Egypt. J. Agron. **Vol. 45**, No. 2, pp. 171-187 (2023)

Egyptian Journal of Agronomy
http://agro.journals.ekb.eg/

Effect of Utilization of Different Materials and Thicknesses Evaporative Cooling Pad on Cooling Efficiency in Greenhouses in Hot-Arid Regions

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THE GOAL of this study was to determine whether locally accessible luffa, straw, and sackcloth fiber pads could replace traditional celdek pads in cooling systems, particularly in greenhouses. The study's goals were to find out how different evaporative pad types and thicknesses, as well as climatic elements, including temperature, pressure drop, relative humidity, and air velocity, affected the greenhouse's ability to cool effectively. The outcomes showed considerable effects of various pad materials on greenhouse cooling effectiveness. The average saturation from the luffa pads was 78.5%, while the average saturation from the straw fiber and sackcloth fiber was 72% and 66.6%, respectively. On the contrary, the celdek pads produced an average saturation of 75.60%. The 300 mm thick pad had a highly significant impact on cooling efficiency, lowering the temperature and slightly raising the relative humidity while also absorbing more water and lowering the pressure. The outcomes also showed that the amount of water had a big impact on cooling effectiveness. Moreover, there was a strong correlation between air velocity, cooling effectiveness, and pressure; as air velocity rose, cooling efficiency declined and pressure increased across the cooling pads. The current study established a negative correlation between temperature and cooling effectiveness. Lastly, the study proved that the luffa pads are a better alternative to the conventional celdek pad as they produced the best results than the other cooling pads.

Keywords: Cooling pads, Greenhouse technology, Relative humidity, Saturation.

Introduction

Evaporative cooling is the reliable, simplest, and efficient methods for cooling greenhouses to improve microclimatic condition (Vega et al., 2022). The system of evaporative cooling pads withdrawn the air from outside to enter through wet porous medium (pad), at the same time when the air is in contact with the wet surface the Sensible and latent heat were occurs, after that the air loses sensible heat, reducing its temperature, while water evaporates from the surface of the pad, raising the humidity of the air and adding latent heat. The air at the outlet of the pad has a lower temperature and a higher relative humidity than the inlet one. wherefore, the high cost of the traditional cellulose pad makes the implementation of this technique unfeasible in small and medium

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Received 02/07/2023; Accepted 21/09/2023
DOI: 10.21608/AGRO.2023.220570.1380

agro-industrial production systems (Laknizi et al., 2021). Evaporative cooling will always follow the laws of nature. Thus, when hot and dry conditions exist, a properly designed and maintained evaporative system will always cool the environment. However, the cooling technologies are not enough and widely known to cater to the needs of greenhouse growers. Hence, a cheap and effective technology suitable to local climatic conditions needs to be developed to boost the greenhouse industry. Considerable focus should be given in understanding the physical processes and documenting microclimatic variations in different established greenhouse designs to come up with relevant conclusions. Moreover, the different cooling mechanisms should be evaluated to improve the existing cooling techniques (Elmsaad & Omran, 2015a). The cooling efficiency is affected by the quantity of the air withdrawn from inside the greenhouse and the inlet air velocity and the pad thickness and types of pads materials, in addition to the influence of the external thermal conditions, Therefore, this experiment was conducted to verify the impact of these factors on the cooling efficiency, which in turn affects the internal environment of the greenhouse and consumes time and resources, as well as to test the validity of the experiment (Damasceno & Obando, 2020). During the hot season, the temperature of ambient air inside greenhouses and animal houses increases to over 40 °C because of thermal stress. In greenhouses, thermal stress negatively affects the emergence, stem strength, flowering, and fruit set and sizes of seedlings (Öztürk, 2003). In several countries, the trend of using fan-pad evaporative cooling systems in agricultural buildings is increasing, but the rate of this increase is inhibited by the high costs of commercial pad materials (Liao & Chiu, 2002). Due to the high costs of traditional commercial cooling pads, it was necessary to search for alternative materials that could be used to manufacture evaporative cooling pads, and they were chosen based on their local availability and low cost. These materials may be a by-product of some agricultural operations to reduce the environmental impact, which include natural resources such as fibers It contains natural cellulose to retain moisture and degrade easily without leaving a negative impact on the environment (Ndukwu & Manuwa, 2014). The need becomes more urgent for off-season production. Various systems have been developed to reduce air temperature and improve thermal stress of plants and livestock. The use of evaporative cooling can decrease air temperatures by 4 °C to 13°C (Öztürk & Başçetinçelik, 2004). The evaporative cooling system has been accepted as an effective, practical, and economically feasible method under hot and arid climatic conditions for many poultry houses and greenhouses (Dagtekin et al., 2009). Commercially available cooling pads are expensive, and accordingly, there is an urgent need to evaluate the performance of suitable locally available materials when used as cooling pads, particularly for rural agricultural buildings (Manoj & Rahul, 2017). In fact, many studies were carried out to evaluate the use of locally available materials as cooling pads, such as: expanded clay, sawdust, vegetable fiber and charcoal (Tinoco et al., 2001), discarded clay bricks, corn- cob and charcoal (Chunchai, 1998); ground sponge, stem sponge, jute fiber and charcoal. Moreover, the reported efficiency of some locally available materials was 79% for charcoal, 48% for hazelnut rind and 96% for wood shavings (Dağtekin et al., 1998); 89.6 to 92.8% for coir fiber; 47.22% to 85.51% for fine fabric and 63.88 to 86.32% for coarse fabric (Liao et al., 1998); 39.9% for palm fiber, 62.1% for jute (Al-Sulaiman, 2002). Cellulose pads, expanded clay and vegetable fiber were recommended as pad materials for evaporative cooling systems by Tinoco et al. (2001). On the other hand, and according to the results of the study by Dzivama et al. (1999), stem sponge showed superior pad material qualities compared to ground sponge, jute fiber and charcoal. Gunhan et al. (2007a) evaluated the suitability of some local materials such as pumice stones, volcanic tuff and greenhouse shading net as cooling pads. They found that volcanic tuff was a good alternative pad material. It gave an evaporative saturation efficiency of 63-81%. Ahmed et al. (2011) studied sliced wood, spen and celdek cellulose as materials for evaporative cooling pads. Sliced wood pads have more cooling efficiency and crop productivity under greenhouse conditions. Radhiyah et al. (2018) tested Luffa and carbon foam as materials of evaporative cooling pads foam. A conducted by Khobragade & Kongre (2016) and Chopra & Kumar (2017) studied on wood-wool and khus-grass as evaporative cooling pads materials. Almaneea et al. (2022) investigated the palm trees waste as evaporative cooling pads materials. The research mentioned above, there are no studies about luffa and straw fiber and sackcloth as wetted pad materials. In addition, both of that pad's materials mentioned above are low in cost and easy-to-find in the world. Therefore, the researchers consider using those materials as evaporative cooling pad in terms of saturation efficiency and pressure drop across wetted pad. The present study mainly aims to solve high-temperature problems, particularly in hot and dry areas. Scientific researchers have developed several ways to reduce temperature and optimize existing methods. The most effective cooling system uses evaporative cooling pads and exhaust fans to facilitate air exchange inside buildings. Evaporative cooling pads present an effective technique for solving the environment control problem by significantly reducing the temperature inside buildings, such as livestock, poultry, and greenhouses. The contribution of the current study is the discovery of new materials that can be used as alternatives to conventional cooling pads, as well as the method of designing and installing these pads. Cooling systems were developed, and their effectiveness was tested. The current study also urges people to use locally available resources in developing their industries, encouraging developed countries to finance such projects, and therefore improving the economic status of individuals. The energy savings from evaporative cooling implies reduced carbon dioxide and other emissions from power plants and decreased electricity demand typically during the peak cooling hours in summer. Some utility companies are actively promoting the use of evaporative cooling to lessen the requirement for new generation facilities. Safety and reliability are also afforded by the simplified maintenance requirements. The current study helps small-scale farmers to invest in greenhouses using local evaporative cooling pads that are low cost and locally available. Moreover, these evaporative cooling pads have simpler maintenance requirements than cooling system equipment. Evaporative cooler users can maintain their peak cooling effectiveness without the need for costly and sometimes unavailable specialized maintenance contracts. This efficiency can be translated into increased reliability and a consistent environment, one that is conducive to improved user productivity and performance which are, in turn, dependent on comfort. Evaporative cooling does not directly use any chemical substances. Therefore, it reduces harmful impact on the environment. If the small-scale farmers invest in greenhouses using this type of cooling system from local materials, they can supply the local market with all kinds of vegetables and fruits and even off-season products, in addition to those for export, hence increasing the profitability of the state and the farmer.

The purpose of this study was to compare the performance of various evaporative cooling pad materials to the use of more traditional pads, such as wetted pads, in terms of greenhouse cooling efficiency. The following specific objectives have been established to accomplish the study's goal: i) To consider the effects of various cooling pad materials and their thicknesses on the greenhouse's cooling efficiency; ii) To evaluate the effects of various cooling pad materials and their thicknesses on the greenhouse's environmental factors, such as temperature, relative humidity, air velocity, and pressure; and iii) To figure out the effects of indoor environmental parameters and water volume on the greenhouse's cooling efficiency. The study performs a number of statistical tests using Statistical Package for Social Sciences (SPSS) software. These analysis tests include A one-way analysis of variances (ANOVA), linear and descriptive regression, as well as correlation analyses.

Materials and Methods

Small-scale greenhouse

The experiments for this study required a greenhouse setting, which was created by building a small-scale arch greenhouse with the following measurements: length= 5m, height= 2.5m, and width= 2m. The greenhouse's cover was constructed from double-layer polyethylene with a 200-micron thickness per layer. In greenhouses, these layers regulate the temperature and reflect heat radiation. Figure 1 shows a picture of the greenhouse constructed for this study. The selected pad materials for this study were straw fiber (SP), sackcloth fiber (SaP), and luffa pads (LP). A 1.5m 1.5m galvanized iron frame was filled with each pad material to create an evaporative-sealed unit with thicknesses of 100, 150, and 300mm. A 10mm square wire sieve mesh was used to cover the front and back faces of the sealed units. Standard celdek pads (CP), which are sold in pre-assembled units, were used as comparative pads. Figure 2 showed the evaporative cooling pads used in the study, whereas Fig. 3 showed the position of the pads connected to the water system in the greenhouse. The selected thickness in this study was based on the standard thickness used around the world (the common thickness used is 150mm). In this study, two thicknesses (100mm and 300mm which were respectively below and above the standard thickness of 150mm) were selected to determine the thickness that will offer the best cooling efficiency. The components of the utilized water system include a water inlet, a water pump, a drainage outlet, a water meter, and a water tank. A water meter was used to measure and register the quantity of water passing through the tubes or pipes. The other end of the greenhouse walls was fitted with four axial exhaust fans to extract air from the inside, thereby allowing the flow of fresh air through the pads and into the greenhouse. Rectangular wind ducts made of translucent Plexiglas sheets were used for easy viewing. The interior of the duct measured 1.5m in length and 1m in width. The duct had two ends: one that was linked to the frame of the evaporative cooling pads and was airtight, and the other that was left exposed. A diagram of the wind duct connected to the water system and the digital anemometer used to measure air velocity and pressure is shown in Fig. 3.

Fig. 1. Show the shape of greenhouse

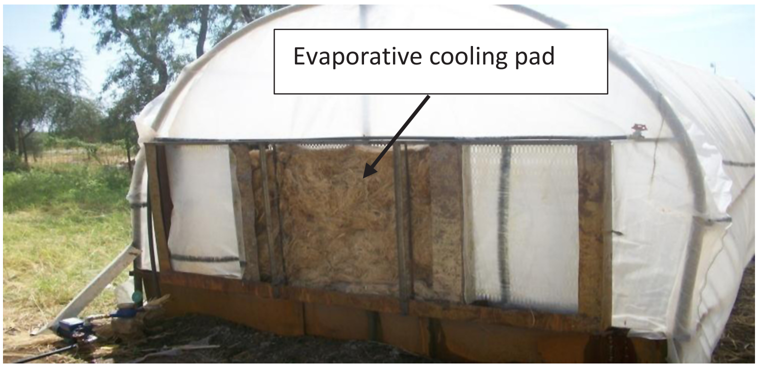

Fig. 2. Position of evaporative cooling pads at one end of the greenhouse

Fig. 3. Types of the evaporative cooling pads in the greenhouse

Experimental procedure

Figure 4 shows the small greenhouse's layout, its parts, and the tools for monitoring the environmental factors. During the experiment, the thermo-hygrometer and the digital anemometer were placed 15 cm from the evaporative cooling pad; they were also placed at 50 cm and 1 m high inside the wind duct and inside the greenhouse, respectively. The experiment was designed to allow water to stream through the pad until cool (at this point, the quantity of water was recorded). The water was allowed to flow at the same rate, and then, the air from the fan was blown into the wind duct for passage through the pad. In addition, three levels of air velocity (i.e., 1, 1.5, and 1.75ms^{-1}) were tested with each type of the pad and different thicknesses (fan speed was manually controlled). Finally, the exhaust fans were switched on to introduce the required amount of air into the experimental setup. At one end of the duct, a 3-phase electric motor-driven axial sucking fan with a diameter of 450 mm was installed. The distance between the fan and the pad's discharge face was 3m. Hourly measurements of the environmental factors were taken from 10:00 a.m. to 4:00p.m. during the summer months, capturing the time of the day with the maximum temperature. Water flowing through the pads was monitored using a water meter that was attached to the water system between the pump and the water inlet.

Mathematic model

Evaporative cooling decreases the inlet temperature without altering its wet bulb temperature. Figure 6 depicts the temperature profile, where ɵ1 and ɵ2 represent the temperature differences on the hot side and cold side, respectively. As per the direct evaporative cooling process, the wet bulb temperature of air (Twet) is constant and lowers the air temperature from T1 to T2 when atmospheric air passes across the cooling pad. Evaporative cooling can be written as follows:

$$m_e = m_{wv2} - m_{wv1} \quad \text{...(1)}$$

Both the side divided by ma, becomes equation no. 2 we get

$$\frac{m}{m} = \frac{mwv2}{m} - \frac{mwv1}{m} \quad \text{.....................................(2)}$$

Specific humidity is represented by ρw and it is also called absolute humidity and humidity ratio.

$$\rho w = \frac{mwv}{m} \quad \text{...(3)}$$

Rearranging equation no 3, we get

$$\frac{m}{m} = \omega 2 - \omega 1 \quad \text{...................................(4)}$$

The general expression for the cooling capacity of the direct evaporative cooling system as follows:

$$Q = m \times Cpa(T1 - T2) \quad \text{.............................(5)}$$

Cooling efficiency is calculated as follows (ASHARE, 2005).

$$\mu = \frac{T_1 - T_2}{T_1 - T_{wb}} x100$$

where: µ = evaporative saturation efficiency in **%**, T_1= inlet dry bulb temperature °C. T_2 = outlet dry bulb temperature °C, T_{wb} = wet bulb temperature in °C. The values of the T_{wb} were determined by using psychometrics chart.

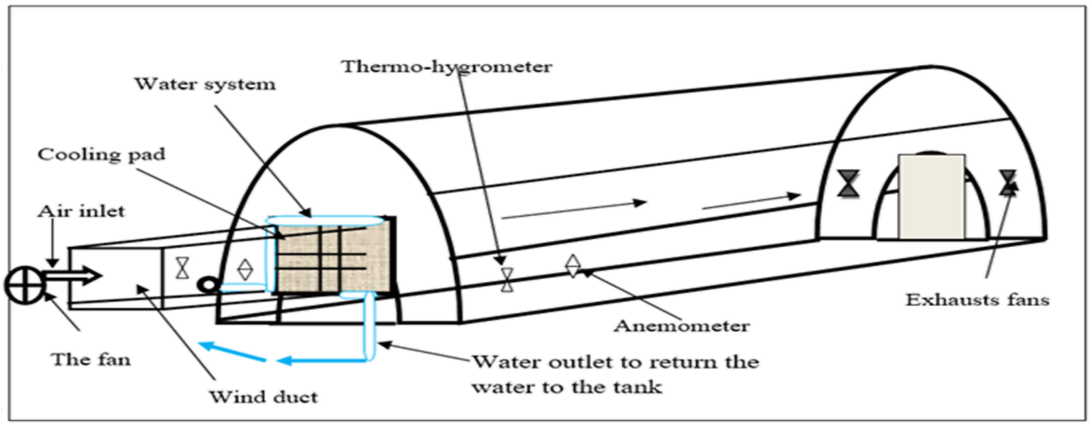

Fig. 4. Illustrates the setup of the small-scale greenhouse

Results and Discussion

The average values of all the experimental parameters, including temperature, RH, air velocity, water quantity, and pressure were calculated using descriptive analysis. The results of comparing the mean scores of all the factors related to the various kinds of evaporative cooling pads are shown in Fig. 5. The following were the greenhouse's overall mean values for the environmental parameters: Air velocity was 1.89m/s (SD= 10.97), the temperature was 26.73°C (SD= 3.07), RH inside the greenhouse was 73.31% (SD = 6.43), total water content was 22.33L/m^2 (SD= 9.87), and pressure was 73.36 pas (SD= 45.96). The celdeck pad (25.77°C), luffa pads (LP; 26.06°C), and straw fiber pad (26.43°C) showed the lowest temperatures inside the greenhouse, while the sackcloth cooling pad (SaP) displayed the highest temperature (28.69°C). Environmental factors outside the greenhouse revealed a greater average outdoor temperature of 40.10°C (SD= 1.54) compared to those inside the greenhouse. The maximum cooling efficiency was attained with the LP compared to the other types of pads. An overall average cooling efficiency of 73.17% (SD= 10.93) was established inside the greenhouse.

Evaporative cooling pad types

Bivariate correlation analysis was used in this part to analyze the connection between evaporative cooling pads, environmental factors, and cooling effectiveness. The type and thickness of the pads were the main issues discussed. The observed correlation between various evaporative cooling pad types, environmental factors, and cooling effectiveness. The findings indicated a significant correlation between the three greenhouse environmental variables of water quantity, pressure, and temperature and the different types of evaporative cooling pads. As previously stated, a substantial connection between cooling efficiency and cooling pad types was also discovered by Hassan et al. (2009) and Sreeram et al. (2015). It was discovered that there is a considerable difference in cooling pad types and quantity of water because, if the quantity of water is less than necessary, the pad fibers will be under-saturated and the cooling efficiency will be decreased since there won't be enough moisture in the air to evaporate. Likewise, the air velocity through the pads was seen to change at various points. According to Flávio et al. (2017) and Al-Amri (2000), air velocity impacts the path that air takes and the amount of time it spends in touch with the moisture source. In evaporative cooling pads, the latent heat absorbed by the water as it changes from liquid to vapor is taken from both the air passing through the media and the water left in the media. Therefore, both air and water are cooled, and their temperature falls. When water passes over the media and air is blown through it, water evaporates and the air is cooled, making the dry bulb temperature of the cooled air almost similar to the air wet bulb temperature. The small amount of latent heat in the original water vapor in the air increased because of increasing water vapor caused by evaporation. This result is in line with the report of Metin et al. (2011) (Table 1).

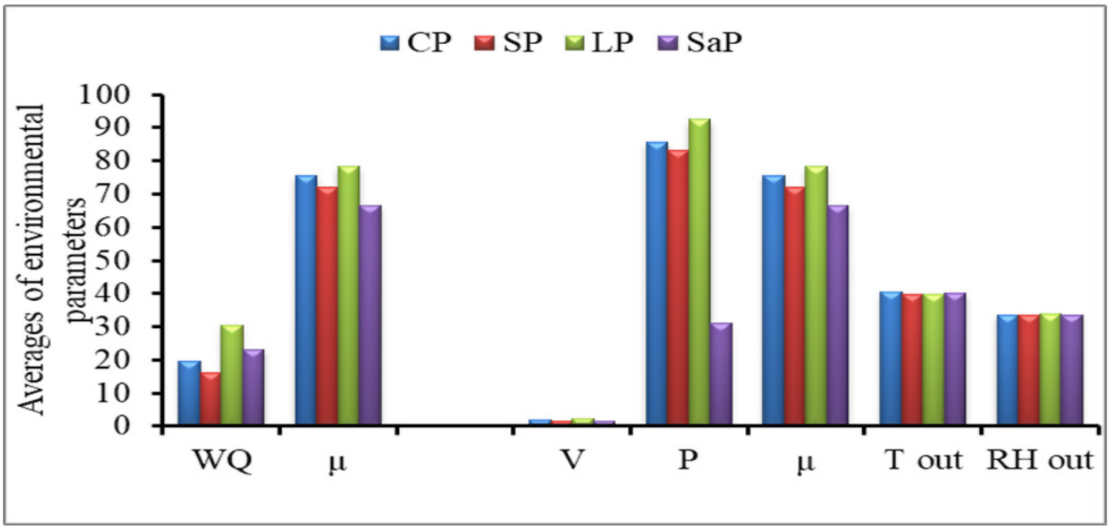

Fig. 5. Averages of all parameters according to types of pads inside the greenhouse

TABLE 1. Relationship between evaporative cooling pad types, environmental parameter and cooling efficiency

	Types	T_{in}	RH_{in}	WQ	V	P	T_{out}	RH_{out}	M
Types	1	-	-	-	-	-	-	-	-
T_{in}	.359**	1	-	-	-	-	-	-	-
RH_{in}	.110	-.446**	1	-	-	-	-	-	-
WQ	.287**	-.685**	.589**	1	-	-	-	-	-
V	.045	-.078	.092	.176	1	-	-	-	-
P	.467**	-.239**	.176	.346**	.175	1	-	-	--
T_{out}	-.386**	-.057	-.163	-.055	.140	-.073	1	-	-
RH_{out}	.000	.132	-.100	-.212*	-.025	.091	.157	1	-
M	.623**	-.768**	-.002	.763**	.108	.283**	-.114	-.176	1

*Correlation is significant at the 0.01 level (2- tailed)

Evaporative cooling pad thickness

The environmental parameters and the thickness of evaporative cooling pads were significantly correlated with one another; the Table 2 also demonstrated a very significant correlation between cooling pad thickness and cooling efficiency. as a substantial correlation between pad thicknesses and environmental conditions. This relationship showed that increasing the pad density ensures adequate water supply to the whole pores and improves the capillarity of the cooling pad, thereby ensuring regular water distribution as reported by Elmsaad et al. (2017a). However, a negative correlation was observed between pad thickness and the temperature and air velocity inside the greenhouse. The cooling efficiency showed a significant reduction with increases in the air velocity and pad thickness. Additionally, cooling pads of 300mm thickness achieved the best cooling efficiency compared to 100mm and 150mm thickness pads because the cooling pads of 300mm thickness supported higher contact areas between air and water. Consequently, the declines in air temperature and the associated increase in water evaporation enhanced the saturation efficiency as earlier reported by Elmsaad & Omran (2015b). The results also indicate that the temperature reduction increases with increasing pad thickness according to Mahmoud et al. (2022).

Impact of the type of evaporative cooling pads on cooling efficiency

The impact of cooling pad type on cooling efficiency (R^2=0.982, F=697.657, P>0.01) and environmental parameters (B=-0.288, t=27.657, P>0.01) was shown in Table 3. Being that the pressure and air velocity within the greenhouse are low, the SaP cooling pad had a higher moisture-holding capacity than cooler air, giving rise to a greater mean temperature inside the greenhouse (26.06°C) compared to the use of other types of pads. Consequently, even if the amount of water is constant, air temperature increases as RH decreases. In general, RH declines when the temperature rises or vice versa, which reduces the effectiveness of cooling. These results concur with those mentioned by Cruz et al. (2006) and Tina (2011). The greenhouse had a higher outside temperature compared to the inside of the greenhouse (Manoj & Rahul, 2017). The high pressure and low airflow resistance of LP reduced the air temperature to the appropriate level, making LP achieve a higher cooling efficiency compared to other types of pads. This outcome was consistent with previous reports by Misra & Ghosh (2018a).

TABLE 2. Relationships between the thickness of cooling pad, environmental parameters and cooling efficiency

	Thickness	T_{in}	RH_{in}	WQ	V	P	T_{out}	RH_{out}	M
Thickness	1	-	-	-	-	-	-	-	-
T in	-.804**	1	-	-	-	-	-	-	-
RH in	.577**	-.446**	1	-	-	-	-	-	-
WQ	.820**	-.685**	.589**	1	-	-	-	-	-
V	-.242**	-.078	.092	.176	1	-	-	-	-
P	.305**	-.239**	.176	.346**	.175	1	-	-	-
T out	-.086	-.057	-.163	-.055	.140	-.073	1	-	-
RH out	-.242**	.132	-.100	-.212*	-.025	.091	.157	1	-
M	.927**	-.768**	.623**	.763**	.108	.283**	-.114	-.176	1

*Correlation is significant at the 0.01 level (2- tailed)

Impact of the thickness of the evaporative cooling pad on the cooling efficiency

The findings of this investigation demonstrated a significantly significant relationship between evaporative cooling pad thickness and cooling efficiency (85.9%, R^2=0.899, F=705.678, P<0.01). (B=0.324, t=28.457, P<0.01 (Table 4). The cooling efficiency increased with the pad thickness because thick pads exhibit poor porosity which increases the airflow time through the pad and the period of evaporation; therefore, the temperature reduces with increasing pad thickness as reported by Soponpongpipat et al. (2010). Hence, there is a significant relationship between the cooling pad thickness and the cooling efficiency in the greenhouse as earlier reported by Elmsaad et al. (2017b).

Impact of the thickness of the evaporative cooling pad on the environmental parameters

Table 5 displayed the considerable effect of cooling pad thickness on the quantity of water and internal temperature of the greenhouse. Clearly, the thickness of the cooling pad had a negative impact on the internal temperature of the greenhouse since a thicker cooling pad increases the duration that air has in contact with the pad surface, which increases external heat loss and lowers the internal temperature inside the greenhouse. This outcome is consistent with the report by Alam et al. (2017). The thickness of the cooling pad also had a substantial effect on the other environmental factors in the greenhouse, such as RH (changed by 33.3%) and pressure (by 9.3%).

Impact of cooling pad types on environmental parameters

Table 6 showed that different cooling pad materials had different levels of impact on the environmental parameters, such as pressure drop (22.3 %), water quantity, and temperature inside the greenhouse.

TABLE 3. Effect of cooling pad types on cooling efficiency inside the greenhouse

	B	t	Sig.	VIF
Types	0.324	28.457	0.000	1.00
R^2	0. 899	-	-	-
F	705.678	-	-	-
Sig. F	0.000	-	-	-
Durbin-Watson	0.300	-	-	-

TABLE 4. Impact of cooling pad thickness on cooling efficiency in the greenhouse

	B	t	Sig.	VIF
Thickness	0.238	27.324	0.000	1.000
R^2	0.789	-	-	-
F	678.540	-	-	-
Sig. F	0.000	-	-	-
Durbin-Watson	0.277	-	-	-

TABLE 5. Impact of cooling pad thickness on environmental factors

Parameters	R^2	F	Sig. F	B	t	Significant
T_{in}	.650	223.463	.000	-.055	-14.613	.000
RH_{in}	.322	59.013	.000	.089	8.675	.000
WQ	.703	231.608	.000	.179	16.043	.000
V	.223	42.750	.003	.043	1.387	.302
P	.089	13.122	.001	.342	3.467	.001
T_{out}	.008	.997	.323	-.002	-.896	.004
RH_{out}	.063	8.128	.009	-.012	-2.505	.006

*Correlation is significant at the 0.01 level (2- tailed)

TABLE 6. Effect of cooling pad types on environmental factors

Parameters	R^2	F	Sig. F	B	t	Significant
T_{in}	.149	20.617	.000	-.530	-4.541	.000
RH_{in}	.212	15.447	.000	3.630	1.203	.000
WQ	.082	10.596	.001	2.524	3.255	.001
V	.092	11.244	.002	.606	2.494	.002
P	22.3	32.999	.000	19.135	5.745	.000
T_{out}	.140	18.543	.001	-.543	-5.532	.001
RH_{out}	.000	.000	1.000	.000	.000	1.000

*Correlation is significant at the 0.01 level (2- tailed)

The impact of environmental indoor factors on cooling efficiency

The findings in Table 7 demonstrated the significant influence of environmental parameters on greenhouse cooling efficiency; all greenhouse factors, including temperature, RH, water volume, pressure drop, and air velocity, had an impact on greenhouse cooling efficiency.

Impact of air velocity on cooling efficiency

The luffa pad provided the highest level of cooling efficiency, while the sackcloth pad provided the lowest level of cooling efficiency, according to the observed effects of air velocity on the evaporative saturation efficiency of pad materials. A 90% cooling efficiency was attained by the 150mm luffa pad at 1.75 air velocity and 32.5L/m^2 water volume. Fig.s 6–11 depict the impact of air velocity on cooling efficiency in relation to pad material and thickness. Increases in air velocity reduce the evaporative cooling effectiveness of the pads. These findings suggest that lower air velocity encourages air contact and water absorption from moist pad surfaces. This lowers air temperature and enhances water evaporation, leading to greater cooling efficiency. These findings support (Misra & Ghosh, 2018b). finding that cooling effectiveness decreases with air velocity. Considering that the 300mm thick pads offer a higher surface area for air-water contact, they had superior cooling efficiency than the 100mm and 150mm thick cooling pads. Therefore, compared to the other pads, the 300mm thick LP had more cooling efficiency. The previously indicated relationship between air velocity and cooling efficiency suggests that increases in air velocity reduce the rate of temperature drop through the pad, while increases in pad thickness resulted in a somewhat higher temperature. According to the findings of RH, the differences in the RH increases with pad thickness and decline with air velocity. This outcome reflects higher evaporation rates because air must pass through the pad more slowly (Dai & Sumathy, 2002). The saturation efficiency was decreased by increasing the flow rate their trends are in opposite direction with respect to the airflow (Laknizi et al., 2021).

TABLE 7. Impact of environmental factors on cooling efficiency

Parameters	B	t	Significant	VIF
T_{in}	-1.544	-5.778	.000	1.952
RH_{in}	.379	3.665	.000	1.615
WQ	.321	3.709	.000	2.677
V	.244	2.598	.001	1.589
P	. 351	3.622	.000	2.820
T_{out}	-.536	-3.446	.000	1.798
RH_{out}	-.094	-.315	.753	1.126
R^2	0.643	-	-	-
F	38.691	-	-	-
Sig. F	0.000	-	-	-
Durbin-Watson	0.567	-	-	-

*Correlation is significant at the 0.01 level (2- tailed)

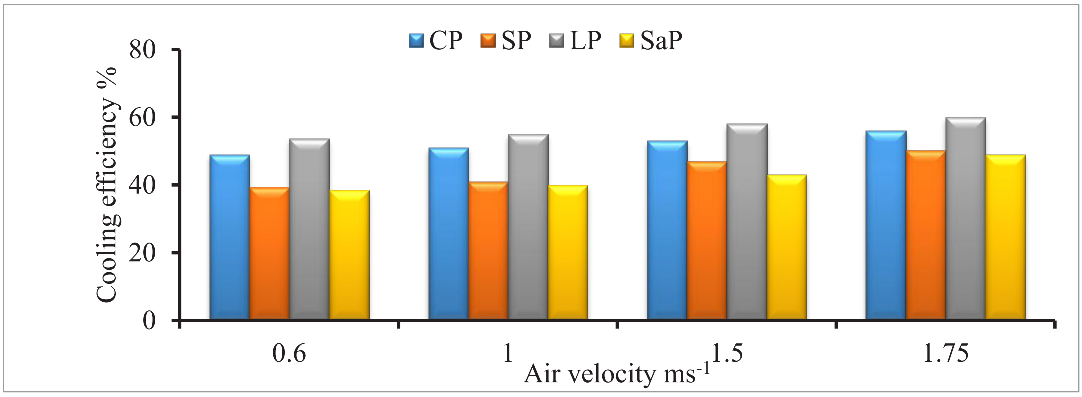

Fig. 6. The relationship between cooling efficiency and air velocity of 100mm thickness of different types of pads

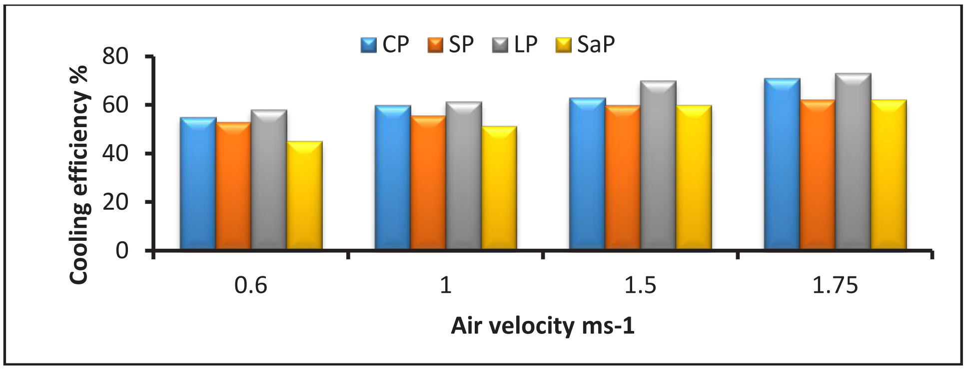

Fig. 7. The relationship between cooling efficiency and air velocity of 150mm thickness of different types of pads

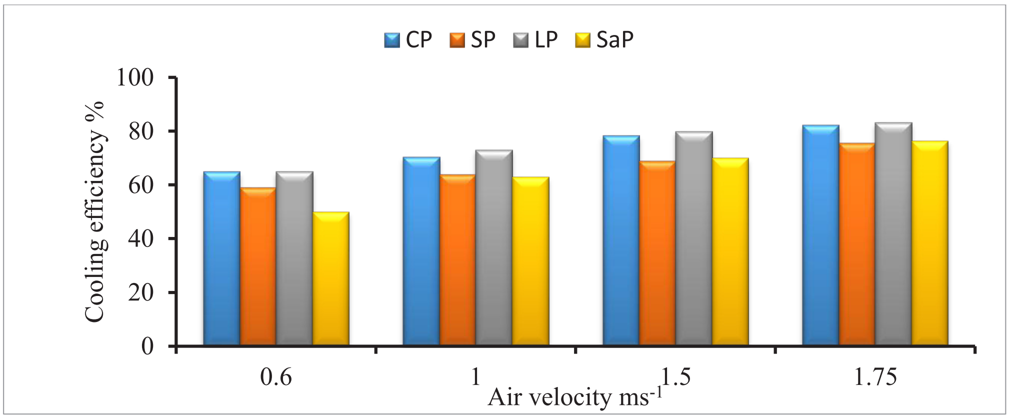

Fig. 8. The relationship between cooling efficiency and air velocity of 300mm thickness of different types of pads

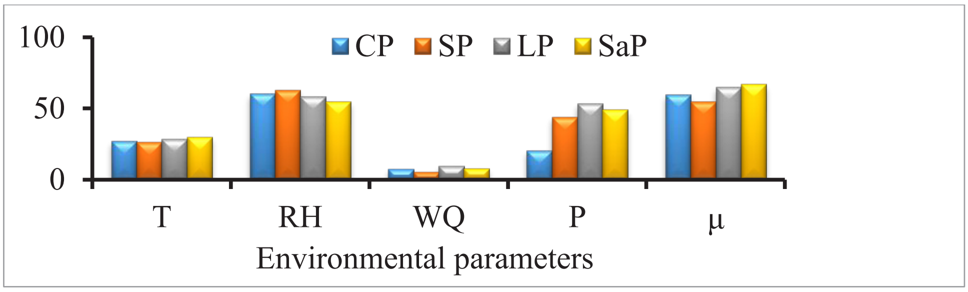

Fig. 9. The relationship between cooling efficiency and air velocity of 100 mm thickness of different types of pads

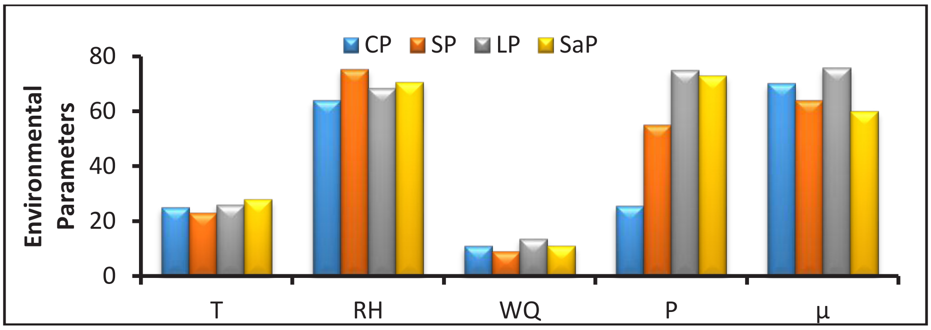

Fig. 10. The relationship between cooling efficiency and air velocity of 150mm thickness of different types of pads

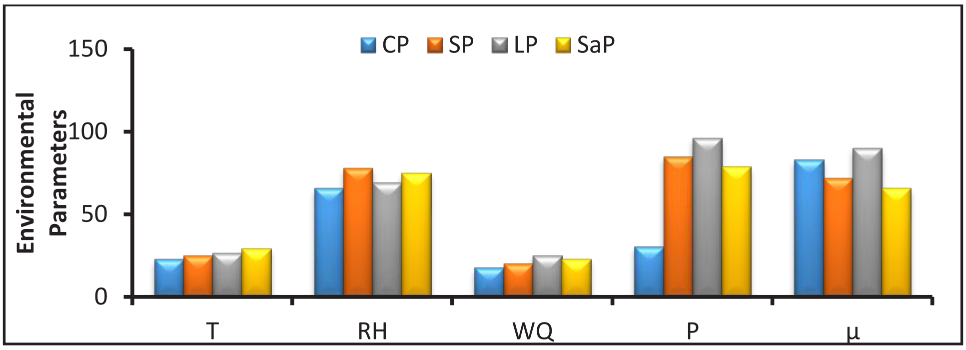

Fig. 11. The relationship between cooling efficiency and air velocity of 300 mm thickness of different types of pads

Effect of pressure on cooling efficiency

In comparison to the 300mm thick pads, the 100 mm and 150mm thick pads showed lower pressure levels. Based on how the pad materials affect the pressure drop of airflow, the pad materials can be ranked from highest to lowest as follows: LP > SP > SaP > CP. The pad type and the thickness of the utilized pad had a substantial impact on the air velocity, pressure drop, and cooling efficiency (Table 6). Increases in air velocity and water flow rate significantly increased the airflow pressure values (P 0.01); water flow rate had a small impact on pressure drop while air velocity had a significant impact. These outcomes are comparable to those of Xuan et al. (2012). Resistance is directly complemented by an increase in pad thickness as it extends the duration that air has in contact with the pad. When air moves through the extra pad thickness, the vapor pressure differential also decreases, slowing the evaporation rate, as previously documented by Hao et al. (2013), who demonstrated that the pressure drop across all forms of cooling pads is larger when the pads are thick, and the air velocity is higher. As the luffa wetted pad had small air pores, it had the highest pressure drop when it came to air velocity. In contrast, the celdek pad had the lowest pressure drop. According to fluid mechanics, the smaller the flow passage's diameter, the higher the pressure drop; as a result, the airflow through the small spaces of the luffa-wetted pad created a substantial pressure drop. Regarding celdek pad, a low-pressure drop was observed across the pad. These outcomes are consistent with previous reports by Alklaibi (2015). Also, the significant difference in pressure between different types of pads due to increased resistance to air flow and water flow through the pads (Vega et al., 2022).

Impact of RH and temperature on cooling efficiency

The analysis of the results revealed a substantial relationship between temperature, RH, and cooling efficiency based on the type and thickness of the pads used. The evaporative cooling pad efficiency relied mainly on the time of day because each time of the day had a different RH and temperature. Figures 12-15 are the daily saturation efficiency of the different pads used in this study (thickness= 300mm, air velocity= 1.75ms^{-1}). Between 2:00 and 4:00 PM, the temperature is at its highest and the RH is at its lowest; hence, it is the ideal period for cooling since it allows the system to drain more water into the air. As shown in the figures, the luffa wetted pad's greatest efficiency was 90.0% at an input air temperature of 26.7°C and a RH of 77.4%. The celdek wetted pad's maximum efficiency was 83.5% at 4:00 pm when the input air's dry bulb temperature was 26.0°C and the RH was 74.0 %. The best efficiency for the straw fiber pad was 79% at 4 p.m. when the input air's dry bulb temperature was 24.0°C and the RH was 75.0%. For the sackcloth-wetted pad, the maximum efficiency was 75.3% at 4:00 pm when the inlet air's dry bulb temperature was 25.0°C and RH was 74.0%. Compared to the other evaporative cooling pads, the sackcloth pad was less effective. These outcomes are consistent with earlier reports (Yıldız et al., 2010). This results in line with Hassan et al. (2021) mentioned that where the higher the air mass flow rate through the cooling surface, the less time the air stream is in contact with the wetted pad. As a result, less water evaporated at the pad leads to lower relative humidity and temperature reduction in the space conditioned by the cooler.

Impact of water quantity on the cooling efficiency of different pad types

The quantity of water showed a significant impact on the cooling efficiency at a 0.01 probability level. According to Table 6, LP produced the most water to thoroughly moisten the pad surface, followed by SaP, CP, and SP. These findings are in line with those of (Jain & Hindoliya, 2011) who found that the effectiveness of cooling increased as water volume rose until the pads were sufficiently moist. The chosen amount of water was sufficient to moisten the entire set of pads, hence this finding again validated the theory put forth (Dhakulkar & Dharme, 2017).

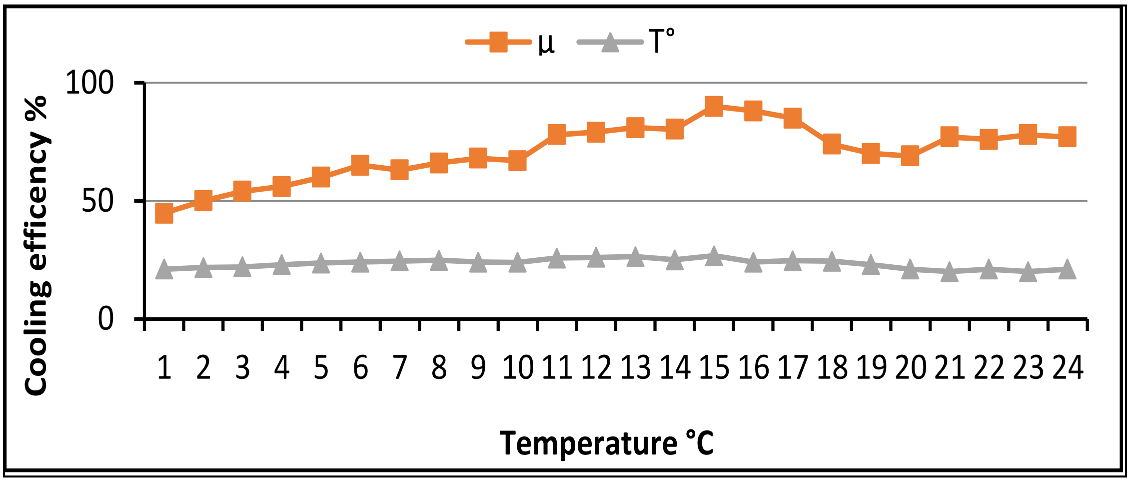

Fig. 12. The daily cooling efficiency of luffa evaporative cooling pads of 300mm thickness

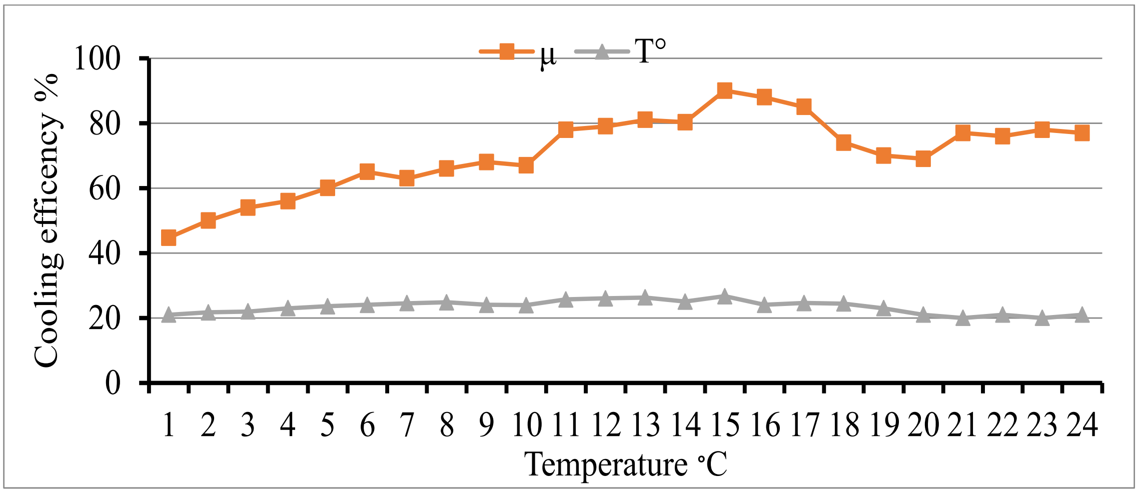

Fig. 13. The daily cooling efficiency of celdek evaporative cooling pads of 300mm thickness

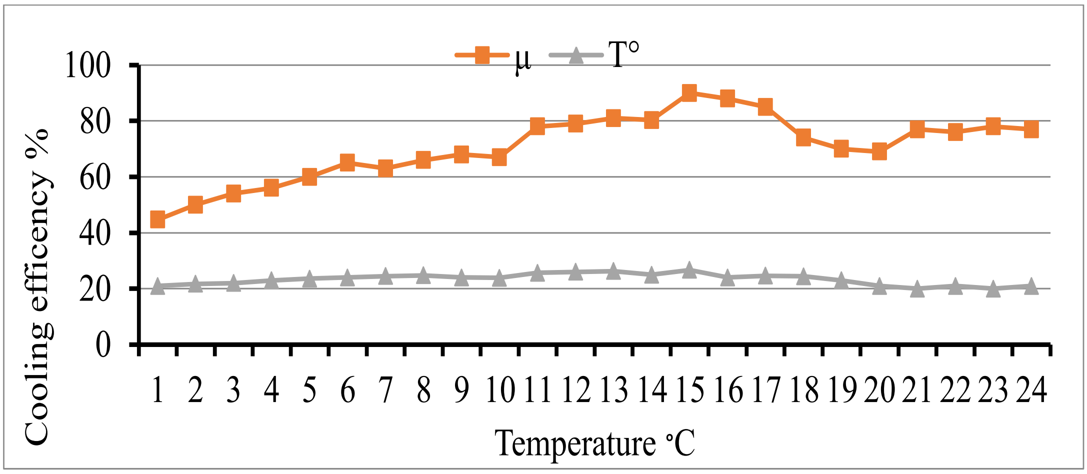

Fig. 14. The daily cooling efficiency of straw fiber evaporative cooling pads of 300mm thickness

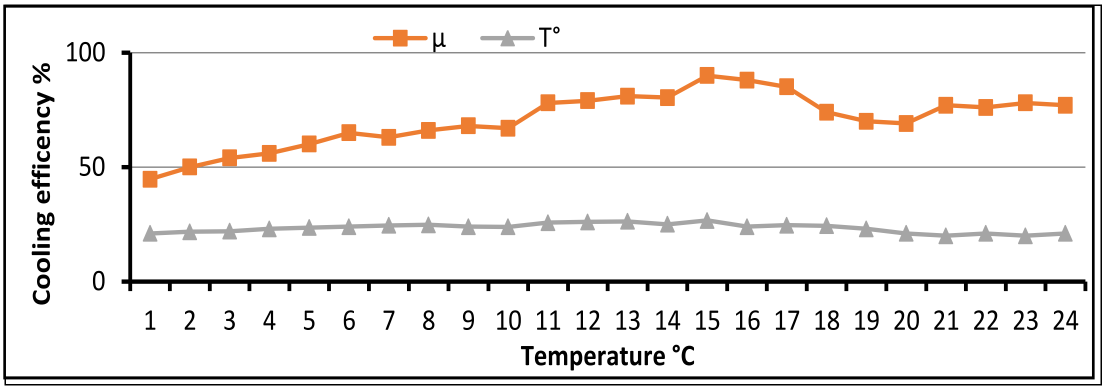

Fig. 15. The daily cooling efficiency of sackcloth evaporative cooling pads of 300mm thickness

Impact of water quantity on cooling efficiency at different pad thicknesses

the water quantity differed significantly for all the studied cooling pad thicknesses ($P< 0.01$; Table 6). As stated by Gunhan et al. (2007b). This outcome may be related to the increase in airflow time at higher pad thicknesses which reduced the airflow rate and pad porosity. Yet, as the amount of water increased, the exposed surface area to air from the entrance decreased while the RH increased. In general, Table 8 presents information on the selected pad materials' working conditions and the highest achieved evaporative cooling efficiency. Haeussermann et al. (2007) pointed out that when choosing pad materials for these evaporative cooling systems, water quantity is a necessary factor that must be taken into account. The air pressure drop via CP was noted to be less than 31.5 Pa in every test case, while the other pads exhibited high values of > 32.5 Pa.

Economic evaluation

This section looked at the cost of evaporative cooling; a payback period was used to calculate how long it would take for a profit to be realized from employing evaporative cooling. The amount of time needed for an investment's profit to equal its cost is referred to as the payback period (Lertsatitthanakorn et al., 2006). The overall cost of building an evaporative 3600 Saudi Arabia Riyal cooling house is about, or 990 USD, and included the cost of building, suction fans, pumps, and cooling pads. The electric power consumption per month cost is 1200 Saudi Arabia Riyal, equivalent to 325 USD for small-scale greenhouses (dimensions: length= 4m, width= 2m, height = 2.5m). The cost of a locally assembled evaporative cooling system is as shown in Table 9; the data suggests the need to promote locally-assembled evaporative cooling systems as an alternative technology for the greenhouse. It should be noted that the costs of the materials used in this study were less than the cost of materials used by some of the reviewed studies. Further cost savings could also be achieved by scaling up the developed system to larger scales.

TABLE 8. Evaporative efficiency and selected pads

Pad materials	Cooling efficiency %	Pad thickness mm
Luffa pad (LP)	78	300
Celdek (CP)	75.6	300
Straw fiber (Spf)	72	300
Sackcloth (SaP)	66.6	300

TABLE 9. Economic evaluation of evaporative cooling pads

Prices per Dollars ($)	Evaporative Cooling Pads per m^2
35 – 55 include transportation	Luffa Pads (LP)
20-40 include transportation	Sackcloth pads (SaP)
40- 50 include transportation	Date Palm fiber pads (SPf)
65- 500 exclude taxes and transportation	Celdeck pads (CP)

Therefore, the locally evaporative cooling system should be promoted as alternative technology for the greenhouse. Additional cost savings could be recognized in larger scale operations. On the other hand, the costs of these materials were used in this study less than the other materials using by other researchers were mentioned in the review and also the commercial pad.

Conclusion

In the current study, a wet LP, SaP, CP, and SP were used in an evaporative cooling system to assess the saturation efficiency and pressure. The average saturation efficiency of the wet LP was determined to be 78.5% following comparison with conventional wet pads, whereas those of CP, SP, and wet SaP were 75.60%, 72%, and 66.6%, respectively. In this investigation, pad thickness, cooling efficiency, and environmental factors were substantially correlated, even though the pressure of the evaporative cooling pads varied greatly. This study demonstrated that increases in pad thickness bring about a corresponding increase in water quantity, pressure, and RH while air velocity and temperature are significantly decreased. Also, it was shown that pad thickness and cooling efficiency had a strong relationship. All the greenhouse variables in this investigation, including temperature, RH, water volume, pressure, and air velocity, had a substantial impact on cooling efficiency. Again, a substantial difference in pressure drops, air velocity, and cooling efficiency was discovered between different pad types and pad thicknesses. The results of this study proved that the luffa pads (LP) should be used for cooling greenhouses to support better temperature, relative humidity, pressure, and water quantity in the greenhouses, and to obtain the best cooling efficiency with less cost. This study encourages the use of locally-sourced evaporative cooling systems as alternative wetted pads in greenhouse technology to save the operation cost by about 40 to 60% and to reduce power consumption.

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تأثير استخدام مواد ذات سمك مختلف من وسائد التبريد البخري على كفاءة التبريد في البيوت المحمية في المناطق الجافة الحارة

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كان الهدف من هذه الدراسة هو تحديد ما إذا كانت وسادات ألياف الليف والقش وقماش الخيش التي يمكن الوصول إليها محليًا يمكن أن تحل محل وسادات (celdek) التقليدية في أنظمة التبريد، وخاصة في البيوت المحمية. كانت أهداف الدراسة هي معرفة كيف تؤثر أنواع وسُمك وسائد التبخر المختلفة، بالإضافة إلى العناصر المناخية، بما في ذلك درجة الحرارة، وانخفاض الضغط، والرطوبة النسبية، وسرعة الهواء، على قدرة البيوت المحمية على البرودة بشكل فعال. أظهرت النتائج تأثيرات كبيرة لمواد الوسائد المختلفة على فعالية تبريد البيوت المحمية. وكان متوسط التشبع من وسائد الليف 78.5%، في حين كان متوسط التشبع من ألياف القش وألياف الخيش 72% و66.6%، على التوالي. على العكس من ذلك، أنتجت منصات celdek متوسطا تشبع 75.60%. وكان للوسادة التي يبلغ سمكها 300 ملم تأثير كبير للغاية على كفاءة التبريد، حيث خفضت درجة الحرارة ورفعت الرطوبة النسبية قليلاً مع امتصاص المزيد من الماء وخفض الضغط. وأظهرت النتائج ذلك أيضا لكمية الماء تأثير كبير على فعالية التبريد. علاوة على ذلك، كان هناك ارتباط قوي بين سرعة الهواء وفعالية التبريد والضغط. ومع ارتفاع سرعة الهواء، انخفضت كفاءة التبريد وزاد الضغط عبر عملية الواح التبريد. أثبتت الدراسة الحالية وجود علاقة سلبية بين درجة الحرارة وفعالية التبريد. وأخيرًا، أثبتت الدراسة أن وسادات الليف هي بديل أفضل لوسائد Celdek التقليدية لأنها تعطي نتائج أفضل من وسائل التبريد الأخرى.