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# Microclimate Characteristics of a Tropical Smart Greenhouse with Integrated Cooling

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***Abstract.*** *Smart greenhouses offer opportunities to manage the growing environment, but their microclimate performance should be evaluated before claims are made about crop productivity. This study describes temperature, relative humidity, and light conditions observed in a greenhouse equipped with an integrated evaporative cooling assembly. Observations were reported over seven days, with measurements grouped into morning, midday, and late-afternoon periods. The reported mean air temperatures were 22.12 °C in the morning, 31.20 °C at midday, and 24.28 °C in the late afternoon. Corresponding mean relative humidities were 76%, 59%, and 70%, respectively. The maximum recorded air temperature was 40.5 °C on the first observation day, while the minimum relative humidity was 49% on the fourth day. Midday light intensity ranged from 10,000 to 21,000 lux. The indoor midday temperature was also reported to average 2.7 °C above outdoor conditions and that indoor and outdoor midday relative humidities were 59% and 57%, respectively. These findings document substantial daily microclimate variation, but the available summaries do not provide matched measurements before and after cooling activation or a complete statistical dataset. Consequently, they cannot establish the magnitude of the system's cooling effect or any improvement in crop yield. The study provides preliminary operational information for greenhouse microclimate management in tropical environments and identifies the need for synchronized indoor–outdoor monitoring and direct on–off performance comparisons.*

***Keywords:*** ***evaporative cooling; greenhouse microclimate; relative humidity; smart greenhouse; temperature.***

## INTRODUCTION

Greenhouse cultivation can provide partial protection from adverse weather, yet enclosure alone does not guarantee a favorable growing environment. The internal temperature, humidity, and incident radiation depend on structural characteristics, ventilation, solar exposure, and climate-control operation. Reviews of greenhouse design emphasize that climatic suitability should be evaluated at the level of the actual facility rather than inferred from the presence of modern equipment (Badji et al., 2022; Dsouza et al., 2023; Vatistas et al., 2022).

Heat accumulation is particularly relevant to tropical greenhouse production systems. Solar radiation can raise air temperature inside protected structures, while temperature and relative humidity vary together over the day. Because evaporative demand depends on both variables, measuring temperature alone provides an incomplete description of the growing environment (Soussi et al., 2022; Wang et al., 2021).

Evaporative cooling commonly combines wetted media with air movement through fans or ventilation openings. Evaporation can lower sensible air temperature, but the resulting conditions depend on ambient humidity,





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airflow, pad characteristics, and the greenhouse structure. Experimental and review literature demonstrates that system performance is site-specific, especially when outdoor air is already humid (Franco et al., 2014; Kapilan et al., 2023; Tawalbeh et al., 2023).

Recent engineering studies have addressed the spatial distribution of cooled air and configurations of evaporative cooling components. These findings show why fan placement and internal air distribution matter for microclimate uniformity, although comparable performance cannot be assumed for an uncharacterized greenhouse (Allali et al., 2024; Pardo-Pina et al., 2024; Tsafaras et al., 2021).

Sensor-supported greenhouse monitoring can improve the temporal resolution of climate records and assist operational decisions. Published systems combine temperature and humidity measurements with data acquisition and control algorithms, ranging from basic monitoring to predictive control (Benyezza et al., 2023; Chen et al., 2022; Contreras-Castillo et al., 2023; Kirci et al., 2022; Morcego et al., 2023). Such technologies are relevant only when reported together with clear measurements and operational conditions.

An Indonesian pilot-greenhouse investigation has illustrated the value of jointly monitoring temperature and humidity in a tropical setting (Eduard et al., 2022). Other studies relate greenhouse climate management to crop outcomes when direct agronomic measurements are collected (Lorenzo et al., 2024). This distinction is important: observations of a microclimate cannot, on their own, establish an increase in yield or validate crop suitability.

The present study uses the seven-day observations available for a smart greenhouse equipped with an integrated cooling assembly to describe its reported temperature, relative-humidity, and light conditions. Its practical contribution is a preliminary descriptive characterization of diurnal microclimate variation in a tropical greenhouse, alongside identification of evidence needed for a later controlled evaluation of cooling performance. The study does not measure growth or productivity of caisim or other crops.

## MATERIAL AND METHODS

### Study Setting and Observation Period

The study was described as a direct observation of the microclimate inside a smart greenhouse operating in a tropical agricultural context. The original text mentions Wailan, North Sulawesi, in the program background but does not explicitly document the geographic coordinates or exact location of the experimental greenhouse. Results were summarized from a seven-day observation period. The calendar dates, greenhouse dimensions, covering material, and orientation were not available in the submitted source and therefore cannot be specified here.

### Cooling System and Measurement Variables

The reported cooling assembly combined a wetted cooling pad, exhaust fan, internal circulation fan or blower, and automated ventilation in a sensor-supported greenhouse system. The original description also referred to monitoring and automatic control. Equipment specifications, sensor models, calibration records, sensor placement, set points, and activation logs were not included in the source material. Consequently, the study is presented as a characterization of observed microclimate conditions, not a replicated controlled trial of individual cooling components.

### Observation Schedule and Data Summarization

Temperature (°C), relative humidity (%), and illuminance (lux) were the



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reported environmental variables. Observations were grouped into morning, midday, and late-afternoon periods. The documented morning and late-afternoon observation windows were 06:00–08:00 and 17:00–19:00, respectively. The exact midday observation window cannot be established from the available records. The number of sensor readings within each period and whether observations were automatically logged or manually transcribed were not stated. Available period means, extrema, and indoor–outdoor contrasts are reproduced without reconstructing daily observations.

### Statistical Interpretation

The initial analysis described a paired t-test for morning-versus-midday temperature and a one-way analysis of variance for humidity by time of day. However, it did not provide the underlying observation matrix, repeated-measures structure, dispersion estimates, test statistics, or assumptions. Furthermore, comparing morning with midday does not isolate the response to system activation. For these reasons, the available values are reported descriptively, and no claim is made that an inferential test establishes cooling effectiveness. No new statistical quantities were estimated.

## RESULTS AND DISCUSSION

### Results

The reported period means showed a clear diurnal gradient, with higher temperature and lower relative humidity at midday (Table 1).

**Table 1.** Reported greenhouse air temperature and relative humidity by observation period

| Observation period | Air temperature (°C) | Relative humidity (%) |
|---|---|---|
| Morning | 22.12 | 76 |
| Midday | 31.20 | 59 |
| Late afternoon | 24.28 | 70 |

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Midday temperature exceeded the corresponding morning and late-afternoon means, while midday humidity was lower. These period averages represent different times of day; they cannot be interpreted as a before–after cooling comparison because cooling operation and external forcing were not matched.

Other reported features of the observation period are summarized in Table 2. These values provide context but have different temporal bases and should not be combined as if derived from identical paired readings.

**Table 2.** Additional descriptive environmental observations reported for the greenhouse

| Indicator | Reported result | Observation basis |
|---|---|---|
| Maximum indoor air temperature | 40.5 °C | Midday, observation day 1 |
| Minimum indoor relative humidity | 49% | Observation day 4 |
| Midday illuminance inside greenhouse | 10,000–21,000 lux | Reported midday range |
| Indoor relative humidity at midday | 59% | Period mean |
| Outdoor relative humidity at midday | 57% | Reported external mean |
| Indoor temperature relative to outside | 2.7 °C higher | Reported mean midday difference |

The additional observations indicate that appreciable midday heat loads occurred during the short observation period. The reported 2.7 °C higher indoor temperature at midday is not evidence of net cooling relative to outdoor air. An afternoon decline in indoor temperature was also reported, but no paired pre-



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activation and post-activation temperature trajectory was provided. Therefore, the magnitude and timing of any system-induced temperature reduction cannot be quantified from these summaries.

**Discussion**

The contrast between the midday and morning microclimate is consistent with the combined effect of solar heating and the daily cycle of the surrounding atmosphere. However, the dataset does not separate naturally occurring daily variation from the operation of the pad, fans, or ventilation components. Prior greenhouse research has documented that evaporative cooling response depends on the external air state, the distribution of airflows, and configuration of the cooling surfaces (Franco et al., 2014; Soussi et al., 2022; Pardo-Pina et al., 2024). These mechanisms are plausible contextual explanations, not effects demonstrated by the present dataset.

The midday relative-humidity mean of 59% inside and the reported outside mean of 57% are close in absolute terms. Without data recorded at matched timestamps, sensor-level variability, and activation history, the difference should not be described as a statistically established improvement. Evaporative methods can change both temperature and humidity, and their net performance may differ substantially between dry and humid climates (Kapilan et al., 2023; Tawalbeh et al., 2023).

The recorded midday illuminance range of 10,000–21,000 lux gives a limited description of available light, but lux is a photometric rather than plant-specific photon-flux metric. Thus, this range cannot by itself establish that the environment met the photosynthetic needs of any particular crop. Likewise, the earlier suggestion that 23 horticultural species were suitable for cultivation was not accompanied by a species list, stated selection criteria, or direct crop measurements. It is therefore treated only as a possible topic for future agronomic assessment rather than a result demonstrated here.

A useful applied outcome of this study is the identification of a monitoring baseline and essential verification steps for greenhouse operation. Studies that assess actual climate-control performance typically include well-documented control logic, synchronized internal and external measurements, or direct comparisons among operational conditions (Eduard et al., 2022; Benyezza et al., 2023; Allali et al., 2024). In contrast, this short dataset provides evidence of diurnal variation but is insufficient to attribute a specific cooling efficiency to the integrated system.

The limits are methodological as well as temporal. Seven days cannot represent the diversity of seasonal weather in North Sulawesi, and there is no documented experimental unit for repeated statistical testing, sensor calibration, system-on/system-off temperature response, water consumption, energy input, or yield. External publications demonstrate that greenhouse climate interventions may influence water demand and crop performance when those outcomes are explicitly measured (Tsafaras et al., 2021; Lorenzo et al., 2024), but such outcomes cannot be inferred for the current facility.

Future observations should preserve timestamps and actuator status, collect synchronized inside–outside sensor measurements, and identify greenhouse geometry and sensor positions. If sufficient pre-activation and post-activation observations exist in the authors' records, they may be reported after verification using a method appropriate for repeated measurement. Otherwise, the descriptive scope adopted here should be retained. Any subsequent statement about caisim productivity would require actual crop observations rather than indirect extrapolation from microclimate conditions



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## CONCLUSION

During the seven-day observation period, the greenhouse exhibited higher mean air temperature and lower relative humidity at midday than in the morning and late afternoon. The reported period means were 22.12, 31.20, and 24.28 °C for temperature and 76%, 59%, and 70% for relative humidity, respectively. The observations characterize short-term diurnal variation but do not quantify the isolated effect of cooling-system activation, establish a consistently optimal crop microclimate, or demonstrate improved caisim productivity. Further evaluation requires paired climate and operating-status records, an appropriately described measurement protocol, and direct crop data if agronomic outcomes are to be claimed.

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