline from August to mid-September. After mid-October, daily fluctuations increased due to frequent rainfall. The presence of rain is associated with clouds that block solar radiation. This supports the explanation by Qian et al. (2007), who stated that radiation is influenced by clouds, causing fluctuations. The effects of clouds and rainfall were also observed in the air humidity graphs inside and outside the greenhouse (see Figures 5a and 5b). Microclimate fluctuations affect ETo, which in turn causes plant water requirements to fluctuate. The daily ETo values are presented in Figure 6b.

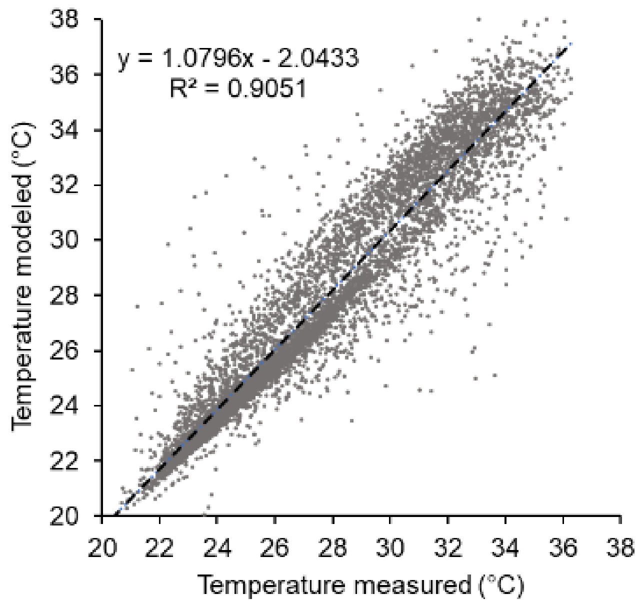

Figure 7. Comparison of measured and modeled greenhouse air temperature

The graph in Figure 6b shows that the trend closely follows the solar radiation pattern in Figure 6a, as solar radiation has a strong influence on ETo. The highest ETo value inside the greenhouse was 1.8 mm/day on October 17, 2024. Meanwhile, the maximum ETo outside the greenhouse occurred on December 13, 2024, reaching 3.7 mm/day. The lowest ETo inside the greenhouse was 0.3 mm/day on December 9, 2024, whereas outside the greenhouse, it was 0.6 mm/day on December 4, 2024. In general, microclimate fluctuations were greater outside the greenhouse than inside, as shown in Table 2. The fluctuations increased after October, when rainfall occurred more frequently.

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Table 2. Standard deviation of air temperature, relative humidity, and radiation.

	Air Temperature (°C)			Relative Humidity (%)	Radiation (MJ/m²/day)
	Mean	Minimum	Maximum		
Inside	0.91	0.87	1.66	5.52	1.26
Outside	0.96	1.00	1.66	7.25	1.97

3.2 Air Temperature inside greenhouse modeling

The calculation results obtained using Equation (3) produced a low R^2 value (less than 0.6), indicating the need for model calibration. Calibration using the Solver tool in Microsoft Excel yielded a value of Q_{st} = 0, indicating that the sensible heat from the plants did not significantly affect the greenhouse air temperature. This value was then used for calculations on other days, resulting in an overall R^2 value of 0.9051 (see Figure 6), indicating that the model accurately predicted the greenhouse air temperature. Of the total of 152 days with 7296 data points, the model yielded a root mean square error (RMSE) of 1.31, indicating that the average prediction error was 1.31 °C. The R^2 value was calculated after excluding missing data (recorded as zero during the RK4 computation), as observed in Figure 7, which occurred on July 19 and 27. This data loss occurred because the outdoor AWS failed to record air temperature, typically between 20:30 and 24:00.

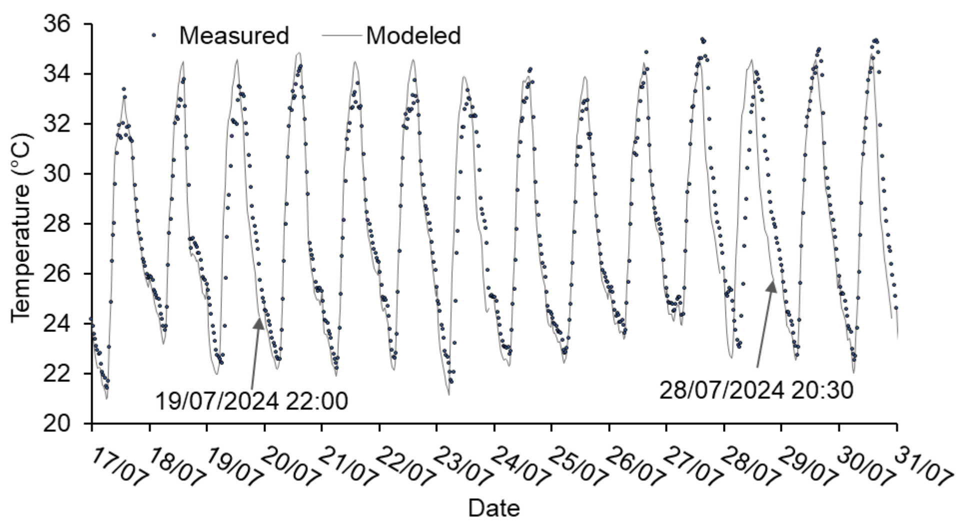

Figure 8. Modeled and measured air temperatures from July 17, 2024, to July 31, 2024.

Compared with other studies, the obtained R^2 value is considered good, even when compared with the reference model of this study, which is more complex; namely, the model by Suhardiyanto et al. (2007), who reported an R^2 of 0.8496. Meanwhile, the study by Hull et al. (2024) on temperature modeling in a greenhouse equipped with evaporative cooling in Africa reported an R^2 value of 0.95 and a similar RMSE of 1.31 °C

However, when compared with models using artificial neural networks (ANN), the R^2 value of this study is slightly lower. For example, Bolandnazar et al. (2023) modeled air temperature in an arid climate (Iran) and achieved an R^2 of 0.91, whereas Wang et al. (2025) modeled minimum air temperature inside a greenhouse in a subtropical climate (Anhui, China) and reported an R^2 of 0.96. Meanwhile, for greenhouses in tropical climates, ANN models tend to yield lower R^2 values than the model in this study. For instance, Arif et al. (2008) obtained an R^2 of 0.879. The ANN model for greenhouse temperature prediction with automated natural ventilation in Greece had a root mean squared error (RMSE, and R2of 0.271 and 0.999,99 respectively (Petrakis et al., 2022).

This simple model is effective because the similar trends between outside and inside greenhouse temperatures (see Figures 5a and 5b) allow the heat transfer model to predict the inside temperature using only the outside air temperature as the main input. However, this model performs poorly in predicting greenhouse air temperature under extreme outdoor temperature conditions, such as on October 22, 2024, and October 17, 2024 (see Figure 5b). The discrepancy between measured and modeled temperature during extreme maximum temperature at outdoor can reach up to 5.3 °C (see Figure 8a), and for extreme minimum temperature at outdoor, up to 4.7 °C (see Figure 8b).

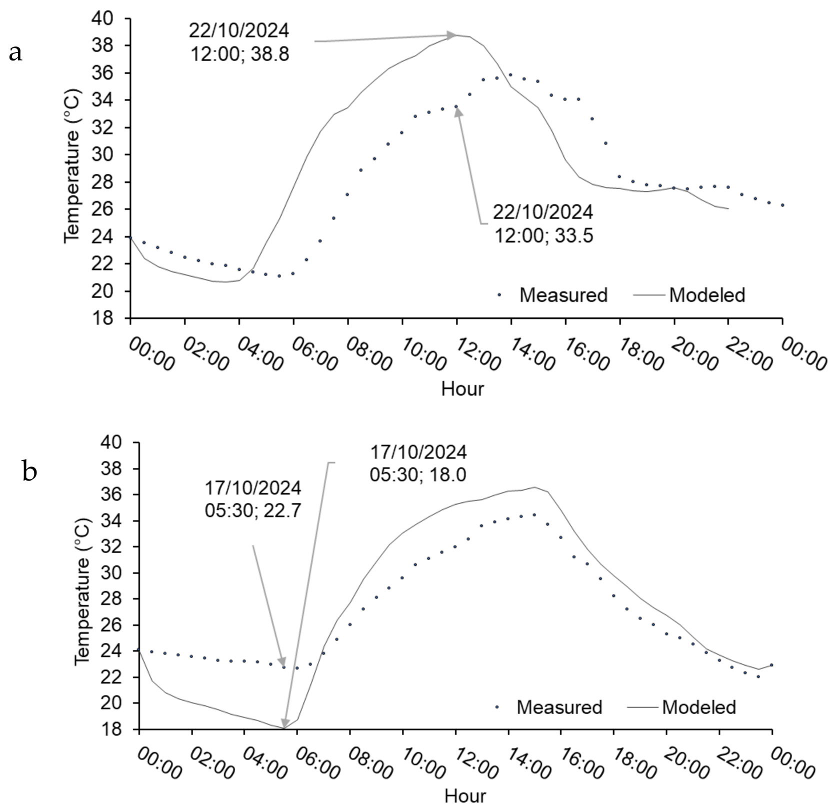

Figure 9. Air temperature inside the greenhouse at the extreme maximum outside air temperature (a) and at the extreme minimum outside air temperature (b).

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Meanwhile, to predict the air temperature inside the greenhouse under extreme internal temperature conditions, such as on September 7, 2024, and October 18, 2024 (see Figure 5a), this model performs quite well. The difference between the measured and modeled temperature during these extreme conditions reached only 0.4 °C, as shown in Figure 9a, and even during the extreme minimum temperature, no significant discrepancy was observed, as shown in Figure 9b. However, in Figure 9b, a notable deviation of 2.5 °C between the model and the measured data is observed at 14:30.

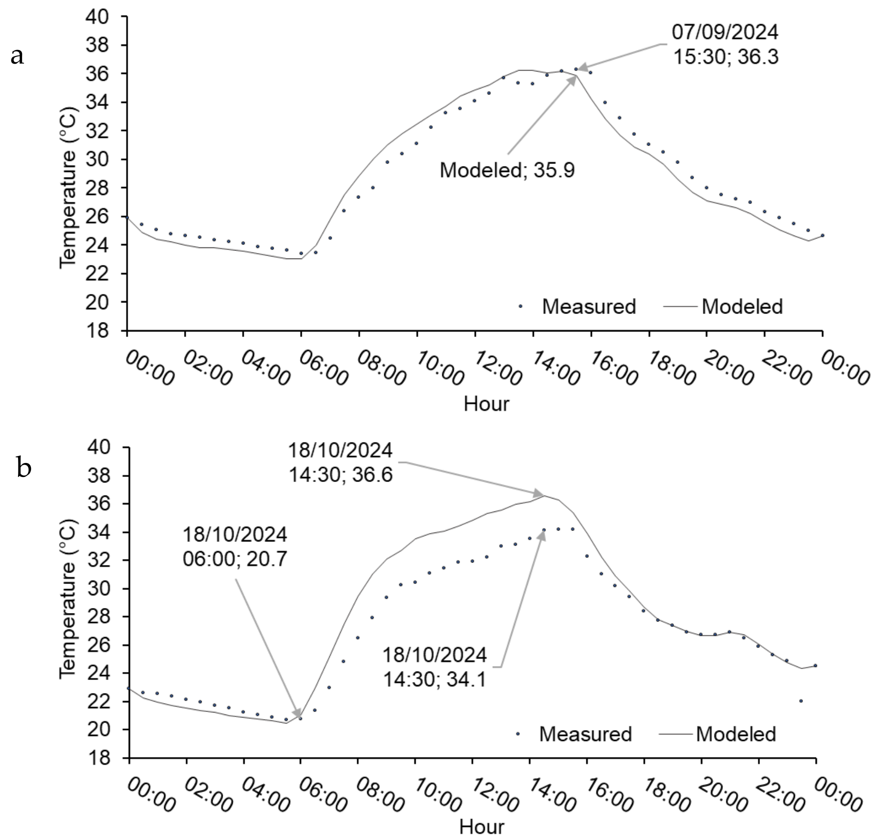

Figure 10. Air temperature inside the greenhouse during extreme maximum air temperature inside greenhouse (a), during extreme minimum air temperature inside greenhouse (b).

4. Conclusion

The microclimate inside the greenhouse exhibited less fluctuation than that outside, with a noticeable increase in variability occurring after October due to frequent rainfall. The simplified heat transfer model demonstrated good performance in predicting air temperature inside the greenhouse, with a coefficient of determination (R^2) of 0.9051 and a root mean square error (RMSE) of 1.31 °C. A limitation of the model is its inability to accurately predict greenhouse indoor temperatures during extreme outdoor temperatures. Therefore, this model requires further development, including considering the possibility of changes in heat transfer parameter values at more extreme temperatures.

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5. AI Writing Statement

The author used ChatGPT (version 5.3), developed by OpenAI, to assist with English language editing and to improve the clarity of the explanation of the numerical method described in this manuscript, including the Runge–Kutta fourth-order (RK4) formulation. All model development, calculations, data analysis, and interpretation were performed and verified by the author, who takes full responsibility for the content of the manuscript.

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