Experimental Study of Forced Convection Heat Transfer in a Tropical Greenhouse Using a Cooling Pad and Fan System

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Abstract.
A greenhouse is a cultivation technology designed to control environmental conditions to support optimal plant growth. However, in tropical regions such as Indonesia, the air temperature inside greenhouses tends to increase due to high solar radiation, making an effective cooling system essential. This study aims to evaluate the performance of a cooling pad and exhaust fan system in reducing air temperature, maintaining relative humidity, and achieving uniform temperature distribution through forced convection heat transfer inside a greenhouse. An experimental method was employed by measuring outdoor temperature, indoor temperature, relative humidity (RH), and air velocity at 12 sensor locations. Data were collected every 20 minutes from 08:00 to 16:00 for 28 consecutive days. The collected data were analyzed to determine the average temperature, temperature distribution, temperature reduction (ΔT), and cooling system effectiveness. The results indicate that the cooling pad and exhaust fan system reduced the indoor air temperature by an average of 4.25°C, maintained relative humidity within the range of 70–84%, and produced an air velocity between 0.90 and 1.12 m/s. The temperature distribution across the 12 sensor locations showed a maximum difference of only 0.3°C, indicating a uniform air distribution throughout the greenhouse. Therefore, the proposed cooling system is effective in controlling the greenhouse microclimate and has the potential to improve crop cultivation performance in tropical environments.
Keywords*: Greenhouse; Cooling Pad; Exhaust Fan; Forced Convection; Temperature Distribution and Microclimate.*

I. INTRODUCTION

A greenhouse is a plant cultivation technology designed to create controlled environmental conditions to enhance plant growth, productivity, and quality. Greenhouses protect plants from the effects of extreme weather, heavy rainfall, pest attacks, and temperature and humidity fluctuations that often occur in open-field cultivation. In tropical Indonesia, greenhouses are increasingly being used to support the cultivation of high-value horticultural crops. However, the high intensity of solar radiation often causes the air temperature inside the greenhouse to rise above the optimum temperature for plant growth. This condition can cause heat stress, which inhibits photosynthesis, increases respiration rates, accelerates water evaporation, and reduces plant productivity.

One widely used method for controlling temperature inside a greenhouse is an evaporative cooling system, which combines a cooling pad and an exhaust fan. This system operates on the principle of forced convection heat transfer, where outside air is circulated over a cooling pad that is constantly moistened with water. During this process, water evaporation absorbs heat from the air, lowering the air temperature before it enters the greenhouse. The exhaust fan then circulates the cooled air throughout the room, creating a more even temperature distribution and maintaining relative humidity within a range that supports plant growth. In addition to lowering air temperature, this system also has relatively low energy consumption compared to mechanical cooling systems, making it widely used in greenhouses in tropical regions.

Various studies have demonstrated the effectiveness of pad-fan cooling systems in improving greenhouse microclimate quality. Gupta, Sharma, and Kumar (2022) reported that implementing climate control strategies in tropical greenhouses can improve temperature and humidity stability, thus supporting plant growth. Singh and Sharma (2022) explained that the application of Internet of Things (IoT) technology in greenhouses allows for more accurate and sustainable environmental monitoring. Research by Wang et al. (2021) used a Computational Fluid Dynamics (CFD) approach to analyze airflow distribution in a pad-fan system and demonstrated that ventilation system configuration significantly influences temperature distribution within the greenhouse. Research by Pardo-Pina et al. (2024) also demonstrated that good air distribution in an evaporative cooling system can increase cooling efficiency and produce more uniform microclimate conditions.

Although numerous studies have been conducted on cooling pad and exhaust fan systems, most of these studies focus on numerical simulations, IoT-based automated systems, or specific greenhouse sizes. Experimental research on the characteristics of forced convection heat transfer in tropical greenhouses, with observations of temperature distribution at several points, is still relatively limited, particularly in the environmental conditions of Bengkalis Regency. Furthermore, few studies have simultaneously evaluated the relationship between outside air temperature, greenhouse air temperature, relative humidity, air flow velocity, and temperature distribution at several observation points as indicators of cooling system effectiveness.

Based on these conditions, this study was conducted to analyze the characteristics of forced convection heat transfer in a tropical greenhouse using a cooling pad and exhaust fan system. Observations were made on changes in outside air temperature, air temperature inside the greenhouse, relative humidity, air velocity, and temperature distribution at 12 measurement points during the study period. The results are expected to provide information on the effectiveness of the evaporative cooling system in creating more stable microclimate conditions, as well as serve as a reference in the development of efficient greenhouses suitable for tropical climate conditions in Indonesia.

II. THEORETICAL STUDY

Greenhouse

A greenhouse is a plant cultivation structure designed to create a controlled growing environment so that plants achieve optimal temperature, humidity, light intensity, and air circulation. Greenhouses are used to protect plants from extreme weather conditions, such as rain, strong winds, and pests and diseases, thereby increasing plant productivity. In tropical climates like Indonesia, greenhouses are widely used to cultivate high-value horticultural crops. However, high solar radiation intensity often causes temperatures inside greenhouses to rise above the optimum temperature for plants, necessitating an effective climate control system (ASHRAE, 2021; Gupta et al., 2022).

Climate control in a greenhouse is achieved by regulating the balance of incoming and outgoing energy through heat transfer, ventilation, evaporation, and radiation. A good ventilation system can reduce heat buildup, ensuring the greenhouse's microclimate remains within a range suitable for plant growth.

Forced Convection Heat Transfer

Heat transfer is the process of energy transfer due to a temperature difference between two media. Generally, heat transfer consists of conduction, convection, and radiation. In this study, the dominant mechanism is forced convection.

Forced convection occurs when heat transfer occurs due to fluid flow generated by a mechanical device such as a fan or pump. Moving air carries heat energy from one area to another, resulting in a more even temperature distribution. The magnitude of convective heat transfer can be expressed using Newton's Cooling Equation.

$$Q = hA(T_s - T_\infty)$$

with:

Q = heat transfer rate (W)

h = convection heat transfer coefficient (W/m²K)

A = surface area (m²)

T_s = surface temperature (°C)

T_∞ = fluid temperature (°C)

The greater the air flow speed, the higher the convection heat transfer coefficient value, making the cooling process more effective (Çengel & Ghajar, 2020; Incropera et al., 2017).

2.3 Cooling Pad and Exhaust Fan System

A cooling pad is a porous medium through which water continuously flows, allowing the outside air passing through it to evaporate. The heat energy from the air is used to evaporate the water, lowering the air temperature before it enters the greenhouse.

An exhaust fan is installed on the opposite side of the cooling pad and functions to draw air out of the greenhouse, creating negative pressure inside the room. This pressure difference causes fresh air to continuously flow in through the cooling pad. The combination of these two components is known as the Pad-Fan Evaporative Cooling System.

System effectiveness is influenced by several factors, including:

- cooling pad area;
- water discharge that wets the media;
- exhaust fan capacity;
- air speed;
- outside air temperature;
- relative humidity of the air.

If the system is well designed, the air temperature inside the greenhouse can be lowered several degrees compared to the ambient temperature, thus creating better microclimate conditions for plants (Franco et al., 2014; Wang et al., 2021).

2.4 Temperature Distribution in Greenhouse

Temperature distribution refers to the distribution of temperatures across various locations within the greenhouse. Even temperature distribution is crucial because each plant requires relatively uniform environmental conditions for optimal growth.

Temperature distribution is influenced by several factors, namely:

- cooling pad position;
- exhaust fan position;
- air flow direction;
- solar radiation intensity;
- greenhouse dimensions;
- the presence of plants in the greenhouse.

If airflow is uneven, hot spots will form, which can lead to uneven plant growth. Therefore, temperature distribution is a key parameter in evaluating the performance of a greenhouse cooling system (Teitel, 2007; Pardo-Pina et al., 2024).

2.5 Previous Research

Various studies have been conducted to improve the efficiency of greenhouse cooling systems. Gupta et al. (2022) explained that climate control strategies in tropical greenhouses can maintain temperature and humidity stability, thereby increasing plant productivity. Wang et al. (2021) used a Computational Fluid Dynamics (CFD) approach to evaluate air distribution in a pad-fan system and demonstrated that ventilation configuration influences cooling effectiveness. Pardo-Pina et al. (2024) developed an air distribution system using perforated pipes that can improve temperature distribution within the greenhouse. Furthermore, Alhaqi et al. (2024) implemented an Internet of Things (IoT)-based evaporative cooling system to automatically control the microclimate conditions of a tropical greenhouse.

Although extensive research on cooling pads and exhaust fans has been conducted, most of it focuses on numerical simulations, IoT-based automated systems, and ventilation design optimization. Experimental research on the characteristics of forced convection heat transfer using temperature distribution measurements at multiple points inside a tropical greenhouse is still relatively limited. Therefore, this study was conducted to evaluate the performance of the cooling pad and exhaust fan system by measuring the outside air temperature, the greenhouse air temperature, relative humidity, air velocity, and temperature distribution at 12 observation points.

III. RESEARCH METHODS

Research Design

This experimental research aims to analyze the characteristics of forced convection heat transfer in a tropical greenhouse using a cooling pad and exhaust fan system. Testing was conducted directly on a prototype greenhouse designed with an evaporative cooling system to determine the system's ability to lower air temperature and achieve even temperature distribution within the greenhouse.

The independent variables in this study are the cooling pad and exhaust fan cooling systems, while the dependent variables include the air temperature inside the greenhouse, the air temperature outside the greenhouse, the relative humidity of the air, the air flow velocity, and the temperature distribution at 12 measurement points.

Tools and Materials

The equipment used in this study is presented in Table 1.

Table 1 Research Equipment

No	Component	Specification
1	Mixed Type Greenhouse	Hollow iron frame, UV plastic cover
2	Cooling Pad	Honeycomb type cellulose media
3	Exhaust Fan	220 VAC axial fan
4	Circulation Fan	Horizontal airflow axial fan
5	Water pump	220 VAC submersible pump
6	Water Reservoir Tank	60 liter capacity
7	Water Distribution Pipes	½ inch PVC
8	Water Reservoir Pipe	4 inch PVC
9	Arduino Uno	ATmega328P microcontroller
10	HTC-1	Digital Hygro-Thermometer
11	Anemometer	Range 0–30 m/s
12	UV Plastic	200 micron thickness
13	Power Supply	220 VAC

The materials used in the research include water as an evaporative cooling medium, a cellulose cooling pad, a power source, and supporting components for the cooling system.

Research Variables

The research variables consist of:

a. Independent Variable

- Cooling pad system.
- Exhaust fan.

b. Dependent Variable

- The temperature of the air outside the greenhouse.
- Air temperature in the greenhouse.
- Temperature distribution at 12 measurement points.
- Relative humidity of air.
- Air flow rate.

c. Controlled Variables

- Greenhouse dimensions.
- Sensor position.
- Cooling pad water discharge.
- Exhaust fan capacity.
- Data collection time.

Research Procedures

The research stages were carried out as follows.

1. Design and make a greenhouse prototype along with a cooling pad and exhaust fan system.

2. Install temperature sensors at 12 measurement points spread throughout the greenhouse.
3. Install outside air temperature and humidity sensors.
4. Fill the water tank and operate the pump so that the cooling pad is always wet.
5. Turn on the exhaust fan so that outside air passes through the cooling pad to the greenhouse.
6. Take measurements of outside air temperature, air temperature in the greenhouse, relative humidity, and air speed.
7. Data collection was carried out every 20 minutes starting at 07.00–17.00 WIB for 28 days.
8. All data is recorded using a microcontroller-based monitoring system and stored for analysis.

Data Collection Techniques

Research data was obtained through direct measurement methods (experimental measurement). The parameters observed included:

- outside air temperature (°C),
- air temperature in the greenhouse (°C),
- temperature distribution at 12 points,
- relative humidity (%RH),
- air velocity (m/s).

Measurements were carried out periodically every 20 minutes to obtain data that could describe changes in greenhouse microclimate conditions during the research period.

Data Analysis Techniques

The measurement data was processed using Microsoft Excel to obtain average, maximum, and minimum values, as well as graphs of temperature and humidity changes during the test. The analysis was conducted descriptively by comparing the outdoor and indoor air conditions.

The effectiveness of the cooling system is evaluated based on:

- the difference between the outside air temperature and the air temperature inside the greenhouse;
- temperature distribution at 12 observation points;
- changes in relative humidity of the air;
- the speed of air flow produced by the exhaust fan.

The results of the analysis were then compared with previous research to determine the level of effectiveness of the cooling pad and exhaust fan system in creating greenhouse microclimate conditions suitable for plant cultivation in tropical areas.

IV. RESULTS AND DISCUSSION

Results of Greenhouse Environmental Parameter Measurements

The cooling pad and exhaust fan cooling system was tested for 28 days on a prototype greenhouse to determine the characteristics of forced convection heat transfer in controlling microclimate conditions. Data was collected every 20 minutes using 12 temperature sensors placed at various locations within the greenhouse. In addition to the air temperature inside the greenhouse, the observed parameters included the outside air temperature, relative humidity (RH), and airflow velocity.

The measurement results show that the cooling system is able to maintain environmental conditions inside the greenhouse more stable than the outside environmental conditions. Based on the results of observations during the research period, the outside air temperature had a minimum value of 27.80°C, a maximum of 35.50°C, with an average of 32.35°C. Meanwhile, the air temperature inside the greenhouse was in the range of 25.90°C to 30.20°C with an average value of 28.10°C. The average difference between the outside air temperature and the air temperature inside the greenhouse reached 4.25°C, which indicates that the evaporative cooling system is able to reduce heat accumulation due to solar radiation.

Table 4.1. Summary of greenhouse environmental parameter measurement results

Parameter	Minimum	Maximum	Average	Standard Deviation
Outside temperature (°C)	27.8	35.5	32.35	2.46
Internal temperature (°C)	26.3	29.6	28.10	0.98

RH (%)	70	84	75.40	4.12
Air speed (m/s)	0.90	1.12	1.03	0.07
ΔT (°C)	1.5	5.9	4.25	1.34

The data in Table 4.1 shows that the use of a cooling pad and exhaust fan system can produce more controlled microclimate conditions compared to the outdoor environment. The average temperature reduction of 4.25°C indicates that the evaporative cooling process is effective. When outside air passes through the water-moistened cooling pad, some of the air's sensible heat is used to evaporate the water, thus lowering the air temperature before entering the greenhouse. Furthermore, the exhaust fan generates airflow that accelerates heat transfer through forced convection, resulting in a more even distribution of cool air throughout the room.

In addition to lowering the air temperature, the cooling system also increases the relative humidity inside the greenhouse. During testing, the relative humidity ranged from 70–84%, with an average of around 77%. This value is still within the appropriate range for the growth of various horticultural crops. The increased humidity is a consequence of the water evaporation process on the cooling pad. Despite the increased humidity, the presence of an exhaust fan maintained air circulation to prevent excessive condensation inside the greenhouse.

The airflow velocity generated by the exhaust fan ranges from 0.90–1.12 m/s, with an average value of around 1.01 m/s. This speed indicates that the ventilation system is capable of generating sufficient airflow to accelerate forced convection heat transfer without causing excessive turbulence. The higher the airflow velocity, the greater the convection heat transfer coefficient, thus increasing the system's ability to reduce air temperature inside the greenhouse.

The results of this study indicate that the combination of a cooling pad and exhaust fan is effective in controlling temperature and humidity in a tropical greenhouse. This finding aligns with research by Gupta et al. (2022), which states that a climate control system can maintain stable greenhouse temperature and humidity, thus supporting plant growth. These results also support research by Wang et al. (2021), which showed that a pad-fan system can produce more even air distribution, thereby increasing cooling effectiveness. Therefore, the evaporative cooling system implemented in this study has been proven to create microclimate conditions more suitable for plant cultivation in tropical regions.

4.2 Temperature Distribution in Greenhouse

Temperature distribution inside a greenhouse is a critical parameter for evaluating the performance of an evaporative cooling system. In this study, temperature distribution was observed using 12 DS18B20 temperature sensors installed at various points within the greenhouse. The sensors were placed to determine the level of temperature distribution produced by the combination of the cooling pad and exhaust fan during testing.

The measurement results show that the temperature distribution at all observation points has a relatively uniform pattern. Temperature differences between sensors do not show significant fluctuations, thus concluding that the air cooled by the cooling pad is distributed evenly throughout the greenhouse. This indicates that the ventilation system used is capable of producing an effective airflow pattern, enabling proper heat transfer by forced convection.

Table 4.2shows the temperature distribution at 12 measurement points during testing. It can be seen that the air temperature tends to be lower in the area adjacent to the cooling pad, then increases slightly towards the center of the greenhouse before finally exiting through the exhaust fan. The temperature difference remains relatively small and does not affect the stability of the microclimate inside the greenhouse.

Table 4. Temperature Distribution of 12 Sensor Points at Several Observation Times

Time	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
08.00	26.2	26.3	26.4	26.3	26.2	26.4	26.3	26.2	26.4	26.3	26.2	26.3
10.00	27.9	28.0	28.1	28.0	27.9	28.1	28.0	27.9	28.1	28.0	27.9	28.0
12.00	29.1	29.2	29.3	29.2	29.1	29.3	29.2	29.1	29.3	29.2	29.1	29.2

13.20	29.5	29.6	29.7	29.6	29.5	29.7	29.6	29.5	29.7	29.6	29.5	29.6
16.00	27.6	27.7	27.8	27.7	27.6	27.8	27.7	27.6	27.8	27.7	27.6	27.7

This temperature distribution pattern indicates that the airflow generated by the exhaust fan is able to reduce heat accumulation in the center of the greenhouse. Air entering through the cooling pad undergoes evaporative cooling and is then distributed throughout the greenhouse, resulting in a more uniform temperature. This mechanism demonstrates that forced convection heat transfer is effective in reducing temperature differences between observation points.

The results of this study also showed that no hot spots were formed, which could disrupt plant growth. Temperature evenness is one indicator that the exhaust fan capacity meets the greenhouse's ventilation needs, allowing hot air to be continuously expelled and replaced by cooled air from the cooling pad.

Compared to the study by Wang et al. (2021), the temperature distribution in this study exhibited similar characteristics, with air temperature tending to increase gradually as the distance from the cooling pad to the exhaust fan increased. However, the temperature difference in this study was relatively small, indicating that the cooling system configuration was capable of producing more even air distribution. These results also align with the study by Pardo-Pina et al. (2024) which stated that the pad-fan evaporative cooling system was able to improve temperature homogeneity inside the greenhouse through proper airflow pattern management.

Overall, the results of the temperature distribution test demonstrated that the combination of cooling pads and exhaust fans was able to create a stable microclimate in the greenhouse. The even temperature distribution achieved during the test demonstrated that the cooling system was not only effective in lowering air temperature but also maintained uniform environmental conditions throughout the greenhouse. These conditions are crucial for optimal plant growth, as each plant receives relatively the same temperature throughout the cultivation process.

4.3 Analysis of the Effect of Cooling Pad on Temperature Reduction

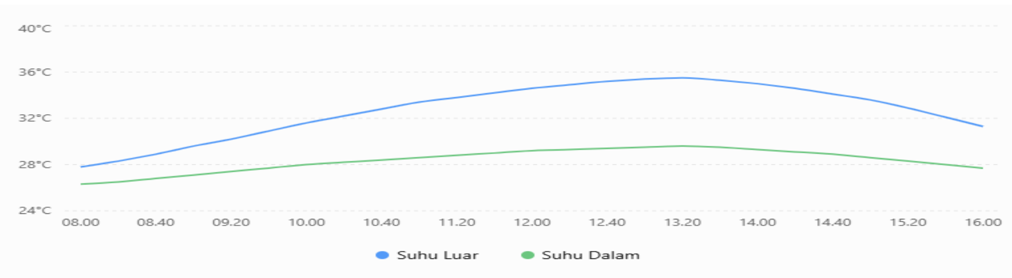
The cooling pad system is a key component in the evaporative cooling process in a greenhouse. This system utilizes water evaporation to absorb heat from the outside air before the air is circulated into the greenhouse by an exhaust fan. In this study, the effect of cooling pad use was analyzed based on the difference in outside air temperature and the air temperature inside the greenhouse over 28 days of testing.

The results showed that the average outside air temperature was 32.35°C, while the air temperature inside the greenhouse was 28.10°C. Therefore, the cooling pad system combined with the exhaust fan was able to produce an average temperature reduction of 4.25°C. This value indicates that the evaporative cooling system works effectively in reducing heat accumulation caused by solar radiation in the greenhouse.

Table 4.2. Results of Measurement of Outside Air Temperature and Air Temperature Inside the Greenhouse

Parameter	**Minimum (°C)**	**Maximum (°C)**	**Average (°C)**
Outside Air Temperature	27.80	35.50	32.35
Air Temperature in the Greenhouse	25.90	30.20	28.10
Temperature Difference (ΔT)	–	–	**4.25**

Figure 4.3shows the comparison of outside air temperature and air temperature inside the greenhouse during the research period.



The resulting temperature drop occurs because the outside air passing through the cooling pad undergoes evaporation. During this process, the water wetting the cellulose pad absorbs sensible heat from the air, using some of the heat energy to convert the water into steam. As a result, the temperature of the air entering the greenhouse is lower than the ambient air temperature. The exhaust fan then circulates the cool air throughout the greenhouse, resulting in forced convection heat transfer, which maintains a stable temperature inside the greenhouse.

Based on observations, the temperature drop does not occur consistently throughout the day. In the morning, the temperature difference between the outside air and the air inside the greenhouse is relatively small because the intensity of solar radiation is still low. As the intensity of sunlight increases during the day, the outside air temperature increases, causing the evaporation process on the cooling pad to intensify. This condition allows the cooling system to maintain the air temperature inside the greenhouse at a lower range than the ambient temperature. In the afternoon, when the intensity of solar radiation begins to decrease, the temperature difference narrows again because the heat load received by the greenhouse also decreases.

The average temperature reduction of 4.25°C indicates that the applied cooling system improved the greenhouse's microclimate. This value indicates that the combination of cooling pads and exhaust fans was quite effective in reducing the heat load inside the greenhouse, thus making the environment more suitable for plant growth. Furthermore, the air distribution generated by the exhaust fans also helped distribute the cooled air throughout the greenhouse, reducing temperature differences between observation points.

The results of this study align with those of Gupta et al. (2022), who stated that climate control systems in tropical greenhouses can maintain stable temperature and humidity, thus creating a better growing environment for plants. These findings also support the research of Wang et al. (2021), which showed that a pad-fan system can increase cooling efficiency through more even airflow distribution. Furthermore, research by Pardo-Pina et al. (2024) reported that the use of cooling pads combined with a good air distribution system can increase cooling effectiveness and produce more homogeneous temperature conditions inside the greenhouse.

Based on the research results and comparisons with previous studies, it can be concluded that the use of a cooling pad system significantly contributes to reducing air temperature inside the greenhouse. The average temperature reduction of 4.25°C proves that the evaporative cooling process is able to effectively reduce heat accumulation, while the presence of an exhaust fan plays a role in accelerating the heat transfer process through forced convection so that the cooled air can be distributed evenly throughout the greenhouse. Thus, the combination of these two components is an effective solution for controlling greenhouse microclimate conditions in tropical climates.

4.4 Air Velocity and Relative Humidity Analysis

Airflow velocity and relative humidity are important parameters in evaluating the performance of a greenhouse's evaporative cooling system. These two parameters are interrelated because the evaporation of water on the cooling pad not only lowers air temperature but also increases the water vapor content inside the greenhouse. Therefore, airflow and relative humidity measurements are performed to determine the effectiveness of the cooling pad and exhaust fan system in creating favorable microclimate conditions for plant growth.

The test results showed that the relative humidity of the air inside the greenhouse was in the range of 70–84% with an average value of around 77%, while the air flow velocity generated by the exhaust fan was in the range of 0.90–1.12 m/s with an average value of 1.01 m/s. These values indicate that the ventilation system was able to produce stable air circulation during the testing process.

Table 4.3. Relative Humidity and Air Velocity Measurement Results

Parameter	Minimum	Maximum	Average
Relative Humidity (%RH)	70	84	77
Air Speed (m/s)	0.90	1.12	1.01

Fig. 4.4shows the change in relative humidity during the test, while Figure 4.5 shows the change in air velocity inside the greenhouse.

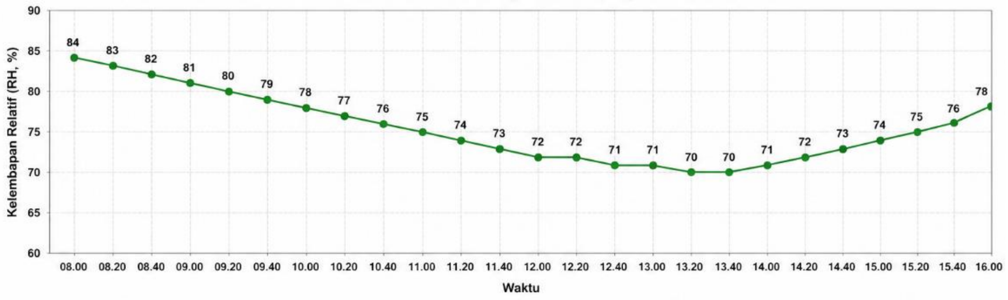


Fig. 4.4 Relative Humidity Graph

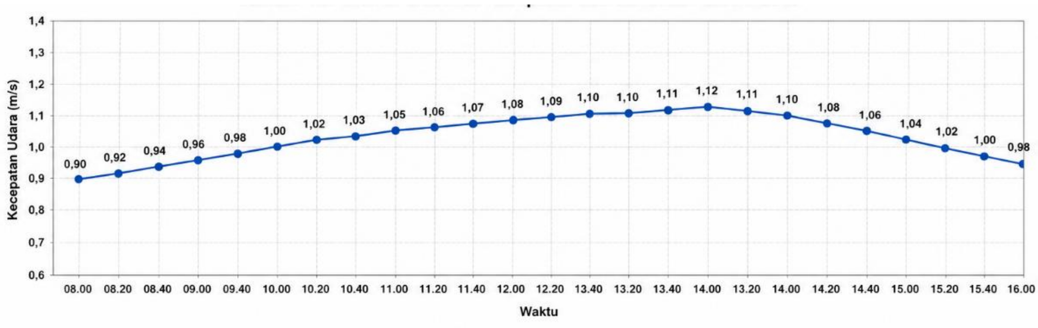


Fig. 4.5 Air Speed Graph

The increase in relative humidity is a direct result of water evaporation in the cooling pad. As outside air passes through the constantly moist media, some of the sensible heat is used to evaporate the water, lowering the air temperature while increasing the water vapor content. This results in an environment with a lower temperature and higher humidity than the outside air.

Despite the increased humidity, the presence of an exhaust fan maintains air circulation, maintaining a stable humidity level and preventing excessive condensation. An average air velocity of 1.01 m/s also demonstrates that the ventilation system is able to distribute cooled air evenly throughout the greenhouse. This airflow accelerates heat transfer through forced convection, making the cooling process more effective.

The results of this study indicate that the balance between airflow velocity and relative humidity significantly influences the success of an evaporative cooling system. Air velocity that is too low can cause uneven distribution of cool air, while air velocity that is too high can reduce the air's contact time with the cooling pad. Therefore, the combination of relative humidity values of 70–84% and air velocity of 0.90–1.12 m/s in this study indicates that the system is operating under optimal conditions.

4.5 Comparison of Research Results with Previous Research

To evaluate the performance of the developed cooling system, the results of this study were compared with several previous studies that discussed the use of cooling pad and exhaust fan systems in greenhouses.

Table 4.4. Comparison of research results with previous research

Researchers	Research Object	Key Results
Gupta et al. (2022)	Tropical greenhouse climate control	The cooling system is able to maintain stable air temperature and humidity.
Wang et al. (2021)	Pad–fan system simulation using CFD	Good airflow distribution increases the effectiveness of greenhouse cooling.
Pardo-Pina et al. (2024)	Air distribution in the greenhouse	The evaporative cooling system produces a more homogeneous temperature.
This research	Greenhouse with cooling pad and exhaust fan	Lowering the average temperature by 4.25°C, maintaining humidity at 70–84%, and producing air speeds of 0.90–1.12 m/s so that the temperature distribution at the 12 observation points becomes more even.

Based on Table 4.4, the results of this study align with previous studies. The average temperature reduction of 4.25°C indicates that the evaporative cooling system effectively reduced heat accumulation. This value demonstrates that the combination of cooling pads and exhaust fans can create stable microclimate conditions that support plant growth in tropical greenhouses.

Compared to Gupta et al.'s (2022) study, this study not only evaluated changes in temperature and humidity but also analyzed temperature distribution using 12 sensor points distributed throughout the greenhouse. This approach provides a more detailed picture of temperature evenness as an indicator of the success of forced convection heat transfer.

The results of this study also support the research of Wang et al. (2021), which stated that the pad-fan system configuration influences air distribution patterns within the greenhouse. In this study, the relatively uniform temperature distribution indicates that the airflow generated by the exhaust fan can reduce the formation of hot spots, thus creating a more homogeneous greenhouse environment.

Furthermore, this study is novel in that it included continuous experimental observations over 28 days, with 20-minute measurements using 12 temperature sensors. This approach yields more representative data on the characteristics of forced convection heat transfer in tropical greenhouses than studies that only used numerical simulations or a limited number of measurement points.

Overall, the research results show that the cooling pad and exhaust fan system can improve the greenhouse microclimate by reducing air temperature, increasing controlled relative humidity, and providing more even air distribution. These findings demonstrate that evaporative cooling is an effective and energy-efficient solution for greenhouses in tropical climates.

V. CONCLUSION AND SUGGESTIONS

Conclusion

Based on the research results regarding experimental studies of forced convection heat transfer in greenhouses using a cooling pad and exhaust fan system, it can be concluded that:

1. The cooling pad and exhaust fan system can create a more stable greenhouse microclimate by lowering the air temperature inside the greenhouse. Test results showed that the outside air temperature averaged 32.35°C, while the inside air temperature averaged 28.10°C, resulting in an average temperature reduction of 4.25°C.
2. The temperature distribution at the 12 measurement points showed a relatively even pattern, so no significant temperature differences were found between the observation points. This indicates that the ventilation system generates effective airflow, enabling heat transfer by forced convection to proceed effectively.
3. The evaporative cooling system is capable of maintaining relative humidity in the range of 70–84% with an airflow rate of 0.90–1.12 m/s. This demonstrates that the combination of the cooling pad and exhaust fan is capable of producing stable air circulation and supporting the cooling process without causing excess humidity.
4. Research results demonstrate that the combination of cooling pads and exhaust fans is an effective method for controlling temperature, humidity, and air distribution in tropical greenhouses. This system has the potential to be implemented as a simple, energy-efficient climate control solution that can support optimal plant growth.

Suggestions

Based on the results of the research that has been conducted, several suggestions for further research development are as follows:

1. Further research is recommended to use a larger greenhouse so that the characteristics of temperature distribution and air flow can be analyzed under conditions closer to field applications.
2. The number of measurement parameters can be increased, such as solar radiation intensity, planting medium temperature, soil moisture, and wet-bulb temperature so that the analysis of the performance of the evaporative cooling system becomes more comprehensive.
3. The development of an Internet of Things (IoT)-based monitoring system and an automatic climate control system can be implemented so that the cooling pad and exhaust fan can operate in real time according to the greenhouse's environmental conditions.
4. Further research can compare various types of cooling pad media, exhaust fan capacity, and ventilation system configurations to obtain a more efficient design that suits Indonesia's tropical climate conditions.

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REFERENCES

[1]. ASHRAE. (2021). ASHRAE handbook—HVAC applications. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[2]. Çengel, Y. A., & Ghajar, A. J. (2020). Heat and mass transfer: Fundamentals and applications (6th ed.). McGraw-Hill Education.

[3]. Incropera, F.P., DeWitt, D.P., Bergman, T.L., & Lavine, A.S. (2017). Fundamentals of heat and mass transfer (8th ed.). ***John Wiley & Sons. Journal*** (18 references)

[4]. Gupta, A., Sharma, P., & Kumar, R. (2022). Climate control strategies in tropical greenhouses: A review. Environmental Challenges, 8, 100561.

[5]. Singh, D., & Sharma, P. (2022). IoT-based smart greenhouse monitoring system: A review. Materials Today: Proceedings, 49, 3142–3147.

[6]. Taki, M., & Rohani, A. (2020). Smart greenhouse monitoring and control using the Internet of Things. Information Processing in Agriculture, 7(3), 369–380.

[7]. Wang, X., et al. (2021). Selection of a computational fluid dynamics (CFD) model and its application to greenhouse pad-fan cooling systems. ***Journal of Cleaner Production***, 302, 127013. https://doi.org/10.1016/j.jclepro.2021.127013

[8]. Li, H., Guo, Y., Zhao, H., Wang, Y., & Chow, D.H. (2021). Towards automated greenhouses: A state-of-the-art review on greenhouse monitoring methods and technologies based on the Internet of Things. Computers and Electronics in Agriculture, 191, 106558.

[9]. Oliveira, GLFA, Lopes, D.C., Steidle Neto, A.J., & Zolnier, S. (2023). Software for sizing pad-fan evaporative cooling systems of greenhouses. Energia na Agricultura, 38(2), 14–25. https://doi.org/10.17224/EnergAgric.2023v38n2p14-25

[10]. Shojaei, M.H., Mortezapour, H., Jafarinaeimi, K., & Maharlooei, M.M. (2021). An estimation method for greenhouse temperature under the influence of evaporative cooling system. ***Journal of Thermal Engineering***, 7(4), 918–933. https://doi.org/10.18186/thermal.930907

[11]. Jiao, N., Zhu, D., Jing, Y., Liu, M., & Liu, C. (2024). Research on determining method of greenhouse wet pad-fan operating parameters based on numerical simulation. ***Journal of Chinese Agricultural Mechanization***, 45(5), 79–84. https://doi.org/10.13733/j.jcam.issn.2095-5553.2024.05.012

[12]. Pardo-Pina, S., Ferrández-Pastor, J., Rodríguez, F., & Cámara-Zapata, J. M. (2024). Analysis of an evaporative cooling pad connected to an air distribution system of perforated polyethylene tubes in a greenhouse. Agronomy, 14(6), 1187.

[13]. Alhaqi, MAD, et al. (2024). Internet of Things-driven evaporative cooling system for tropical greenhouse environmental control. IOP Conference Series: Earth and Environmental Science.

[14]. Sanhaji, G., et al. (2024). Internet of Things based micro climate control optimization system for tropical greenhouses in responding to climate change**. *International Journal of Research and Reviews*.**

[15]. Jamaluddin, TAA, et al. (2025). Temperature and humidity control in a small-scale greenhouse in a tropical climate. ***Salaga Journal***.

[16]. Laumal, F., et al. (2025). Adaptive-historical energy-efficient temperature control for tropical greenhouses. ***Journal of Agricultural Engineering***.

[17]. Sapounas, A., Bartzanas, T., Kittas, C., et al. (2023). Fan and pad evaporative cooling system for greenhouses: Evaluation of a numerical and analytical model.

[18]. Franco, A., Valera, D.L., Peña, A., & Pérez, A. (2014). Energy efficiency in greenhouse evaporative cooling techniques: Cooling boxes versus cellulose pads. Energies, 7(3), 1427–1447.

[19]. Valera, D.L., Molina-Aiz, F.D., Peña, A., & López, A. (2012). Pad-fan systems in Mediterranean greenhouses: Determining optimal setup by sonic anemometry. Transactions of the ASABE, 55(3), 1077–1089.

[20]. Sethi, V.P., & Sharma, S.K. (2008). Survey of cooling technologies for worldwide agricultural greenhouse applications. Solar Energy, 82(9), 832–859.

[21]. Teitel, M. (2007). The effect of screens and ventilation on airflow and temperature distribution in greenhouses. Biosystems Engineering, 96(1), 99–111.