Journal of Environmental and Development Studies - JEDS
Journal homepage: https://talenta.usu.ac.id/jeds

# Thermal Performance Analysis of an Air-Based Hybrid PV/T Solar Collector in a Greenhouse under Varying Mass Flow Rates

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**ARTICLE INFO**

**Article history:**
Received 06 July 2026
Revised 29 July 2026
Accepted 01 August 2026
Available online 01 September 2026

E-ISSN: 2745-4592

**How to cite:**
Ginting J. R., Chandrasari A. Z., Rajani A. Thermal Performance Analysis of an Air-Based Hybrid PV/T Solar Collector in a Greenhouse under Varying Mass Flow Rates. Journal of Environmental and Development Studies 2026. 7(2):009–018.



http://doi.org/10.32734/jeds.v7i2.26380

**ABSTRACT**

Solar photovoltaic panels often experience electrical efficiency degradation due to heat accumulation, which can be effectively mitigated using hybrid photovoltaic/thermal (PV/T) systems. While a PV/T system concurrently generates electrical and thermal energy, the scope of this specific study is exclusively limited to evaluating its thermal performance and heat distribution. This study analyzes the thermal performance of an air-based hybrid PV/T solar collector integrated with a greenhouse. Because the system does not utilize phase change materials, the primary variable evaluated is the air mass flow rate, which is controlled by adjusting the number of active fans in both the PV/T collector and the greenhouse exhaust. Experimental data were collected over three days between 09:00 and 15:00 WIB. The testing was simplified into three operational scenarios: maximum PV/T - maximum greenhouse, maximum PV/T - minimum greenhouse, and minimum PV/T - minimum greenhouse. The numerical air velocities recorded were 3.70 m/s for the maximum PV/T setup and 2.35 m/s for the minimum. Concurrently, greenhouse exhaust velocities were 3.18 m/s (10 fans) and 2.03 m/s (6 fans). Findings revealed that the highest average useful heat reached 368.28 W during the maximum PV/T-minimum greenhouse scenario, highlighting optimal heat accumulation. Conversely, the highest average thermal efficiency was achieved in the maximum PV/T-maximum greenhouse scenario at 25.30%, demonstrating better air circulation and thermal stability. Ultimately, the results indicate that PV/T air velocity strongly governs heat extraction from the panels, whereas greenhouse exhaust velocity dictates heat retention inside the chamber.

**Keywords:** Air Collector, Fan Speed, Greenhouse, Mass Flow Rate, Photovoltaic Thermal.

## 1. Introduction

Solar energy is a highly promising renewable energy source for development in tropical regions due to the abundant solar radiation available almost year-round. Photovoltaic (PV) panels can convert solar radiation into electrical energy; however, a significant portion of the absorbed radiation is converted into heat. Heat accumulation within the panels must be controlled, as elevated operating temperatures can degrade electrical performance and result in wasted thermal energy without optimal utilization (Amrizal et al., 2021).

An air-based hybrid photovoltaic/thermal (PV/T) system offers a viable alternative to address this issue. In this system, air is circulated through a duct beneath the PV panel to absorb heat from both the panel and the absorber, after which the heated air is channeled into a greenhouse. Utilizing air as the working fluid provides several advantages, including relatively simple construction, low operational costs, and a reduced risk of leakage compared to water-based systems (Fudholi et al., 2019; Dunne et al., 2023).

The integration of a PV/T system with a greenhouse is of particular interest, as the hot air generated by the collector can significantly influence the thermal conditions of the enclosed space. In agricultural applications, controlling the greenhouse temperature is essential for maintaining microclimate stability. Therefore, variations in the air mass flow rate controlled via fan settings must be analyzed to identify a configuration capable of balancing heat extraction from the panels with heat accumulation inside the greenhouse (Jadallah et al., 2020; Zhou et al., 2025).

This study focuses on three days of experimental testing, utilizing field measurement data collected between 09:00 and 15:00 WIB. The primary variation across the test days is the fan quantity configuration in both the PV/T system and the greenhouse, specifically operating under maximum and minimum conditions. While electrical performance is inherently critical to evaluating the overall efficiency of a PV/T system, this study deliberately isolates the thermal component. This approach was chosen to establish an empirical baseline for understanding how dynamic mass flow rates dictate heat extraction and microclimate temperature profiles within a greenhouse, specifically without the stabilizing influence of Phase Change Materials (PCM). Consequently, the objectives of this research are to determine the actual mass flow rates, analyze temperature variations within the greenhouse, and calculate both the useful heat and the thermal efficiency of the air-based PV/T collector. The findings aim to identify the most effective configuration for extracting heat from the collector, as well as the configuration that maximizes heat accumulation within the greenhouse (Pido et al., 2023).

## 2. Method

*2.1 System Configuration and Field Documentation*

The experimental system consists of an air-based PV/T collector, flexible ducting, and a greenhouse chamber. The PV/T panel absorbs solar radiation, and the heat generated beneath the panel is carried away by a fan-driven air stream. The heated air is then channeled through the ducting into the greenhouse, while the greenhouse exhaust fans regulate air circulation and heat extraction from the test chamber

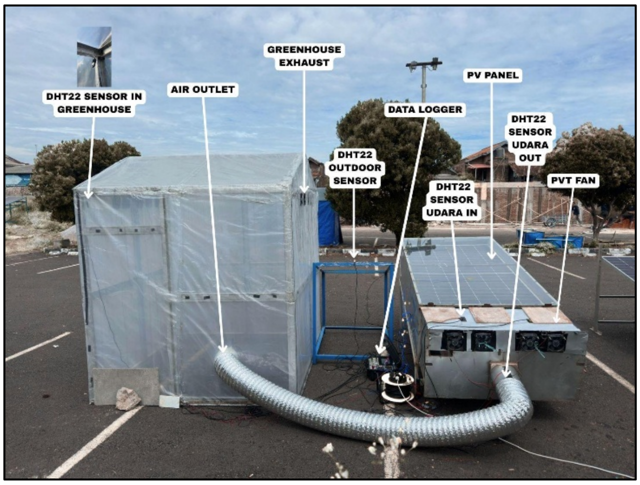


Figure 1. Actual documentation of the air-based PV/T-greenhouse system and key component descriptions.

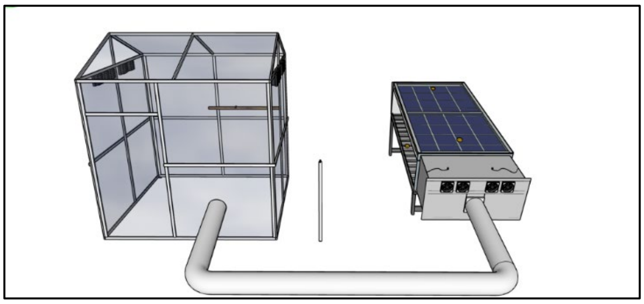

Figure 2. 3D model of the air-based PV/T-greenhouse system and key component descriptions.

Description for Figures 1 and 2: 'A' indicates the greenhouse with a double-layer UV plastic envelope; 'B' represents the PV/T panel; 'C' shows the flexible ducting serving as the hot air channel to the greenhouse; 'D' indicates the fan/inlet chamber of the PV/T system; 'E' points to the area containing sensors, cables, and the data logger; 'F' represents the field test frame supporting the experimental setup. Component documentation is necessary as the panel position, surrounding surface conditions, and airflow direction can influence radiation and temperature readings during field testing (Barokah et al., 2025).

*2.2 Greenhouse Specifications*

Table 1. Specifications of the greenhouse, UV plastic, and exhaust fans

| **Parameter** | **Value** | **Unit** |
|---|---|---|
| Greenhouse length | 215 | cm |
| Greenhouse width | 196 | cm |
| Total greenhouse height | 238 | cm |
| Greenhouse floor area | 4.21 | $m^2$ |
| Greenhouse volume | 9.30 | $m^3$ |
| UV plastic envelope | 2 | layers |
| Minimum number of exhaust fans | 6 | units |
| Maximum number of exhaust fans | 10 | units |
| Exhaust fan size | 12 x 12 | cm |

*2.3 PV/T Specifications and Measurement Instruments*

The PV/T system employed is an air-based collector utilizing a photovoltaic panel with a capacity of 100 Wp. The panel is positioned above the air channel, featuring a 6 mm protective glass and a zinc-based absorber on the underside to facilitate heat absorption. The airflow within the PV/T collector is controlled by fans, with a maximum configuration of 4 fans and a minimum configuration of 2 fans. This system does not utilize phase change materials (PCM); therefore, the T5-T6 readings in the data processing are treated as air-channel/mid-duct temperatures rather than the temperature of a heat storage material. The configuration of the air channel and the heat-absorbing surface is designed to ensure a more effective interaction among the air, panel, and absorber (Choi & Choi, 2020; An et al., 2024).

The measurement instruments include K-type thermocouples for reading temperatures T1 to T8, DHT22 sensors for measuring air temperatures DHT1 to DHT8, a solar power meter for solar radiation intensity, an anemometer/thermal anemometer for air velocity, and a data logger for recording test data. Data acquisition was conducted at 10-minute intervals between 09:00 and 15:00 WIB. This periodic recording pattern is necessary to ensure that thermal responses resulting from changes in radiation, temperature, and airflow can be consistently compared (Kim et al., 2024).

Table 2. Measurement sensor locations

| **Sensor** | **Measurement location** |
|---|---|
| T1-T2 | Glass temperature |
| T3-T4 | Bottom PV temperature |
| T5-T6 | Air channel/mid-duct temperature |
| T7-T8 | Zinc absorber temperature |
| DHT1-DHT2 | Inlet air |
| DHT3-DHT4 | Outlet air |
| DHT5-DHT7 | Air inside the greenhouse |
| DHT8 | Ambient air |

*2.4 Testing Scenarios and Mass Flow Rates*

The testing variations were organized over three days. The maximum and minimum conditions are expressed not only qualitatively but also quantitatively through measured air velocity values. The maximum PV/T configuration utilized an air velocity of 3.70 m/s, whereas the minimum PV/T configuration operated at 2.35

m/s. The maximum greenhouse configuration employed 10 exhaust fans with an air velocity of 3.18 m/s, while the minimum greenhouse configuration used 6 exhaust fans with a velocity of 2.03 m/s.

**Table 3.** Classification of air mass flow rate variations

| Day | Scenario | PV/T Fans | VPV/T (m/s) | m˙PV/T (kg/s) | GH Fans | VGH (m/s) | m˙GH (kg/s) |
|---|---|---|---|---|---|---|---|
| Day 1 | Max PV/T - Max Greenhouse | 4 | 3.70 | 0.063 | 10 | 3.18 | 0.542 |
| Day 2 | Max PV/T - Min Greenhouse | 4 | 3.70 | 0.063 | 6 | 2.03 | 0.208 |
| Day 3 | Min PV/T - Min Greenhouse | 2 | 2.35 | 0.040 | 6 | 2.03 | 0.208 |

*2.5 Data Processing Equations*

Data processing was performed by averaging the readings from sensors located at identical measurement positions. Missing data on the test sheets were estimated based on the testing time patterns to ensure that the graphs for the three scenarios could be interpreted comprehensively. The equations employed are expressed formally. The term Quseful represents the useful heat actually carried by the air flowing out of the PV/T collector. The mass flow rate determines the calculation of useful heat in an air collector, the specific heat of air, and the temperature difference between the outlet and inlet air (Simon-Allue et al., 2023; Tiwari et al., 2018).

$$T_{glass} = \frac{T_1 + T_2}{2} \quad (1)$$

$$T\_PV = \frac{T_3 + T_4}{2} \quad (2)$$

$$T\_channel = \frac{T_5 + T_6}{2} \quad (3)$$

$$T\_absorber = \frac{T_7 + T_8}{2} \quad (4)$$

$$T\_in = \frac{DHT_1 + DHT_2}{2} \quad (5)$$

$$T\_out = \frac{DHT_3 + DHT_4}{2} \quad (6)$$

$$\Delta T_{air} = T_{out} - T_{in} \quad (7)$$

$$\dot{m}_{PVT} = \rho \times A_o \times V_{PVT} \quad (8)$$

$$Q_{useful} = \dot{m}_{PVT} \times c_p \times (T_{out} - T_{in}) \quad (9)$$

$$\eta\_termal = \frac{Q_{useful}}{G \times Ac} \times 100\% \quad (10)$$

Where ρ is the air density at 1.20kg/m3, cp is the specific heat of air at 1005J/kg·K, Ao is the effective outlet area of the PV/T system at 0.0142m2, Af is the effective area of the greenhouse fan at 0.0142m2, n is the number of active fans, G is the solar radiation intensity, Ac is the effective collector area at 2.44m2, Quseful is the useful heat carried by the air stream from the collector, and ηthermal is the thermal efficiency of the PV/T collector. This thermal efficiency framework is consistent with air-based PV/T studies that evaluate useful thermal energy against the incoming solar energy (Talal et al., 2024).

## 3. Result and Discussion

*3.1 Solar Radiation Conditions*

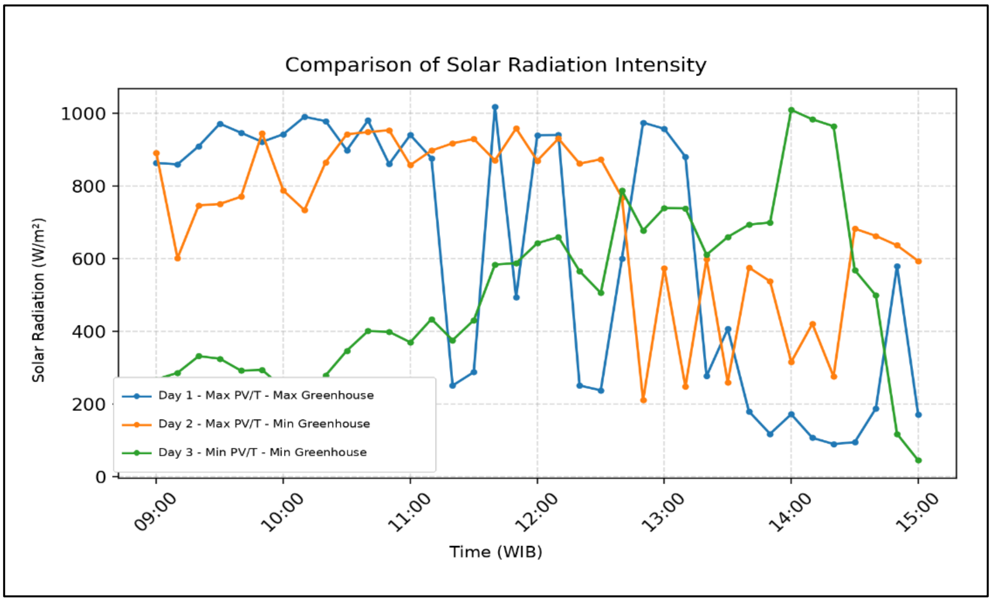


Figure 2. Comparison of solar radiation intensity across the three testing scenarios.

Based on Figure 2, the highest average solar radiation occurred on Day 2 at 710.22 W/m2, whereas the lowest average radiation was recorded on Day 3 at 503.95 W/m2. Testing different scenarios on different days with fluctuating weather conditions introduces a methodological challenge, as absolute temperature responses and raw useful heat outputs become heavily dependent on the available solar energy input. To address this weather variance and prevent biased comparative conclusions, the evaluation in this study relies on thermal efficiency as a normalized metric. By calculating efficiency as the ratio of useful heat to the actual solar radiation received during each specific test period, the performance of the varying mass flow rates can be objectively benchmarked across different days.

3.2 *Comparison of Numerical Mass Flow Rates*

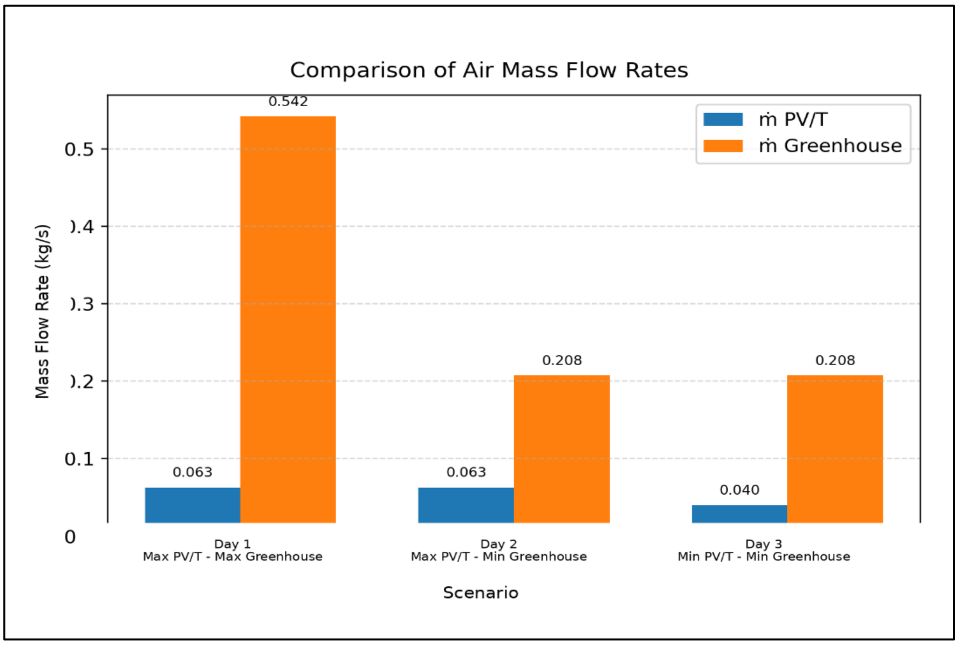


Figure 3. Bar chart of PV/T and greenhouse mass flow rates for each scenario.

Figure 3 demonstrates that the maximum PV/T mass flow rate was 0.063 kg/s, while the minimum PV/T mass flow rate was 0.040 kg/s. The highest greenhouse mass flow rate occurred in the 10-exhaust-fan configuration at 0.542 kg/s, and its minimum value was observed in the 6-fan configuration at 0.208 kg/s. These values serve as the baseline for evaluating the thermal performance across the different scenarios.

*3.3 PV/T Outlet-Inlet Air Temperature Difference*

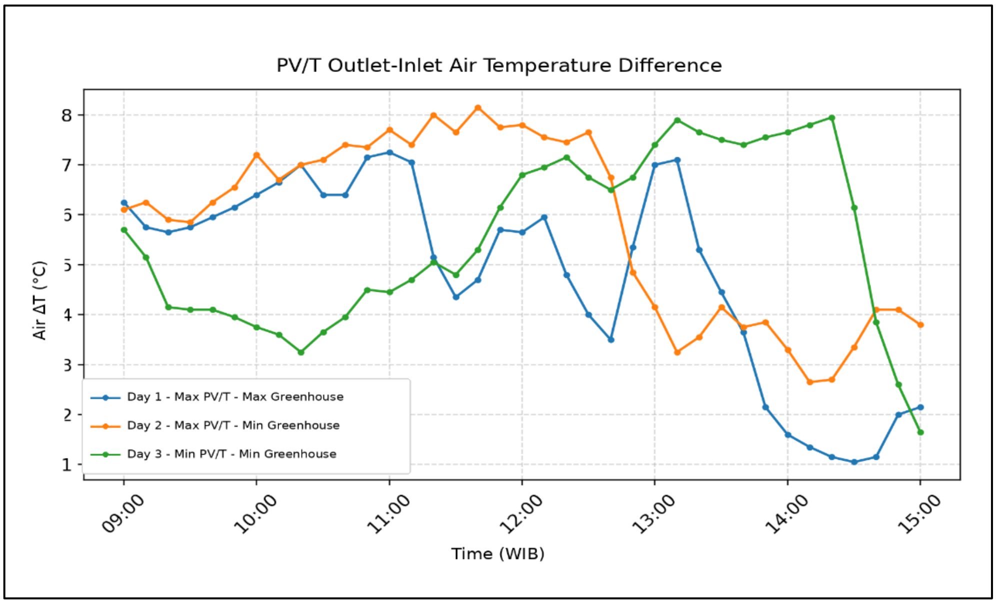


Figure 4. Outlet-inlet air temperature difference in the PV/T system.

The highest average air ΔT was obtained on Day 2, reaching 5.81°C. This condition indicates that the air exiting the collector had a significantly higher temperature compared to the entering air. Under the maximum PV/T scenario, the higher airflow rate facilitated a more rapid transfer of heat from beneath the panel to the greenhouse.

***3.2 Greenhouse Temperature***

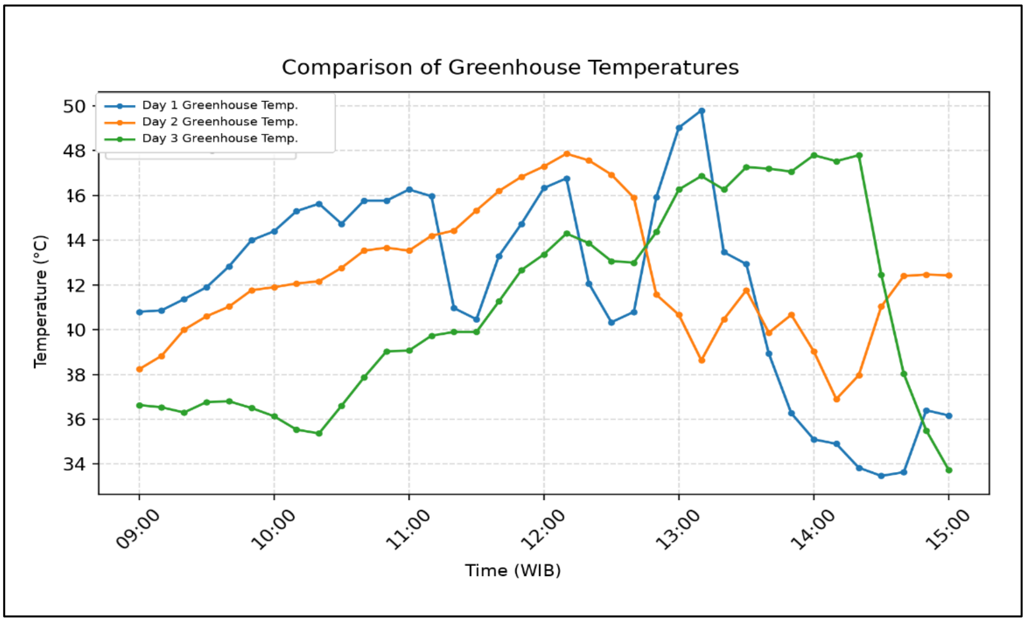


Figure 5. Comparison of greenhouse temperatures across the three scenarios.

Figure 5 illustrates the comparison of greenhouse temperatures under the three fan setting scenarios. On Day 1, the maximum PV/T and maximum greenhouse configuration resulted in relatively high initial temperatures due to a large heat flow from the collector; however, the temperature subsequently decreased more rapidly in the afternoon as the 10 exhaust fans effectively removed heat from the test chamber. On Day 2, the PV/T remained at maximum capacity while the greenhouse operated with minimum exhaust, causing the hot air to be retained longer within the chamber and producing the highest average greenhouse-to-ambient temperature difference of 5.72°C. On Day 3, the greenhouse temperature continued to rise despite the PV/T operating at minimum capacity, although changes in solar radiation and the heat accumulation trapped by the double-layer UV plastic envelope more heavily influenced this trend. Consequently, the greenhouse temperature graphs not only present the magnitude of the temperatures but also elucidate the effects of the combined PV/T airflow and exhaust fans on heat accumulation. The minimum greenhouse configuration is more suitable when the objective is to retain heat within the chamber, whereas the maximum greenhouse configuration is preferable for maintaining air circulation and mitigating excessive temperature increases.

*3.3 Useful Heat and Thermal Efficiency*

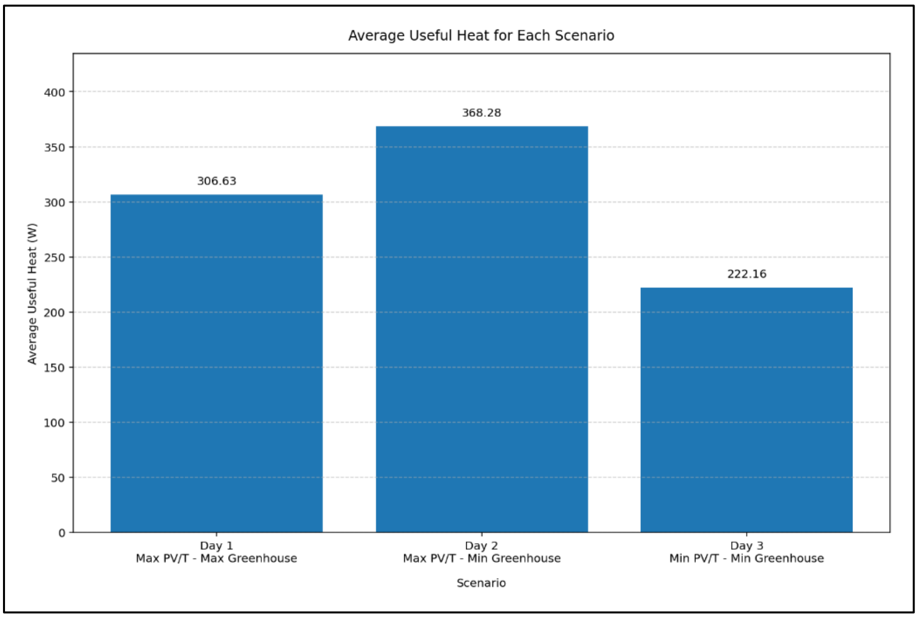


Figure 6. Comparison of average useful heat across all scenarios.

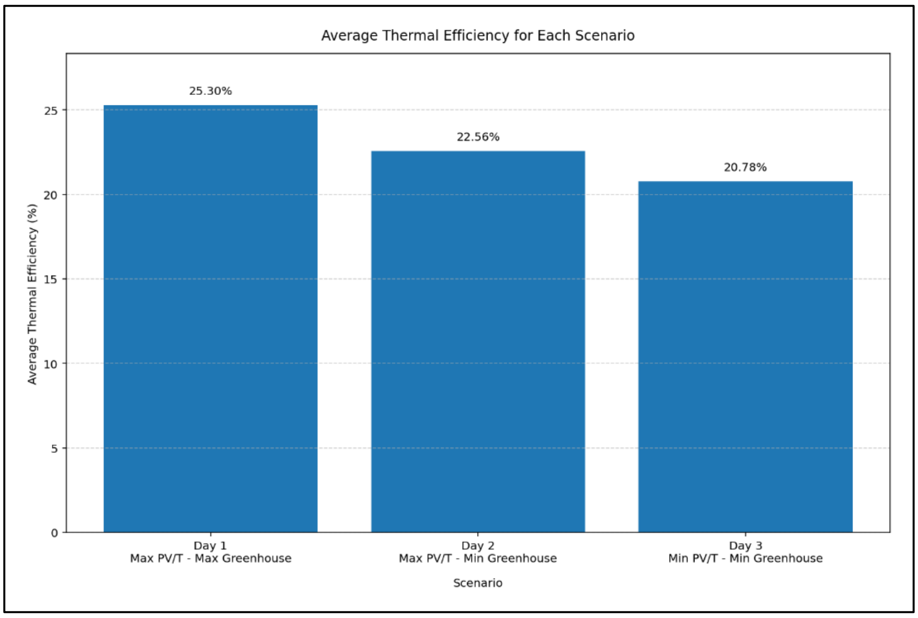


Figure 7. Comparison of average thermal efficiency across all scenarios.

In this study, Quseful or useful heat represents the utilizable heat derived from the air stream after passing through the PV/T collector. This value is obtained by multiplying the PV/T air mass flow rate, the specific heat of air, and the outlet-inlet air temperature difference. Therefore, Quseful is influenced not only by the rise in air temperature but also by the flow velocity, which determines the amount of heat-carrying air mass. This reinforces the fact that the evaluation of an air-based PV/T system must concurrently analyze useful heat, incoming radiation, and flow conditions (Herrando et al., 2023).

Table 4. Summary of data processing results for the three scenarios

| Day | Scenario | Gavg (W/m2) | Air ΔT (°C) | TGH−Tamb (°C) | Quseful (W) | ηthermal (%) |
|---|---|---|---|---|---|---|
| Day 1 | Max PV/T - Max Greenhouse | 626.19 | 4.84 | 2.10 | 306.63 | 25.30 |
| Day 2 | Max PV/T - Min Greenhouse | 710.22 | 5.81 | 5.72 | 368.28 | 22.56 |
| Day 3 | Min PV/T - Min Greenhouse | 503.95 | 5.52 | 3.24 | 222.16 | 20.78 |

As shown in Table 4, the highest average raw useful heat was recorded on Day 2 (Max PV/T - Min Greenhouse) at 368.28 W. While this suggests optimal heat accumulation, this absolute value is heavily skewed by the inherently high solar irradiance (710.22 W/m2) experienced on that specific day. Consequently, utilizing thermal efficiency is crucial for a normalized comparison. The highest average thermal efficiency was achieved on Day 1 at 25.30%, despite having lower solar radiation than Day 2. On Day 1, the maximum PV/T and maximum greenhouse configuration facilitated a more stable and proportional heat transfer, resulting in the highest efficiency relative to the actual solar energy received. This normalized approach confirms that while Day 2 generated more absolute heat due to weather conditions, Day 1's fan configuration was mechanically more efficient at converting the available radiation into useful thermal energy.

The comparison among the three scenarios demonstrates that increasing the number of PV/T fans tends to enhance the collector's ability to extract heat from the panels. Theoretically, this active heat removal not only generates the evaluated useful thermal energy but also cools the photovoltaic modules. Lowering the operating temperature of the solar cells mitigates heat-induced performance degradation, meaning the electrical efficiency of the PV panel is inherently protected or improved as more heat is extracted, even though this specific electrical parameter was not quantitatively measured in the current scope. However, the number of greenhouse fans determines the rate at which heat is released from the greenhouse chamber. The minimum greenhouse configuration is more suitable when the primary goal is to increase heat accumulation, whereas the maximum greenhouse configuration is more optimal for maintaining air circulation and room temperature stability.

These findings align with studies on the application of PV/T systems for indoor environmental control, which position airflow regulation as a critical factor in thermal stability (Cao et al., 2025). Furthermore, the thermal efficiency obtained in this study, which ranges from 20.78% to 25.30%, provides a realistic benchmark for practical, low-cost air-based PV/T configurations without Phase Change Material (PCM) in tropical climates. This performance is consistent with the global baseline for conventional air-based collectors, where recent field measurements typically report thermal efficiencies between 20% and 35% depending on solar irradiance fluctuations, duct geometry, and specific local ambient conditions (Simon-Allue et al., 2023; Kim et al., 2024). While advanced configurations utilizing complex internal turbulators or PCM storage can exceed 40% efficiency (Herrando et al., 2023), the present setup demonstrates that manipulating simple fan configurations alone can achieve a reliable thermal output highly suitable for direct integration into agricultural greenhouses.

Nevertheless, an important physical limitation of the current experimental setup must be acknowledged. As depicted in the system documentation (Figure 1), a relatively long flexible duct channels the heated air from the PV/T collector into the greenhouse chamber. Because this ducting is uninsulated and exposed to ambient environmental conditions, sensible thermal losses are inevitable during fluid transport. Consequently, the actual temperature of the air exiting the PV/T outlet is theoretically higher than the temperature ultimately recorded entering the greenhouse. Future system designs should incorporate heavily insulated ducting with optimized lengths to minimize these transmission losses, thereby ensuring that the maximum extracted thermal energy is delivered directly into the greenhouse.

## 4. Conclusions

The experimental testing was simplified into three scenarios based on the measurement data: maximum PV/T - maximum greenhouse, maximum PV/T - minimum greenhouse, and minimum PV/T - minimum greenhouse. The numerical values of the air velocities employed were 3.70 m/s for the maximum PV/T configuration, 2.35 m/s for the minimum PV/T, 3.18 m/s for the maximum greenhouse utilizing 10 exhaust fans, and 2.03 m/s for the minimum greenhouse utilizing 6 exhaust fans. The highest average useful heat was achieved on Day 2 (Max PV/T - Min Greenhouse scenario), amounting to 368.28 W. The highest average thermal efficiency was recorded on Day 1 (Max PV/T - Max Greenhouse scenario), reaching 25.30%. The maximum PV/T configuration enhanced heat extraction from the collector, whereas the minimum greenhouse configuration intensified heat accumulation within the greenhouse chamber. This empirical analysis is limited exclusively to thermal parameters. Future investigations must incorporate the electrical performance of the PV panels under these varying mass flow rates to evaluate the overall exergy and energy efficiency of the hybrid system.

## 5. Acknowledgements

The authors gratefully acknowledge the Mechanical Engineering Study Program, Faculty of Engineering, Universitas Widyatama, for providing essential institutional support and facilities throughout this research. We also deeply appreciate our supervising lecturers for their continuous guidance, constructive feedback, and insightful discussions from the project's inception to its conclusion. Special thanks are extended to the Research Center for Energy Conversion Technology, National Research and Innovation Agency (BRIN), for their collaborative expertise and access to facilities, which were vital to this experimental work. Lastly, we thank all colleagues, technical staff, and other contributors whose time and effort ensured the successful equipment design, field testing, data collection, and manuscript preparation.

## 6. Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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