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Two-Stage Evaporative Cooler for Mushroom-Growing Houses in Hot and Humid Climates

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ABSTRACT

Shiitake (*Lentinula edodes*) is one of the most cultivated mushrooms in the world, and it prefers a temperate climate. The improvement of warm-weather shiitake strains is one way to increase shiitake yield in Thailand. Mushroom-growing houses should be equipped with mechanical cooling to control and establish the optimal environment for cultivation. In this study, an Indirect–Direct Evaporative Cooling (IDEC) system consisting of a cooling coil and evaporative cooling (cellulose pad) was tested for its suitability for shiitake cultivation from August 2020 to December 2020. Under optimal shading of, and growing conditions, the IDEC system maintained the air temperature (27–28°C) and relative humidity in the required ranges. The mushroom compost was almost completely brown after the 100-day test and ready for the next fruiting phase. When compared with the fan-pad system, regression analysis showed that the two systems exhibited similar performance and had similar equipment costs. However, the IDEC system had a lower air temperature at a lower relative humidity, and its efficiency was over 100%. This study demonstrated that the IDEC system can be applied to promote shiitake cultivation in hot and humid climates.

Keywords: Evaporative cooling, *Lentinula edodes*, Regression analysis.

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INTRODUCTION

Mushrooms are an excellent functional food and are rich in not only flavor but also nutrients and bioactive substances for preventing diseases (Krishan, 2015). With the improved development of mushroom species and cultivation technologies, global mushroom production has very rapidly grown in the last 20 years. In 2018, mushroom cultivation market was at 127.74 Million Tons (MT), and the market is estimated to grow by an additional 20.84 MT by 2026. Significant growth is expected because of increased demand for quality and healthy foods (Rishikesh, 2020). Mushrooms are not plants, but the fruiting structures of these specialized fungi act as the principal decomposers in the ecological system. They can be used to degrade agricultural solid waste into growing substrates to recycle the nutrients back into the soil. Thus, mushroom cultivation is an important part of sustainable agriculture, especially in small farming systems.

Mushroom cultivation generally consists of substrate preparation, spawn inoculation, incubation (mycelium growth), and fruiting. During the incubation and fruiting stages, mushrooms are sensitive to environmental factors such as temperature, humidity, light, and CO_2, but the temperature is the most dominant factor (Hamed *et al*., 2018). Oysters, wood ears, and paddy straws need a subtropical or tropical climate, while button and shiitake require a temperate climate for growth. However, the growth temperature also depends on the strain type; for example, warm-weather shiitake strains fruit between 10 and 28°C, while the optimum temperature for cold-weather strains is

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between 7 and 15°C (Irwan, 2009).

Shiitake (*Lentinula edodes*) is a major mushroom type cultivated around the world. It is popular because of its flavor, high nutritional value, and medicinal properties, which include anticancer, antimicrobial, antidiabetic, hypotensive, and hypocholesterolemic activities (Wasser, 2005). Shiitake is an economically viable crop in Thailand, but high yields are limited to regions with low winter temperatures, so, it makes up only 3% of the gross mushroom product. The Department of Agriculture (Thailand) has been developing shiitake strains that can be grown at higher temperatures of up to 28 °C to increase the yield. However, mushroom houses still need to be equipped with mechanical cooling.

Evaporative Cooling (EC) is one of the most efficient cooling techniques for controlling the temperature and humidity inside a greenhouse (Mohammad *et al*., 2020). Major EC types include indirect, direct, and two-stage or mixed-mode (Debajit and Sudip, 2018). Indirect EC is a simple technique where surface sensible heat is converted into the latent heat of vaporization by water flowing on the top of the roof. This cools the air temperature inside the greenhouse without direct contact between air and water. Fog cooling is a popular Direct Evaporative Cooling (DEC) technique that provides cooling by pressurizing and spraying water as small droplets (Diameter: 2–60 μm). A high evaporation rate that absorbs sensible heat occurs, cooling the air in the greenhouse. The Fan-Pad System (FPS) is a type of DEC; its simple construction and operation has led to widespread use for greenhouse cooling. The main components of the FPS are a porous heat transfer medium for air and water, which is usually a cellulose pad, and a fan, which is located at the opposite wall. The FPS is effective for greenhouse cooling in hot and dry climates (Marouen *et al*., 2019); however, a major disadvantage of the FPS is the non-uniform air temperature over long airflow distances. Bartzanas and Kittas (2005) studied the application of an FPS for achieving greenhouse cooling in a hot and dry climate for cut rose production. They reported that although the internal temperature was 10°C lower than the outside ambient air, the temperature gradually increased along the pad to the fan axis (60 m) by 8°C at noon. Mehmet and Hasan (2015) observed similar experimental results, where the air temperature increased by approximately 7°C from pad to fan in an 8-m long greenhouse. Fog cooling provides uniform temperature and humidity; however, its efficiency is limited by insufficient natural air convection and nozzle clogging. López *et al*. (2012) compared the energy and water consumptions of a fog system and an FPS and showed that the fog system consumed more energy than the FPS (7.2–8.9 vs. 5.1 kWh, respectively) but considerably less water (9.4 vs. 122.3 L h^{-1}, respectively). Many studies have tested DEC for greenhouses, but few have considered its application to mushroom cultivation, especially in hot and humid climates (Thepa *et al*., 1999).

The Indirect–DEC (IDEC) system is a two-stage cooler consisting of an indirect heat exchanger that precools the air and a DEC. According to the psychrometric chart, an IDEC should have a lower outlet-air temperature than the FPS. The efficiency of the IDEC system can be estimated as the ratio between the air temperature drop and Wet Bulb Depression (WBD) or the difference between the Dry Bulb Temperature (DBT) and Wet Bulb Temperature (WBT) at the air inlet. The IDEC system's efficiency can exceed 100% when the outlet-air temperature is below that of the WBT of the inlet air (Hisham *et al*., 2004). The EC efficiency decreases at a high Relative Humidity (RH) (Ali *et al*., 2021); the results of the study conducted by Ali *et al*. (2021) suggested the application of EC efficiency in air conditioning in regions where the WBT is below 24°C (Camargo *et al*., 2006). However, the application of an IDEC to mushroom cultivation, which requires a high RH, has not yet been studied.

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The main objective of this study was to experimentally investigate the performance of the IDEC system for shiitake mushroom houses in Thailand, which has a hot and humid climate. Besides, we aimed to use the test results to set up models for regression analysis and compare the performances of the IDEC system and FPS, by considering the costs and factors affecting the system performance. These results would be useful for designing the cooling system of mushroom-growing houses in hot and humid climates.

MATERIALS AND METHODS

The IDEC system was constructed and tested at the Kasetsart University, Kamphaeng Saen Campus, which is located at 14.02372° N, 99.97487° E in the western part of central Thailand, as shown in Figure 1. The seasons are summer (mid-February to mid-May), rainy (mid-May to mid-October), and winter (mid-October to mid-February). The 2019 ambient climate data for the campus (Figure 2) were taken from the Thai Meteorological Department to plan the test in 2020.

In the experiments, the IDEC system was operated for shiitake mycelia growth, which takes approximately 4–6 months after inoculation until fruiting initiation. Based on the climate data, the test was started in August 2020 (rainy season) and ended in December (winter season) 2020 to correspond with the lowest temperatures, which are suitable for shiitake growth. The IDEC system was set to run during the day and shut down at night because the temperature was then in the acceptable range. The air RH was not a critical variable in this stage. The airflow through the pad was tested during April 15–20, 2020. The data were statistically analyzed using Microsoft Excel, and the performances of the FPS and IDEC system were compared. A schematic of the IDEC system is presented in Figure 3.

Figure 3 shows a schematic of the IDEC, which includes a 1.5-kW axial flow fan. The Cooling-Coil Unit (CCU) contains a finned-tube-type water-to-air heat exchanger that is 0.40-m wide, 0.60-m high, and 0.05-m thick. There are 16 rows for 48 tubes. The DEC unit contains a 15-mm-diameter pipe with 1 mm holes for spraying water on a structured packing material, which is a rigid cellulose pad made of corrugated paper with dimensions of 0.70×0.70×0.20 m^3 and a specific surface area of 370 $m^2\,m^{-3}$. Water is circulated using a centrifugal-type pump with a power rating of 373W. Two water tanks were made of PVC, and each had a

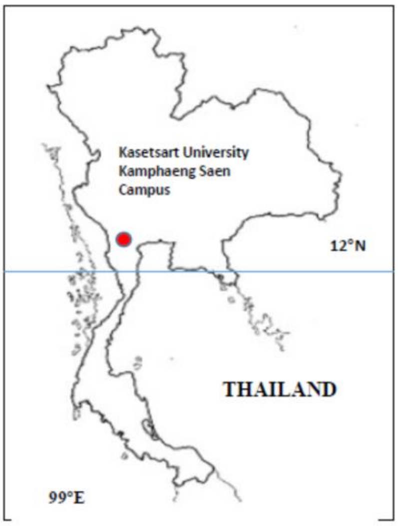

Figure 1. Location of the Kasetsart University, Kanphaeng Saen Campus, Thailand.

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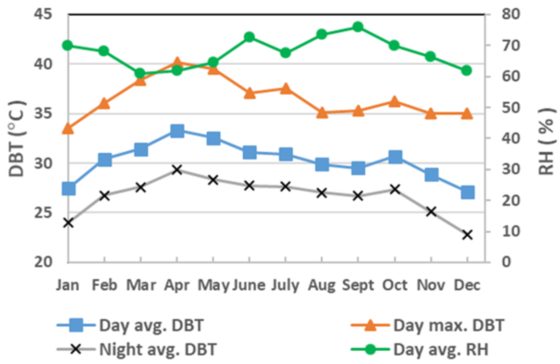

Figure 2. Climate data for the study area in 2019.

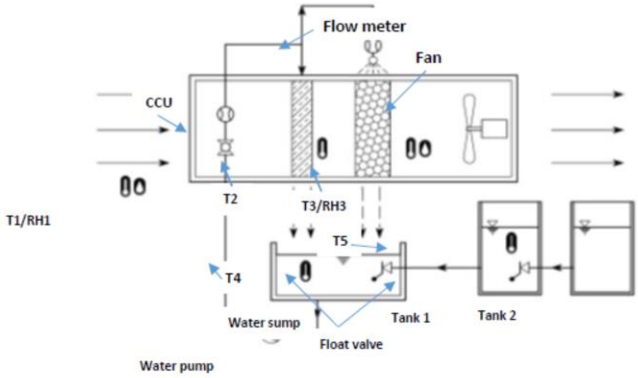

Figure 3. Schematic diagram of the IDEC system.

capacity of 1 m^3. A float control valve was installed in each tank to maintain a steady water level. The fan speed was regulated using a frequency inverter. Water in the sump flowed into the CCU tubes, and the water was sprayed over the pad by the water pump in parallel tracks. The makeup water from tank 1 was used to periodically fill the water sump and maintain a steady water level. Meanwhile, tank-1 was filled from tank-2, which had tap water added to it, and was left for 2–3 days to allow evaporation of chlorine before use. A night cooling system was used to lower the water temperature in tank-1 at night; the details of the system are provided in a previous study (Chantana, 2019).

The mushroom house, which was 3.0 m long, 2.5 m wide, and 2.0 m high, was made of sandwich panels with 0.05 m thick insulation ($k= 0.04\ W\ m^{-1}\ K^{-1}$) and located under a building roof to realize shading. Two ventilation fans, each with a capacity of 1,150 $m^3\ h^{-1}$, were mounted on the mushroom house walls and operated when the IDEC system was shut down. The main component of the shiitake compost was pasteurized sawdust packed in clear plastic bags with a diameter of 0.10 m and height of 0.15 m. Two hundred bags of compost were inoculated with spawn or grain/mycelium mixture and placed on shelves in the mushroom house. The shiitake strain is a warm-weather-type strain that can grow at temperatures up to 28°C.

Measurement System

The measured variables were the air temperature, RH, water temperature, and flow rate, as presented in Figure 3. The rotator-type flow meters were used with a

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±1% accuracy at full scale. A microcontroller (esp32 DOIT) was used to receive signals from the temperature and humidity sensors and record data in a memory card and on a cloud system through NETPIE. The sensors in the duct were SHT 20 with an accuracy of ±0.3°C and ±2% RH, and the waterproof sensors in the water tank and sump had an accuracy of ±0.5°C. The measuring instrument and sensors were supplied by the suppliers located in Bangkok, Thailand. The IDEC system was run from 8 am to 6 pm, and data were recorded every 15 minutes after 1 hour of steady-state operation. The recorded data were then averaged for every 1 hour. To ensure the steady-state condition, only data that were recorded 1 h after the system started were used for calculation. Figure 4 shows the IDEC system, night cooling system, microcontroller, and mushroom house.

Theory and Data Reduction

Figure 5 shows a psychrometric chart of the cooling process for the IDEC system (ASHRAE, 2016). First, the outside air moves across the heat exchanger, where only the sensible heat is lost, and the air DBT decreases (AB). The air then goes through the pad, where its temperature is further reduced to approach the WBT of the precooled air of the constant enthalpy process, and the humidity increases (BC). By contrast, the cooling range of DEC is limited to the WBT of the inlet air (AE). Point D represents the saturated state at which RH= 100%.

The IDEC system's efficiency (ε) (Issam and Hind, 2017) is given as follows:

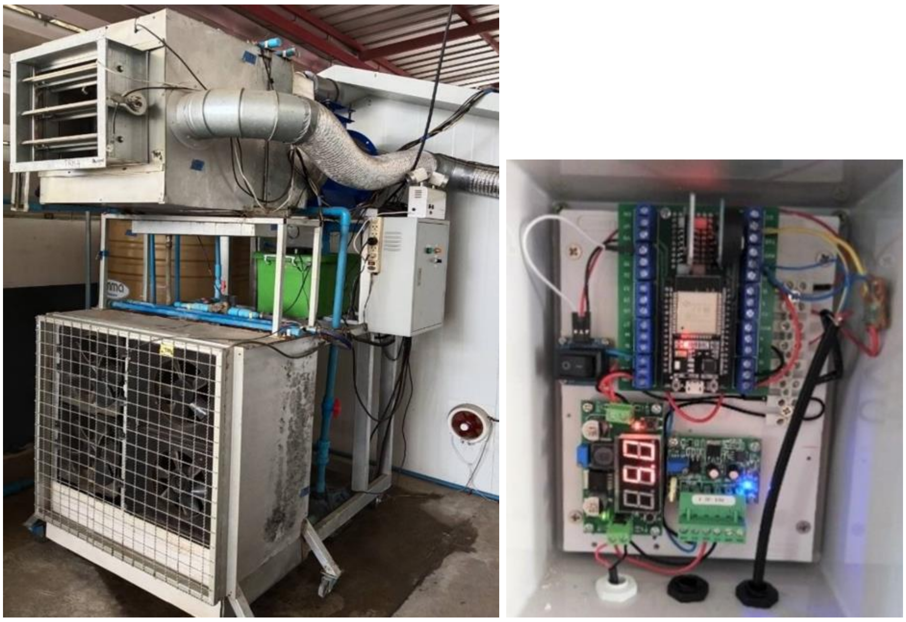
$$\varepsilon = \frac{(T_{db,i} - T_{db,o})}{WBD_i}, \qquad (1)$$

Where, ε is the cooling efficiency (%), $T_{db,i}$ and $T_{db,o}$ are the DBTs of the inlet and outlet air, respectively (°C), and WBD_i is the WBD of the inlet air (°C).

The coil efficiency (η) is calculated as follows:

$$\eta = \frac{[\dot{m}_{cw} c_p (T_{cw,o} - T_{cw,i})]}{[(\dot{m} c_p)_{min} (T_{ai} - T_{cw,i})]}, \qquad (2)$$

Where, $\dot{m}_{cw}$ is the cold water mass flow rate, T_{ai} and $T_{cw,i}$ are the Temperatures of the inlet air and cold water (°C), respectively, and $T_{cw,o}$ is the Temperature of



(a) (b)

Figure 4. Experimental setup and measurement system: (a) Indirect–direct evaporative cooling system with a night cooling system, and (b) Panel of the data collection system.

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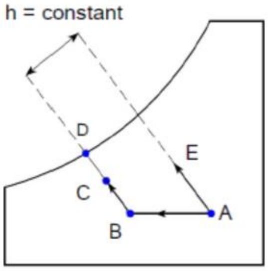

Figure 5. Psychrometric chart of the IDEC process.

the outlet cold water (°C).

The WBT is calculated as follows (Stull, 2011):

$$WBD = DBT\tan^{-1}\left[0.151977(RH + 8.313659)^{1/2}\right] + \tan^{-1}(DBT + RH) - \tan^{-1}(RH - 1.67633) + 0.00391838(RH)^{\frac{3}{2}}\tan^{-1}(0.023101RH) - 4.686035 \quad (3)$$

The uncertainties of the calculated variables are given by the following relationship (Taylor, 1982):

$$\frac{\delta X}{X} = \sqrt{\left(\frac{\delta Y_1}{Y_1}\right)^2 + \left(\frac{\delta Y_2}{Y_2}\right)^2 +..+ \left(\frac{\delta Y_n}{Y_n}\right)^2} \quad (4)$$

The uncertainties of the variables $Y_1,\ldots, Y_n$ are used in combination as shown in Equation (4) to calculate the uncertainty of the variable X, which is given by $\frac{\delta X}{X}$. The uncertainty results are presented in Table 1.

The required minimum airflow rate of the fan for shiitake cultivation is 2–4 fresh air exchanges per hour during pinhead initiation and cropping (Stamet and Chilton, 1983). The airflow rate $Q^{\bullet}_{flow}, m^3\ min^{-1}$) can be calculated from the number of air exchanges (ACH) and mushroom house net volume ($V_{vol.}, m^3$) as follows:

$$(ACH) \times \frac{(V_{vol.})}{60} = Q^{\bullet}_{flow} \quad (5)$$

The net volume is the volume of the mushroom house with the volumes occupied by the trays, shelves, substrate, and other fixtures subtracted. The number of air exchanges was set to 4, and the minimum airflow rate was calculated to be 1.05 m^3 min^{-1} or 66 m^3 h^{-1}.

Table 1. The uncertainties in calculated variables.

Variables	Uncertainty (%)
T_{wb}	4.81
ε	4.84
η	1.54

RESULTS AND DISCUSSION

IDEC Tests

Table 2 presents the inlet and outlet temperatures and RHs for the IDEC system, which was tested from August 2020 to December 2020. The system was shut down when the inlet-air RH was 100%, and the operation days are presented in the table.

The average outlet-air temperature was 27–28°C, which was 4–6°C lower than the inlet-air temperature. This temperature drop was not high compared with previous studies on IDECs in dry climates. Abbouada and Alumhanna (2012) experimentally applied an IDEC system to a greenhouse in a hot and dry climate. They reported that the air temperature drop was 15.6°C below the outside air temperature and the overall system efficiency was more than 100%. In their study, the WBD was up to 17.1°C. The WBD is not high in humid climates, which affects the EC performance, and increases in winter because of the lower WBT (Hui and Chueng, 2009). In the study area, the average annual WBD was only 4.97°C in 2020. The outlet RH was sufficient for the mycelium growth stage but should be increased for the next shiitake fruiting stage.

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Table 2. Maximum and minimum values for the inlet and outlet-air temperatures and humidity values.

Month	Operation days	Inlet-air DBT (°C)		Inlet-air RH (%)		Outlet-air DBT (°C)		Outlet-air RH (%)	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Aug	15	30.93	34.50	46.48	68.57	26.60	27.80	81.39	84.07
Sept	29	30.19	32.79	63.10	84.16	27.56	28.03	86.52	92.77
Oct	15	30.18	32.60	63.00	89.60	27.42	28.93	85.68	94.50
Nov	26	26.18	34.01	55.19	83.10	23.08	26.43	80.16	95.28
Dec	15	24.10	30.30	45.61	70.10	21.36	27.05	81.24	88.36

The mushroom house was installed under a roof to provide shade to lower the inlet-air temperature (Ahmed *et al*., 2019), which was 1–3°C lower than the outside air temperature. A traditional mushroom house is similar to a cottage made from cogon grass; combining it with shading from trees or netting is an effective and cheap means for lowering the inside air temperature.

The temperature of the water discharged from the pad was close to the air WBT (Alklaibi, 2015) but increased when the water left the CCU. Thus, the temperature of the water in the sump depended on the environment, which affected the system performance (Obando *et al*., 2020).The water in tank-1 was then cooled at night using the night cooling system. The final water temperature approached the WBT (Hou *et al*., 2016), and the results were consistent. During the test, the average WBT at night was 24.03 °C.

Table 3 presents the IDEC system's efficiency calculated using Equation (1). A system's efficiency higher than 100% means that the system can reduce the air temperature below that of the inlet WBT, which is the advantage of the IDEC system compared with the FPS. However, this does not have much effect on lowering the air temperature in a climate with a high RH, as previously shown in Table 2. The efficiency varied throughout the day with the environmental parameters as they affected the performance of the pad. The CCU efficiency did not vary much and stayed within the range of 30%0–35%.

Table 3. Results of the IDEC system's efficiency.

Month	System efficiency (%)	
	Min	Max
Aug	0.72	0.88
Sept	0.81	1.11
Oct	0.83	1.15
Nov	0.68	0.91
Dec	0.61	0.87

Regression Analysis

Multiple linear regressions were performed on data from the pad-only test using Microsoft Excel to evaluate the effect of the outdoor air temperature and RH on the outlet-air Temperature drop (ΔT). The resulting P values at a 95% confidence interval were less than 0.05, implying that the relationship between the variables was significant (Kenneth and Patrick, 2010). However, the P value was much higher for the RH than that for the inlet temperature. The relationship between the outdoor environmental parameters and ΔT is given as follows:

$$\Delta T_{FPS} = 0.61373T - 0.02325RH - 14.4349 \quad (6)$$

Similar results were obtained using the IDEC system; the p values for both the inlet-air temperature and RH were considerably less than 0.05. The result is shown in the following equation:

$$\Delta T_{IDEC} = 0.18642T - 0.07912RH + 3.9368, \quad (7)$$

Where, the temperature and RH are for the inlet air. The R^2 values for Equations (6) and (7) were 0.9893 and 0.9033, respectively. The air temperature drop calculated using

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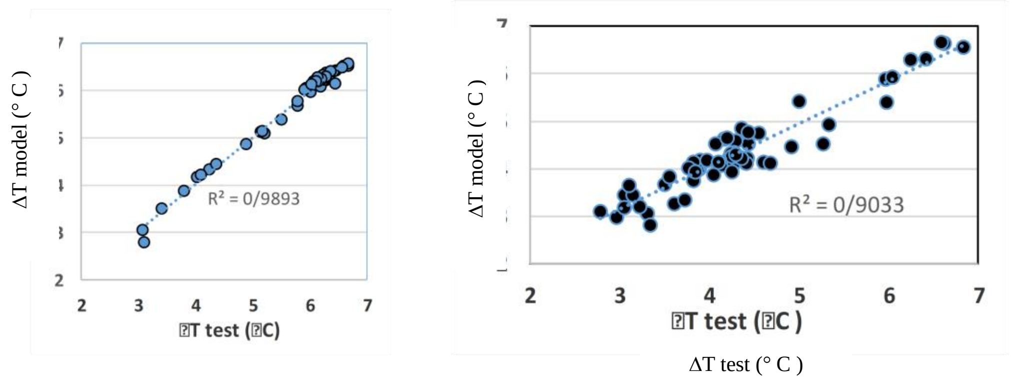
Equations (6) and (7) compared with the test data are shown in Figure 6.

Predicted Outlet-Air Temperature

Figure 7 shows the predicted outlet temperatures using Equations (6) and (7) based on the monthly average climate data for 2020. The FPS and IDEC similarly performed at high RH (i.e., the summer and rainy seasons). The pad-only results were compared with those of a few studies using an FPS for mushroom houses in hot and humid climates. Hanchaiyungwa (2003) showed that the FPS outlet temperature for shiitake compost in the cultivation stage was 27–28°C for a maximum ambient temperature of 34°C. Rattanathanaopat (2003) showed that an FPS integrated with a cooling coil used in poultry houses lowered the outlet-air temperature 1–2°C more than the FPS alone. The pad alone can be used in the rainy season for the mycelium growth stage; however, the IDEC system is more suitable in winter because it can provide a lower air temperature.

Energy Costs

The system costs were compared for the two mushroom houses commonly used by smallholding farmers. Each house had



ΔT test (° C) (a) (b)

Figure 6. Comparison of temperature drops from the model and experimental data: (a) FPS and (b) IDEC system.

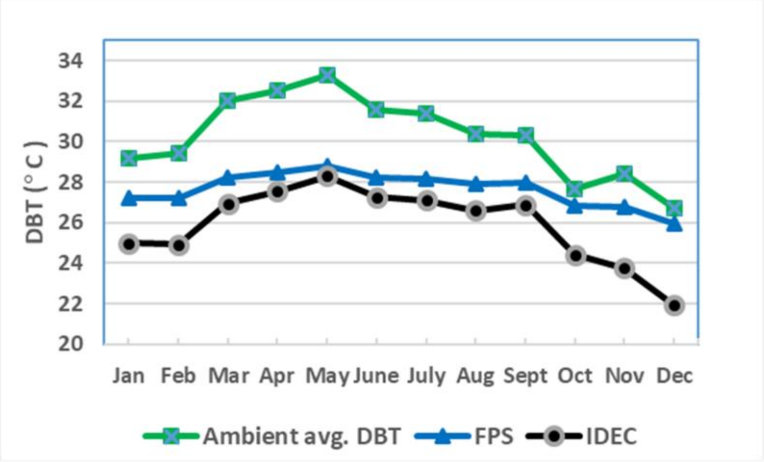


Figure 7. Predicted outlet temperatures from the IDEC system and FPS.

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dimensions of a 3 m width×15 m length×3 m height. The sizes of the main equipment (i.e., pad and fan) were obtained as follows:

- FPS: The airflow rate is 146 $m^3 h^{-1}$ per square meter of floor area (ASHRAE, 2007). The fan size for each mushroom house was 0.45 m and 186.5 W. The required airflow rate was defined as 76 $m^3 min^{-1}$ per square meter of pad area (Bartok, 2013). Thus, the pad area was 1.5 m^2 for the mushroom houses, which had a floor area of 45 m^2.
- IDEC: The airflow rate was calculated using Equation (5) as 515 $m^3 h^{-1}$. The centrifugal fan size was 560 W, which was sufficient to supply the air for the two mushroom houses.

Assuming the same pad size, the total costs of the FPS and IDEC system (including the CCU) were estimated as 9,820 and 21,250 THB (32.71 THB= 1 USD), respectively. Each mushroom house had approximately 4,000 composts, and the gross weight of the shiitake production was estimated as 1,200 kg with 4–5 months of cultivation (3–4 harvests). The revenue would be 120,000 THB (32.71 THB= 1 USD); therefore, the investment would be returned by selling one crop harvest (assuming the production cost was 50%). Thus, it can be concluded that the two systems have comparable equipment costs. However, the temperature distribution in a mushroom house is a very important factor that must be considered in a system. The mushroom composts that are normally placed on the shelves can increase the air pressure drop of the FPS as the airflow from one end of the room to the opposite wall. This increases the uneven temperature distribution, which is a major disadvantage of the FPS. The pressure drop can be reduced by placing the composts on the floor; however, this reduces the quantity of composts compared with when they are placed on shelves for the same floor area. This means that for the same amount of compost, a larger building is required, which increases the investment costs. The air supplied through the duct can be adjusted more easily to achieve a uniform temperature distribution (Bowman, 1991; Han *et al*., 2009). Further investigation is required regarding the effects of mushroom compost on the air pressure drop.

Shiitake Mycelium Growth on Composts

Figure 8 shows the shiitake compost used in the test after 4 months. The compost was browned over 60–70% of the surface area, and it was ready for fruiting when completely browned. In contrast, for compost not in the mushroom house, the mycelium slowly grew and finally spoiled. André-Ledoux *et al*. (2020) showed that the compost inoculated in sawdust and tested in a tropical climate at an average temperature of 21.5°C without mechanical cooling reached the fruiting stage after 94 days. Thus, the temperature has a great effect on mushroom growth, and any cooling


(a) (b)

Figure 8. Shiitake compost after 100 days: (a) Inside, and (b) Outside the house.

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technique is important for hot climates.

CONCLUSIONS

The results showed that the combined effects of shading, warm-weather shiitake strain, and suitable cultivation period allowed the IDEC system to produce an outlet-air temperature in the required range. After 4 months of testing, the shiitake compost was browned over 60–70% of the surface and was almost ready for the next fruiting. Further, the regression analysis showed that the performances of the FPS and IDEC system were comparable at high RH. However, the IDEC system produced 4 °C lower air temperature in winter. The costs of the systems were not considerably different and could be earned back by selling one crop harvest. The effect of the compost on the uneven temperature distribution in mushroom houses should be further investigated. The results of the present study will further guide research on improving Evaporative Cooling (EC) for shiitake cultivation in hot and humid climates.

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REFERENCES

1. Abbouada, S. K. and Almuhanna, E. A. 2012. Improvement of Evaporative Cooling System Efficiency in Greenhouses. *Int. J. Latest Trends Agr. Food Sci.*, **2**(**2**): 83-89.
2. Ahmed, H. A., Tong, Y., Yang, Q., Al-Faraj, A.A. and Abdel-Ghany, A.M. 2019. Spatial Distribution of Air Temperature and Relative Humidity in the Greenhouse as Affected by External Shading in Arid Climates. *J. Integr. Agric.*, **18**(**12**): 2869-2882.
3. Ali, C., Adil, A., Sait, U. and Beyhan, Y. 2021. Efficiency of Two Different Types of Evaporative Cooling Systems in Broiler Houses in Eastern Mediterranean Climate Conditions. *Therm. Sci. Eng. Prog.*, **22**: 100844.
4. Alklaibi, A. M. 2015. Experimental and Theoretical Investigation of Internal Two-Stage Evaporative Cooler. *Energy Convers. Manag.*, **95**: 140-148.
5. André-Ledoux, N., Idriss, N. P., Christopher, S. and Noumbo, T.G. 2020. Cultivation of Lentinus squarrosulus Mont. and Lentinus sajor-caju Fr. on Agroforestry Wastes under Field Conditions. *Int. J. Agric. Sci. Vet. Med.*, **8**(**2**): 20-25.
6. ASHRAE. 2007. *ASHRAE Handbook-HVAC Applications*, *PP.22.10-22.13*. Retrieved from https://www.knovel.com
7. ASHRAE. 2016. *ASHRAE Handbook-HVAC Systems and Equipment*. PP. 41.5- 41.6. Retrieved from https://www.knovel.com
8. Bartok, J. W. 2013. *Fan and Pad Evaporative Cooling System*. Retrieved from https://ag.umass.edu/greenhouse-floriculture/fact-sheets/fan-pad-evaporative-cooling-systems
9. Bartzanas, T. and Kittas, C. 2005. Heat and Mass Transfer in a Large Evaporative Cooled Greenhouse Equipped with a Progressive Shading. *Acta Hortic.*, **691:** 625-632.
10. Bowman, G. E. 1991. Application of Multiple Jets to the Supply and Distribution of Conditioned Air in Mushroom Cropping Houses. *J. Agric. Eng. Res.*, **49**: 151-159.
11. Camargo, J. R., Ebinuma, C. D. and Cardoso, S. 2006. Three Methods to Evaluate the Use of Evaporative Cooling for Human Thermal Comfort. *Revista de Engenharia Térmica*, **5**(**2**): 9-15.
12. Chantana, C. 2019. A Cooling System for a Mushroom House for Use in the Upper Central Region Climate of Thailand. *Science and Technology*. *Naresuan Univ. J.*, **27**(**3**): 10-19.
13. Debajit, M. and Sudip, G. 2018. Evaporative Cooling Technologies for Greenhouses: A Comprehensive Review. *Agric. Eng. Int.: CIGR J.*, **20**(**1**): 1-15.
14. Han, J. H., Kwon, H. J., Yoon, J. Y., Kim, K., Nam, S. W. and Son, J. E. 2009. Analysis of the Thermal Environment in a Mushroom House Using Sensible Heat

[DOI: 10.52547/jast.25.2.457]

Balance and 3-D Computational Fluid Dynamics. *Biosys. Eng.*, **104**(**3**): 417-424.

15. Hanchaiyungwa, N. 2003. *Feasibility Study and Energy Consumption of Evaporative Cooling for lentinun edodes (Berk.) Sing House*. Master's Thesis (in Thai), King Mongkut's University of Technology Thonburi, Bangkok, Thailand.
16. Hamed, A., Ehsan, B., Mohsen, B., Miha, H., Mohammad, A. T. G., Nicholas, D. and Emran. Z. 2018. *Influence of Relative Humidity and Temperature on Cultivation of Pleurotus Species*. Retrieved from https://www.redalyc.org/journal/485/48557888005/html/
17. Hisham, E. D., Hisham E. and Ajeel, A. Z. 2004. Performance Analysis of Two-stage Evaporative Coolers. *Chem. Eng. J.,* **102:** 255-266.
18. Hou, T.F., Hsieh, Y., Lin, T., Chuang, Y. and Huang, B.J. 2016. Cellulose-Pad Water Cooling System with Cold Storage. *Int. J. Refrig.,* **69**: 383-393.
19. Hui, S. C. M. and Cheung, W. Y. 2009. Two-Stage Evaporative Cooling Systems in Hot and Humid Climate. *Proceedings of the Tianjin-Hong Kong Joint Symposium*, Tianjin.
20. Irwan, M. L. A. 2009. Development and Production of Lentinula *edodes* (Shiitake mushrooms) on Inoculated Logs of a Range of Tree Species. Master's Thesis, University of Melbourne, Victoria, AU.
21. Issam, M. A. and Hind, D. R. 2017. Enhancement of Evaporative Cooling System in a Greenhouse Using Geothermal Energy. *Renew. Energy*, **11**: 321-331.
22. Kenneth, N. B. and Patrick, C. 2010. *Data Analysis with Microsoft Excel.* Cole, Brooks. Boston.
23. Krishan, K. 2015. Role of Edible Mushrooms as Functional Foods-A Review. *South Asian J. Food Technol. Environ.*, **1**: 211-218.
24. López, A., Valera, D. L., Molina-Aiz, F. D. and Peña, A. 2012. Sonic Anemometry to Evaluate Airflow Characteristics and Temperature Distribution in Empty Mediterranean Greenhouses Equipped with Pad-Fan and Fog Systems. *Biosys. Eng.*, **113**(**4**): 334-350.
25. Marouen, G., Khaled, M., Ezzedine, N., Rabah, B. and John, K. C. 2019. Greenhouse Design and Cooling Technologies for Sustainable Food Cultivation in Hot Climates: Review of Current Practice and Future Status. *Biosys. Eng.,* **183:** 121-150.
26. Mehmet, A. D. and Hasan, H. S. 2015. Performance Analysis of a Greenhouse Fan-Pad Cooling System: Gradients of Horizontal Temperature and Relative Humidity. *J. Agric. Sci.,* **21**: 132-143.
27. Mohammad, A., Alaaa, H. S., Akbar, A. J., Hassn, E. S., Matthew, J. H., Raziyeh, F., Mahdieh, D. and Abdelazim, N. 2020. Towards a Sustainable Greenhouse: Review and Emerging Practices in Analysing Greenhouse Ventilation Requirements to Sustain Maximum Agricultural Yield. *Sustainability*, **12**(**2794**): 1-18.
28. Obando, F. A., Montoya, A. P., Osorio, J. A., Damasceno, F. A. and Norton, T. 2020. Evaporative Pad Cooling Model Validation in a Closed Dairy Cattle Building. *Biosys. Eng.*, **198**: 147-162.
29. Rattanathanaopat, N. 2003. Improving Efficiency of Evaporative Cooling on Poultry. Master's Thesis (in Thai). King Mongkut's University of Technology Thonburi, Bangkok, Thailand.
30. Rishikesh, K. 2020. Marketing and Distribution of Mushroom. In: "*Cases in Management*", (Eds.): Kirti, K., Padmalochan, B. and Bhushan, P. S. B. Patil Institute of Management, Pune, PP. 57-60.
31. Stamets, P. and Chilton, J. S. 1983. The Mushroom Cultivator: A Practical Guide to a Growing Mushrooms at Home. Agarikon Press, Washington, USA.
32. Stull, R. 2011. Wet-Bulb Temperature from Relative Humidity and Air Temperature. *J. Appl. Meteorol. Climatol.,* **50**(**11**): 2267-2269.
33. Taylor, J. R. 1982. *An Introduction to Error Analysis.* 2nd Edition. University Science Books, California.
34. Thepa, S., Kirtikara, K., Hirunlabh, J. and Khedari, J. 1999. Improving Indoor Conditions of a Thai-Style Mushroom House by Means of an Evaporative Cooler and Continuous Ventilation. *Renew. Energy*, **17**(**3**): 359-369.
35. Wasser, S. P. 2005. Shiitake (*Lentinus edodes*). In: "*Encyclopedia of Dietary Supplements*." Marcel Dekker, New York, PP. 653-664.

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خنک کننده دو مرحله ای تبخیری برای سالن‌های پرورش قارچ در آب و هوای گرم و مرطوب

س. چانتانا

چکیده

شیتاکه (Lentinula edodes) از قارچ های بسیارکشت شده در جهان است و آب و هوای معتدل را ترجیح می دهد. در تایلند، بهبود سویه های شیتاکه ویژه هوای گرم یکی از راه های افزایش عملکرد آن است. سالن¬های¬ پرورش قارچ برای کنترل و ایجاد محیط بهینه برای کشت باید مجهز به خنک کننده مکانیکی باشد. در این بررسی، یک سامانه خنک‌کننده تبخیری¬غیرمستقیم (IDEC) متشکل از یک کویل(coil) خنک‌کننده و خنک‌کننده تبخیری (پد سلولزی) برای مناسب بودن آن برای کشت شیتاکه از ماه اوت ۲۰۲۰ تا دسامبر ۲۰۲۰ آزمایش شد. در شرایط رشد و سایه بهینه، سامانه IDEC دمای هوا (در محدوده ۲۷-۲۸ درجه سانتیگراد) و رطوبت نسبی را در محدوده های مورد نیاز حفظ کرد. کمپوست قارچ پس از آزمایش ۱۰۰ روزه تقریباً کاملاً قهوه ای شد و برای مرحله باردهی (fruiting) بعدی آماده بود. در مقایسه با سامانه فن-پد (fan-pad) و تجزیه و تحلیل رگرسیونی، هر دو سامانه عملکرد مشابهی از خود نشان دادند و هزینه تجهیزات مشابهی داشتند. با این حال، در رطوبت نسبی کمتر، دمای هوا در سامانه IDEC کمتر بود و راندمان آن بیش از ۱۰۰٪ بود. این بررسی نشان داد که سیستم IDEC را می توان برای ترویج کشت شیتاکه در آب و هوای گرم و مرطوب به کار برد.

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