



## A Utilizing Plant Waste Materials As Pads In Evaporative Cooling System Powered By Solar Energy For Environmental Control In Greenhouses

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### ***Abstract***

**Background:** The study was conducted to achieve optimal pad performance, which can provide an ideal environment for plant growth and production. This study was conducted near Al-Salihiya city in Sharqia Governorate. The study evaluated the performance of three types of evaporative cooling pads (cellulose, rice straw, and palm fiber), with 50% and no shading, and with fans on for two minutes and off for (3 minutes, 5 minutes, and 8 minutes). The performance evaluation included environmental parameters (temperature, relative humidity, water consumption, vapor pressure drop, cooling efficiency, and electrical cooling efficiency) hourly, from 9 am to 5 pm, daily. The data showed that the best results were achieved with cellulose pads, followed by rice straw, and the lowest results were achieved with palm fiber pads. The rice straw pad demonstrated effective results as an alternative to commercial cellulose in terms of efficiency, operation, and environmental conditions. The pad achieved a cooling efficiency of 61-71.5% in shaded conditions, and 57-62.5% without shade. It also achieved good electrical cooling efficiency, ranging from 1.1-1.75 °C/kWh in shaded conditions. The pad also achieved cooling at 10.4 °C, 62% humidity, and a cooling efficiency of 71.5%, with a water consumption of 3.5 liters/m<sup>2</sup>/day. On the other hand, the system's operating periods yielded mixed results, but the best results were achieved with 3 minute idle periods without shade and 5 minutes with shade. Shading also achieved good results in reducing the heat load and increasing the efficiency of the alternative pads

**Keywords:** *Fan and pad cooling, alternative cooling pads, greenhouse climate control, and shading*



## 1. Introduction:

The popularity of greenhouses for sustainable food production is undeniable, offering year-round growth, lower water usage, and increased yields. However, maintaining optimal temperatures, especially in hot and dry climates, is a major hurdle. Traditional cooling methods are often expensive and energy-hungry, making them unsuitable for all growers. Scientists are looking for new ways to cool greenhouses that are cheaper, better for the environment, and use less energy. One promising solution is evaporative cooling, which is a simple, low-energy solution that utilizes water's natural cooling properties as it evaporates.

Evaporative cooling systems are a game-changer for hot, arid regions, which make up a significant portion of the country. These systems offer a double benefit: they are environmentally friendly, causing minimal harm compared to traditional air conditioning, and highly energy efficient. This low energy demand makes them ideally suited to be powered by solar panels, a sustainable and readily available energy source in these regions according to (1). They also tell us according to their sources that half of the conventional cooling devices in the south west USA were replaced by simple direct evaporative air coolers, this would save 18 million barrels of oil per year. The greenhouse's temperature is successfully lowered by the solar evaporative cooling system, creating a climate that is ideal for plant development (2). They also explained that a few examples of the variables that affect the system's cooling capability are water supply, airflow rate, and sun radiation. Their study emphasizes how crucial it is to properly design and operate a system to optimize its energy efficiency and performance.

(3). Showed that the use of a solar evaporative cooling system in low-cost greenhouses can enhance crop production by creating a favorable microclimate for plant growth, and according to (4), the planning, building, and operation of a solar-evaporative cooling greenhouse that uses little energy. The study investigates the different parts and methods of building a cheap greenhouse that uses solar power for evaporative cooling. In addition to discussing the significance of sustainability and energy efficiency in greenhouse operations, the writers offer tips and tricks for designing and refining the cooling system. As (5), also highlight the significance of low-cost greenhouse construction in promoting sustainable agriculture. The study emphasizes the need for affordable and energy-efficient greenhouse designs that incorporate renewable energy technologies. The authors provide recommendations for optimizing greenhouse construction methods to enhance energy efficiency and reduce environmental impact.

A key component in evaporative cooling systems is the cooling media to help the water evaporate. Traditionally, this cooling media is made of cellulose pad or synthetic materials, that are made of expensive, non-biodegradable materials, and may need frequent maintenance. Recently, researchers have become interested in using leftover materials from agriculture as an alternative cooling media. Since commercial cooling pads can be expensive, there's a pressing need to evaluate the performance of suitable, locally sourced materials, especially for rural agricultural buildings (6). Extensive studies have been conducted on options like date palm fibers (stem), jute and luffa fibers as suitable evaporative cooling materials (7).

Other studies explored celdek cellulose pads, straw pads and sliced wood pads (8). The coconut coir pads, jute fiber pads and sackcloth pads (9). Activated carbon foam and luffa pad (10). Cellulose, khus-grass, and wood-wool pad material (11). Celdek, khus, coconut coir and bamboo fiber (6). Local palm tree "Nakheel" waste that are leaflet, leaf base, bulb, and roots (12). Despite this extensive research, there's a lack of studies specifically investigating the use of straw pad and palm fibers as wetted pad materials in evaporative cooling systems. Evaporative cooling offers energy savings, reducing emissions from power plants and lessening peak summer electricity demand. Some utility companies are actively promoting its use to minimize the need for new power generation facilities. Simplified maintenance requirements enhance safety and reliability. Several studies have explored the impact of greenhouse design and environmental factors on plant growth and yield. Studies by (13) and (14) suggest that covering greenhouses with black and green shade nets (63% shade) improves tomato seedling germination and growth rates compared to transparent plastic film or open fields. This highlights the



potential benefits of shading for regulating temperatures and sunlight exposure. While evaporative cooling systems using pads and fans are effective for temperature control (15), they can create uneven temperature distribution within the greenhouse. This can be detrimental to plant growth, prompting growers to combine cooling with shading techniques. Research by (16) indicates that air temperature is a critical factor influencing seedling germination, plant growth, and yield in greenhouses. Increasing shade levels (63% and 75%) during summer days effectively reduced temperatures but also increased humidity. Therefore, a balance must be achieved between advantages and disadvantages to achieve successful plant production.

In this research, we aim to investigate the effectiveness of reusing selected agricultural by-products as solar-powered evaporative cooling media for greenhouse cooling. We will evaluate the cooling performance under different shading conditions, on-off periods, and assess the system's efficiency, energy consumption, and overall impact on crop growth and yield. To achieve these objectives, we will conduct a series of laboratory and field experiments using various agricultural by-products, such as crop residues, straw, and fibers. We will measure and analyze relevant parameters, such as temperature differences, humidity levels, water and energy consumption, and crop performance indicators. The collected data will be statistically analyzed to determine the effectiveness of the reused cooling media and its impact on greenhouse conditions. By reusing agricultural by-products as evaporative cooling media, the results of this study will provide valuable insights for greenhouse operators, researchers, and policymakers seeking to enhance the efficiency and environmental sustainability of greenhouse agriculture.

## 2. Materials and Methods

### 2.1. Study Site

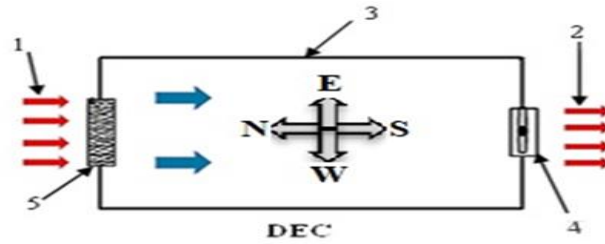
The study was conducted during the summer of 2022 in Al-Salihiya city (30° 34' 00" N 031° 30' 00" E) Sharqia Governorate, Egypt. The region has a hot, dry, desert climate with average high temperatures of 38.3°C during summer. Three greenhouses with the same specifications were operated simultaneously to achieve the changes within two months. The greenhouse design was in a modified Quonset (flat arch) shape with dimensions of 9 m wide, 40 m long, and 4 m high at the maximum height of the arch. The greenhouse was oriented from north to south so that the cooling pad is in the north direction and the fan is in the south direction to reduce solar radiation inside the greenhouse and take advantage of the north-west winds in Egypt. It was equipped with an evaporative cooling system, and lighting to be under full environmental control and provide appropriate conditions inside the house. This greenhouse was operated using solar power and electricity as a power source.

### 2.2. Greenhouse Design and Construction

The galvanized steel frame (pipes with an outer diameter of 76 mm and a thickness of 3 mm) was provided with brackets spaced every 3 meters and fixed to concrete bases. The frame members are related to joints and anchor bolts (diameter 6 mm). The roof was sloped at a 22-degree angle and covered with a single layer of UV-protected polyethylene (200 µm thick and 90% light transmittance). 10 mm thick double-walled polycarbonate panels were used on the east and west walls, surrounded by aluminum frames. The north wall was provided with a one-meter-high wall to support the pad and the collection basin, while the south wall contained a wall to support two cooling fans.

### 2.3. Evaporative cooling system

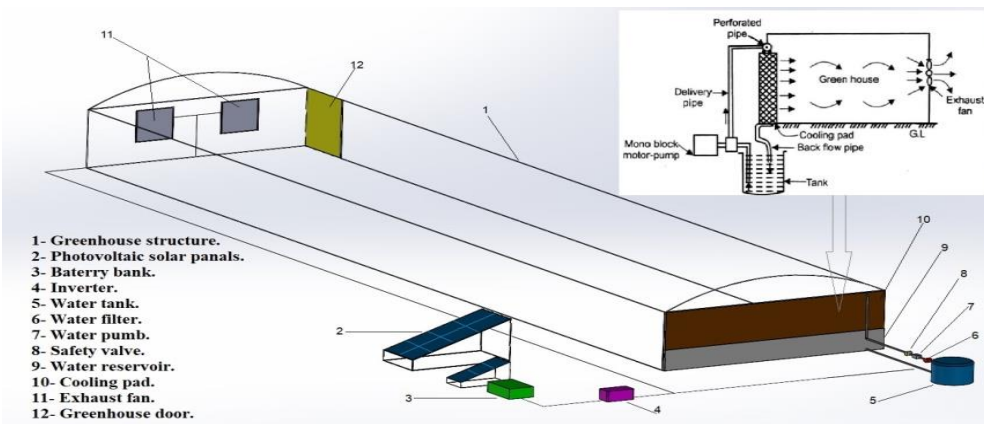
The major parameters affecting the thermal plant comfort are temperature and relative humidity, which can be handled by evaporative cooling systems. The evaporative cooling (EC) technology is based on heat and mass transfer between air and cooling water. one evaporative cooling systems of direct evaporative cooling (DEC) was used under all experiments for cooling atmosphere inside the greenhouse in the hot summer months. The direct cooling pad apparatus was positioned on the north wall of the building as shown in Fig. 1.



1. Inlet air (hot air),
2. Outlet air,
3. Greenhouse,
4. Dynamic ventilation Fan,
5. Cooling pad,
6. Cooling fan.

**Fig. 1. A schematic diagram of greenhouse orientation.**

In DEC as shown in Fig. 2, water was pumped by pump power of 750 W with 60 Lit/min. volume to the pipes, which were positioned above cooling pad. The cooling pad was constructed from local materials of (Cellulose, Palm fiber and Rice straw) with dimensions of 9×1.8 m and 10 cm thickness. These pipes were perforated, and the water fell on the pad as droplets. The pads were wet from the pipes that were positioned above them. Excess and falling water from the pad were collected in the water reservoir and returned to the tank. When the outdoor hot air was passed through the pad, the air temperature was decreased and humidified. The humidifier added water to the incoming air stream to be cooled inside the greenhouse.



**Fig. 2. A schematic diagram of the greenhouse, and PV system.**



**Fig. 3. pictorial view of the used modified Quonset greenhouse**



Each of the three greenhouses was equipped with two fans, **1380** mm in diameter with maximum air capacities 44000 m<sup>3</sup>/hr. The used specification fan was DJF-1380 model, 1400 rpm rotational speed and operated by motor power of 1100 W. The fan was positioned on the south wall in the opposite direction of the air inlet place that was taken into consideration when designing the house. Every plant live weight needs 4 m<sup>3</sup>/h air flow rate per kg. Ventilation control is achieved by adjusting the air inlets and the fans (by switching fans on or off). The system is equipped with a set of operating timers to be operated at specific intervals, so that the system operates for a fixed period of 2 minutes and stops for different periods (3 minutes, 5 minutes, 8 minutes). Half of the greenhouse models were covered with black external shade netting, providing a 50% shading ratio for the duration of the experiment.

#### 2.4. Photovoltaic Power System

The evaporative cooling system was powered by a dedicated 8.25 kW grid-connected photovoltaic (PV) system installed adjacent to the three greenhouses. The system utilized 15 monocrystalline silicon PV modules, each rated at 550 W, arranged in a series-parallel configuration to produce an array voltage of approximately 480 V DC. During daylight hours, these panels served as the primary energy source, converting solar radiation into DC electricity. This high-voltage DC power was routed through a Maximum Power Point Tracking (MPPT) charge controller to optimize energy transfer and regulate charging conditions for the batteries. A pure sine wave inverter/charger converted the regulated DC into 240 V AC to operate all critical components of the cooling system, including pumps, axial fans, control units, and instrumentation. Four 12 V, 200 Ah AGM batteries were connected in series to form a 48 V storage bank capable of supplying backup power for 2–3 hours during solar downtime. The inverter/charger was carefully sized to accommodate the peak load demands of the cooling system while maintaining stable and efficient operation. Although the system included a transfer switch to draw auxiliary power from the utility grid when needed, it was primarily designed to function autonomously using solar energy and battery storage. Each system component played a vital role: the PV modules harvested energy, the MPPT controller ensured efficient power conversion, and the battery bank guaranteed continuity during low-sunlight periods. Performance metrics such as solar generation and load consumption were logged in real time to monitor the energy balance and support operational optimization.



Fig. 4. 15 monocrystalline silicon PV modules, each rated at 550 W.

#### 2.5. The cultivated plant

A test crop (cucumber) was used to evaluate the effectiveness of the different types of evaporative cooling pads on off-season production of crops. The crop parameters studied included stem length and diameter, leaves number and width. Seeds *BARRACUDA* is the most productive category in the winter season, where the plant had a strong burden that resists thermal stress.

#### 2.6. Instrumentation

Internal and ambient temperatures of air were measured with hour intervals during experiments. TM-40 X series (Tenmars Electronics Company) was used to measure temperature with an accuracy  $\pm 1^\circ\text{C}$ ,



humidity with an accuracy  $\pm 3.5\%$  and the air speed with an accuracy  $\pm 3\%$ . Added to inlet and outlet water temperatures were measured by 0.85 mm diameter of copper – constantan thermocouples. All thermocouples were calibrated and connected directly to a digital millimeter. The pyranometer was mounted on a horizontal plane 1 m above ground. The analog voltage signal was digitized by the weather station datalogger every 15 minutes. Calibration was performed by the manufacturer and verified onsite using a reference cell pyranometer. Relative humidity (RH) was measured using capacitive sensors (0-100% RH,  $\pm 2\%$  accuracy, Sensirion).

**3. Data Analysis:**

**3.1. Pad surface area:**

The surface area of pad depends on the amount of air to be displaced per minute and velocity of air through the ( $pad_{area}$ ) was determined from the following equation:

$$pad_{area} = \frac{q_{air}}{v_{air}} \dots\dots\dots (1)$$

Where:  $pad_{area}$  is the surface area of pad ( $m^2$ ).  $Q_{air}$  is the amount of air to be displaced per minute ( $m^3 / min$ ). And  $v_{air}$  velocity of air through the pad.

$$q_{air} = vol_{gh} \times f_{gh} \dots\dots\dots (2)$$

Where:  $q_{air}$  is the amount of air to be displaced per minute ( $m^3 / min$ ).  $vol_{gh}$  Is the volume of greenhouse and  $F_{gh}$  is the constant factor taken as a (1.5-1.8) equal as average 1.65.

**3.2. Evaporative cooling efficiency:**

Cooling efficiency depends on ambient temperature, relative humidity, and the wet temperature. The cooling efficiency ( $\eta_{cooling}$ ) was determined from the following equation according to , (17):

$$\eta_{cooling} = \frac{T_{out\ db} - T_{evp\ db}}{T_{out\ db} - T_{out\ wb}} \times 100, (\%) \dots\dots\dots (3)$$

Where,  $T_{db-out}$ , is the air temperature prior to cooling pad in  $^{\circ}C$ ,  $T_{db- evp}$ , is the cooled air temperature just leaving the cooling pads in  $^{\circ}C$ , and  $T_{wb-out}$ , is the wet-bulb temperature of the air prior to the cooling pad in  $^{\circ}C$ .

$$\Delta T = T_{ao} - T_{ai} \dots\dots\dots (4)$$

Where:  $T_{ao}$  is a temperature out greenhouse and  $T_{ai}$  is a temperature in greenhouse according to (18).

**3.3. Temperature reduction ( $\Delta T$ ):**

The temperature difference between outside the house ( $T_{ao}$ ) and inside the house ( $T_{ai}$ ) was used to describe the performance of evaporative cooling systems. Temperature reduction ( $\Delta T$ ) was calculated using the following equation:

$$\Delta T = T_{ao} - T_{ai} \dots\dots\dots (5)$$

Where:  $T_{ao}$ : Outlet dry-bulb temperature of the air stream ( $^{\circ}C$ ) and  $T_{ai}$ : Inlet dry-bulb temperature of the air stream ( $^{\circ}C$ ).

**3.4. The vapor pressure drop (VPD, kPa) was calculated from  $T_a$  and RH measurements as:**

$$VPD = \frac{(VP_{sat} - VP_{air})}{1000}, (Kpa) \dots\dots\dots (6)$$

$$VP_{sat} = 610,78 \exp \left( \frac{a(k-273,16)}{k-b} \right), (Pa) \dots\dots\dots (7)$$

$$VP_{air} = 0,01 \times RH \times VP_{sat}, (Pa) \dots\dots\dots (8)$$

$$K = T(c^{\circ}) + 273,13, \text{kelvin} \dots\dots\dots (9)$$

$a = 17,2693882$  and  $b = 35,86$  are constant according to (19).

**3.5. Consumed energy:**

Electric meter related to experimental systems to measure the consumed electrical energy. This electric meter was obtained from engineering industries company, Egypt.

**3.6. Efficiency of the PV panel**

The efficiency of the PV panel to calculate the gained energy from the incident solar energy for each tilt angle at winter and summer seasons was determined using the following equation:

$$\eta_{PV} = \frac{I_{PV} \times \dot{V}_{PV}}{SR \times A_{PV}} \times 100 \quad \text{according to (20)} \dots\dots\dots (10)$$



Where:  $\eta_{PV}$  = The PV efficiency (%),  $I_{PV}$  = Output current of the PV (Ampere),  $\tilde{V}_{PV}$  = Output voltage of the PV (Volt),  $SR$  = Average solar radiation ( $W/m^2$ ),  $A_{PV}$  = Surface area of the PV panel ( $m^2$ )

**3.7. Electrical energy**

The required electrical energy was calculated as the following equation:

$$E_e = I \cdot V \cdot \text{Cos}\theta \quad \dots\dots\dots (11)$$

Where:  $E_e$  = Electrical energy of the fans and pump (Wh),  $I$  = Current intensity (Ampere),  $V$  = Voltage (Volt) and  $\text{Cos}\theta$  = power factor (0.7) , (21)

**3.8. Power consumption:**

The total consumed electrical power of cooling system equipment was obtained as follows according to (22),

$$\text{TPC} = P_{cs} \times O_h \quad \dots\dots\dots (12)$$

Where: TPC is total power consumption per day,  $P_{cs}$  is the power consumption of the fans and pump, and  $O_h$  is actual daily operating hours.

$$P_{cs} = p_{cs \text{ fan}} + p_{cs \text{ pump}} \quad \dots\dots\dots (13)$$

Where:  $p_{cs \text{ fan}}$  per watt is the power consumption of the fans, and  $p_{cs \text{ pump}}$  which is the power consumption of the pump per hour.

$$O_h = \left( \frac{2}{S_p + O_p} \right) \times \text{Daily experiment hours} \quad \dots\dots\dots (14)$$

Where:  $S_p$  is the stop period, and  $O_p$  is the operating period.

**3.9. Electrical cooling efficiency:**

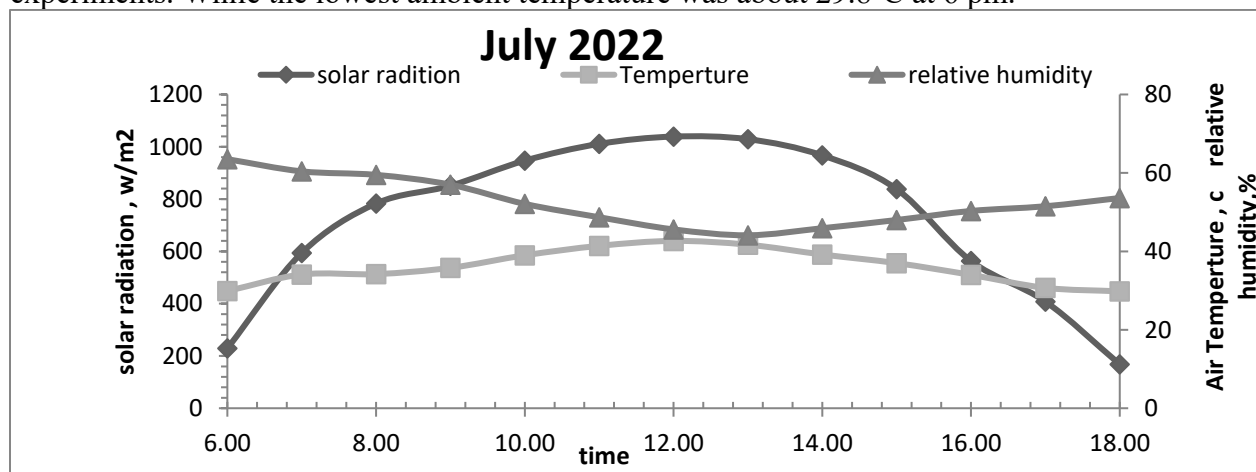
$$\text{ECE} = \Delta T / \text{TPC} \quad \dots\dots\dots (15)$$

Where:  $\Delta T$  is the temperature reduction, and TPC is the total consumed electrical power.

**4. Results:**

**4.1. Climate conditions**

Solar radiation and ambient temperature were recorded as climate conditions during the summer experimental periods of July and August 2022. Recorded climate data for the beginning experimental date of 1<sup>st</sup> July and the end date of 30<sup>th</sup> august from 6 am to 6 pm gave approximately the same behavior as shown in Fig. 4 and 5. Solar radiation was increased gradually to be reached its highest value of 1039 and 1028  $W/m^2$  at 12 pm and then decreased during the mentioned, in that order. With respect to ambient temperature, obtained data clarified that the highest value was about 43.74°C at 1 pm during the experiments. While the lowest ambient temperature was about 29.8°C at 6 pm.



**Fig. 5. Climatic conditions of the experimental region dated on July 2022**

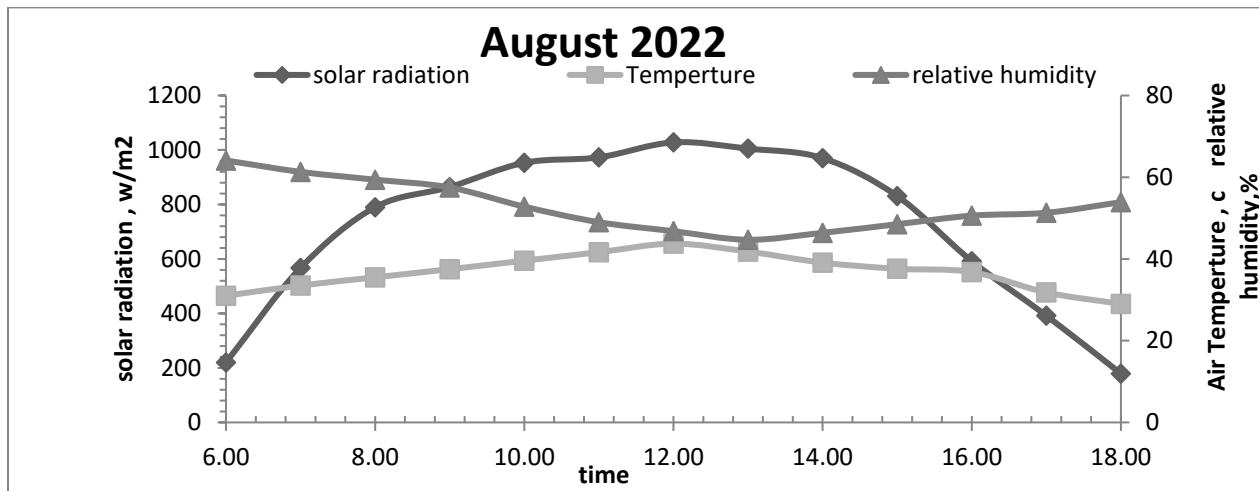


Fig. 6. Climatic conditions of the experimental region dated on August 2022

4.2. Temperature reduction

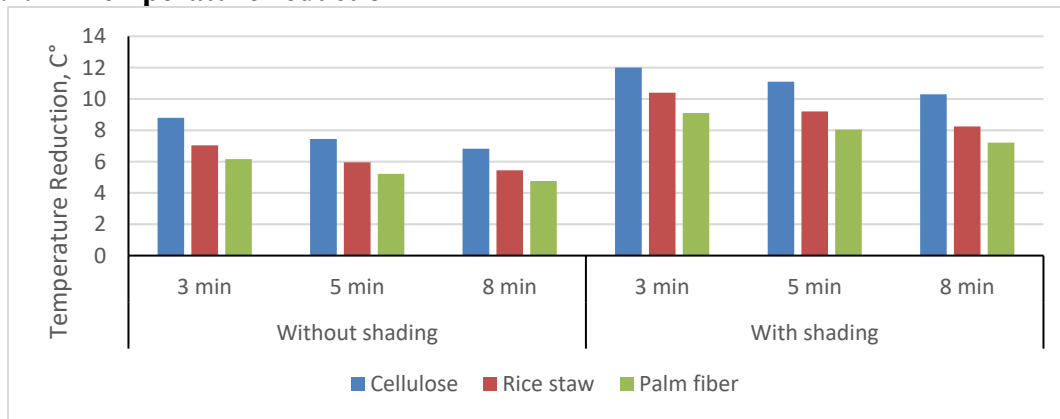


Fig. 7. Effect of Pad material and stopping period on temperature reduction with and without shading at 1 pm.

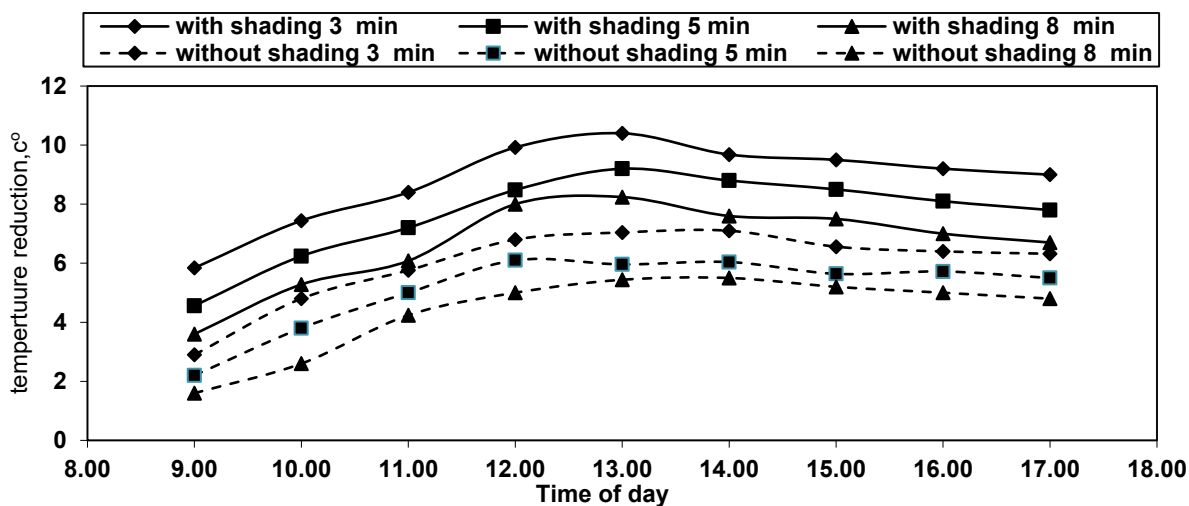


Fig. 8. Temperature reduction versus time of day at different fan stopping periods with and without shading for rice straw pad material.

The data shows that using different pad materials in evaporative cooling pads results in varying levels of temperature reduction in the greenhouse. Cellulose pads provide the greatest temperature reduction, lowering the temperature by 8.8°C, 7.45°C, and 6.8°C for fan stopping periods of 3 mins, 5 mins, and 8



mins respectively without shading. In comparison, rice straw pads reduce the temperature by 7.04°C, 5.96°C, and 5.44°C, while palm fibers pads result in the least cooling with reductions of 6.16°C, 5.22°C, and 4.76°C for the three fan stopping periods, (23) and (24).

When examining the effect across different times of day, cellulose pads consistently provide the greatest temperature reduction. For example, at 9am cellulose pads lowered temperatures by 7.3°C, 5.7°C and 4.5°C for the three fan stopping periods with shading, compared to 5.84°C, 4.56°C, and 3.6°C for rice straw. In the afternoon at 2pm, cellulose cooling reached 11.8°C, 10.7°C and 9.5°C, while rice straw only reduced temperatures by 9.68°C, 8.8°C and 7.6°C. The superior cooling capacity of cellulose is maintained throughout the day, (25) and (24).

As shown in table 1, Cellulose pads showed the highest significant ( $p \leq 0.01$ ) temperature reduction at 9.4122°C compared to 7.7133°C for rice straw and 6.7511°C for palm fiber. Using a 3 min stopping period led to significantly ( $p \leq 0.01$ ) higher reduction at 8.9167°C over 5 min (7.8311°C) and 8 min (7.1289°C). With shading had significantly ( $p \leq 0.01$ ) higher reduction at 9.5119°C versus without at 6.4059°C.

Interactions: High significant ( $p \leq 0.01$ ) interaction between pad type and shading. Addition of shading increased temperature reduction by 2.5997°C for cellulose pads from 6.8125°C without shading to 9.4122°C with shading. Comparatively smaller increases with shading for rice straw (1.3219°C) and palm fiber (1.1355°C).

The ANOVA revealed that shading, pads materials, and stopping periods all had highly significant effects on temperature reduction (all  $p \leq 0.01$ ). Of these main effects, shading exhibited the strongest influence, with an F-statistic of 1882. There was a significant interaction between pads materials and shading ( $p = 0.0014$ ) as well as between stopping periods and shading ( $p \leq 0.01$ ), indicating the effects of pads materials, and stopping periods depended on the level of shading. However, there was no significant interaction between pads materials and stopping periods ( $p \geq 0.05$ ), suggesting the effect of pads materials did not depend on stopping periods. The three-way interaction between all factors was also not significant ( $p \geq 0.05$ ). The model explained 97.5% of the variability, suggesting a good fit. In summary, all three factors impacted temperature reduction, with shading having the dominant effect, and some evidence of two-way interactions between the factors.

Table 1: Statistical analysis of the study data according to the Statistix 9 program, and shows the main effects and interaction

Main effects and interactions:	Temperature reduction, (C°)	Cooling efficiency, (%)	Relative humidity, (%)	Water Consumption, (lit/m <sup>2</sup> /day.)	VPD, (Kpa)
<b>Pads:</b>					
Cellulose	9.4122 a	77.083 a	59.250 c	4.4667 a	1.9741 a
Rice straw	7.7133 b	62.550 b	66.233 b	3.6667 b	1.9322 a
Palm fiber	6.7511 c	55.667 c	68.100 a	3.2500 c	1.8098 b
<b>Stopping period:</b>					
3 min	8.9167 a	69.967 a	59.583 c	4.4833 a	2.1696 a
5 min	7.8311 b	64.333 b	65.667 b	3.8500 b	1.8695 b
8 min	7.1289 c	61.000 c	68.333 a	3.0500 c	1.6769 c
<b>Shading:</b>					
With shading	9.5119 a	68.333 a	67.133 a	3.1444 b	1.7745 b
Without shading	6.4059 b	61.867 b	61.922 b	4.4444 a	2.0362 a
P value					
Pads	0.0000	0.0000	0.0000	0.0000	0.0000
Stopping period	0.0000	0.0000	0.0000	0.0000	0.0000
Shading	0.0000	0.0000	0.0000	0.0000	0.0000
Pads × Stopping period	0.8376	0.0000	0.0000	0.0000	0.0011
Pads × Shading	0.0014	0.0001	0.0000	0.0001	0.5901
Stopping period × Shading	0.1594	0.0000	0.0000	0.0000	0.0037
Pads × Stopping period × Shading	0.3146	0.0000	0.0000	0.6661	0.8911
<i>Note:</i> Means in the same column(s) followed by the same letters are not significantly different according to Duncan's Multiple Range Test (DMRT).					



In summary, cellulose cooling pads, shorter fan stopping times, and shading all contribute to optimized temperature reduction inside greenhouses using evaporative cooling. Further studies could examine combinations of these factors to determine settings that maximize cooling while optimizing water and energy usage.

### 4.3. Cooling efficiency:

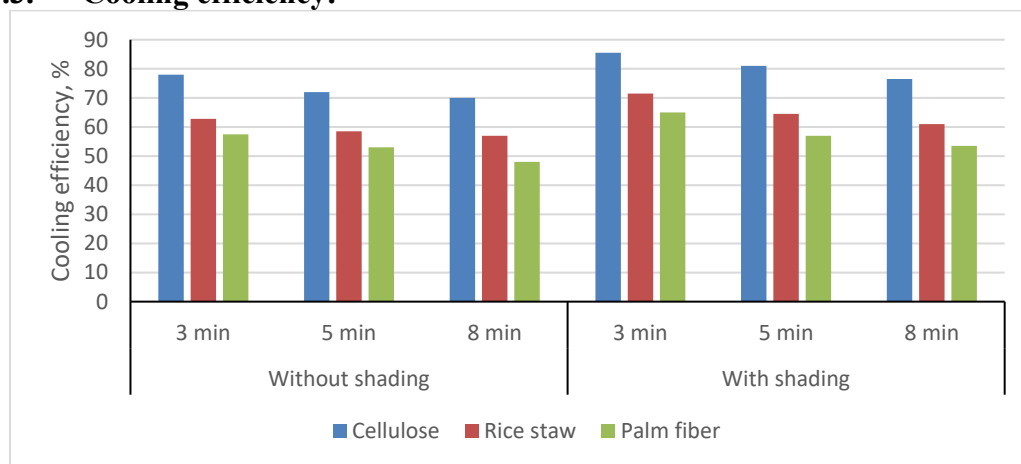


Fig. 9. Effect of Pad material and stopping period on cooling efficiency with and without shading at 1 pm .

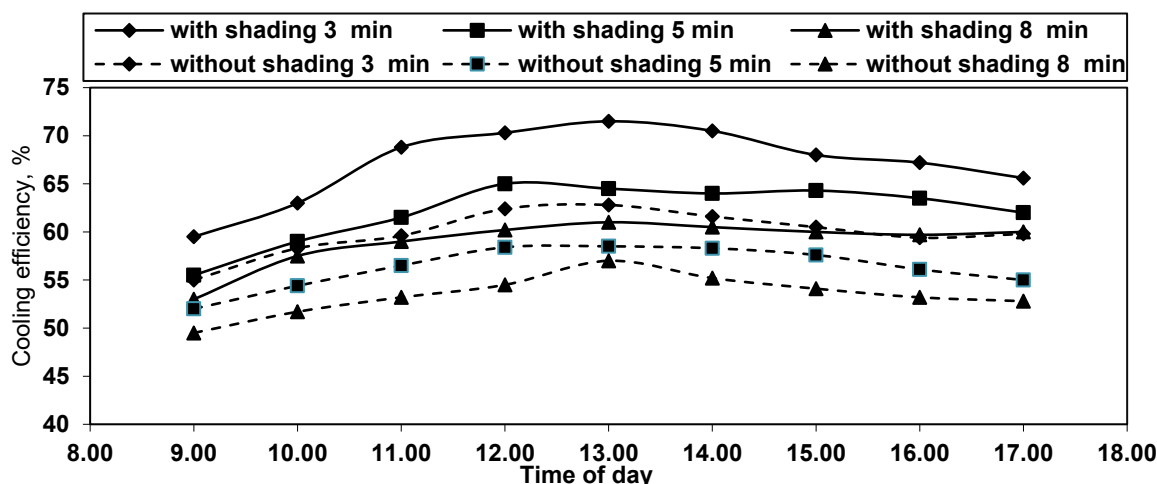


Fig. 10. Cooling efficiency versus time of day at different fan stopping periods with and without shading for rice straw pad material.

Overall, greater cooling efficiency is achieved throughout the day with shorter fan stoppage times and the utilization of shading. Passive cooling systems in hot regions can operate more efficiently if certain parameters are optimized. Additional study could look at the impacts at different times when the fans stop and other shade arrangements. Cellulose pads demonstrated the greatest cooling efficiency in the absence of shading, with values ranging from 70–78% during the various fan stopping intervals. Palm fibers pads had the lowest efficiency at 49–57.5%, while rice straw pads had a reasonably high efficiency of 57–62.8%. According to (24) and (26). With shading, the cooling efficiency increased for all pad materials and fan stopping periods. Cellulose remained the most efficient at 85% (3 min), 81% (5 min), and 76% (8 min). rice straw was 61–71.5%, and Palm fibers was 53.5–65%, (8) and (24) . The high cooling efficiency of cellulose pads is likely due to their greater moisture retention and surface area for evaporative cooling. Palm fibers and rice straw are more porous. The differences between materials were smaller with shading, suggesting shading helps compensate for lower performing pads.

As shown in table 1, Cellulose pads had significantly ( $p \leq 0.01$ ) higher efficiency at 77.083% over rice straw at 62.550% and palm fiber at 55.667%. 3 min stopping had significantly ( $p \leq 0.01$ ) higher efficiency



at 69.967% versus 64.333% at 5 min and 61.000% at 8 min. With shading was significantly ( $p \leq 0.01$ ) higher at 68.333% over without at 61.867%.

Interactions: Significant interactions between pad type and stopping period ( $p \leq 0.01$ ), pad type and shading ( $p \leq 0.01$ ), and stopping period and shading ( $p \leq 0.01$ ). For cellulose pads, efficiency dropped by 16.283% from 3 min to 8 min stopping, versus a smaller drop of 7.700% for palm fiber, indicating longer stopping periods impacted cellulose pad efficiency more negatively.

The analysis of variance revealed that pads materials, stopping periods, shading, and their interactions had highly significant ( $p \leq 0.01$ ) effects on cooling efficiency. The large F-statistics relative to error indicate pads materials, stopping periods, and shading were the most impactful factors. The significant two-way and three-way interactions suggest the effects of pads materials, stopping periods, and shading were interdependent. Overall, ANOVA provides compelling evidence that cooling efficiency was influenced by pads materials, stopping periods, shading, and their interactions. The replicate factor was not significant, indicating negligible differences between replicates.

In summary, cellulose pads, short fan stopping periods, and shading together maximize cooling efficiency. Selecting appropriate materials and optimizing fan operation and shading are critical factors in the performance of passive cooling systems using evaporative cooling pads.

4.4. Relative humidity:

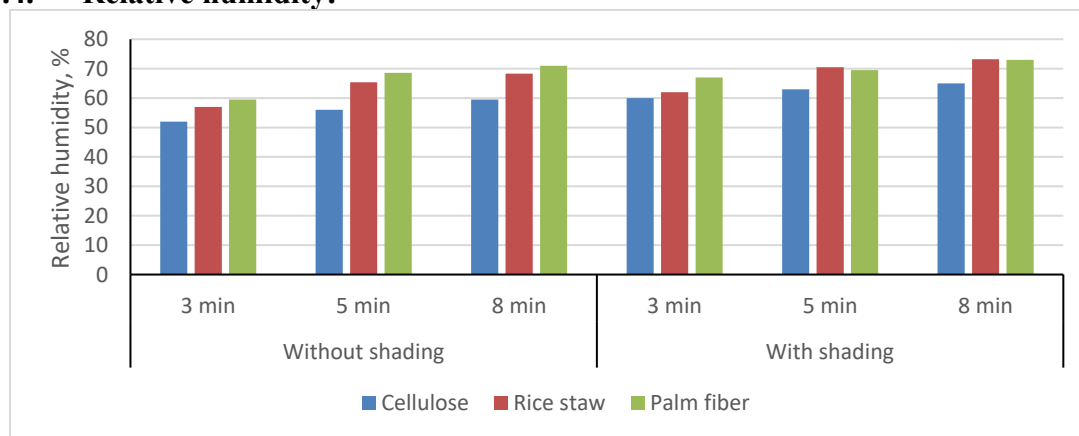


Fig. 11. Effect of Pad material and stopping period on relative humidity with and without shading at 1 pm .

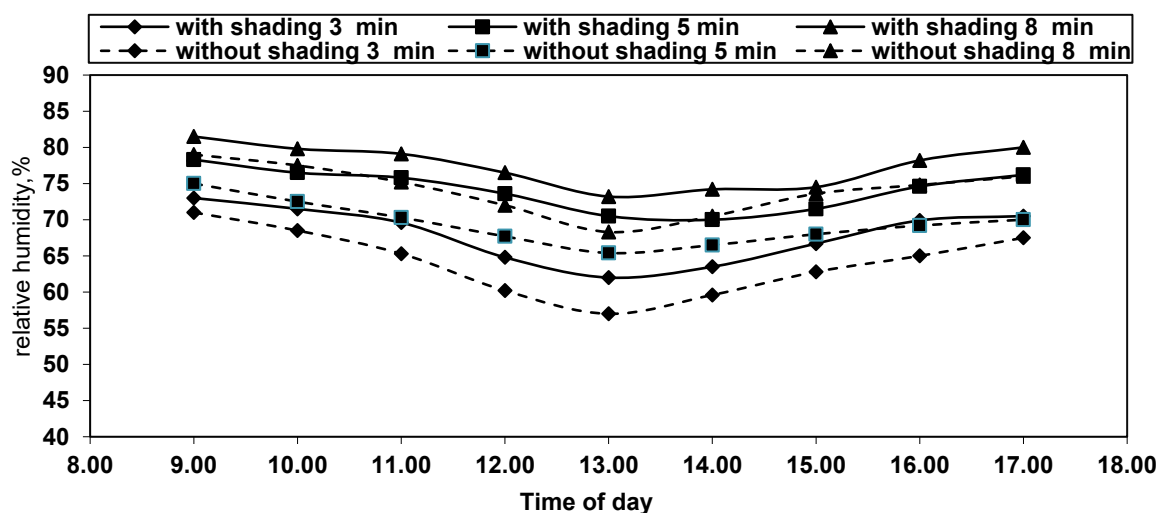


Fig. 12. Relative humidity versus time of day at different fan stopping periods with and without shading for rice straw pad material.

Relative humidity generally increases as the fan stopping period increases from 3 mins to 8 mins, both with and without shading. This is because with longer fan stopping periods, less humid air is circulated



out, allowing humidity to build up. Relative humidity is consistently higher with shading compared to without shading for all fan stopping periods. This is because shading reduces air circulation and ventilation, trapping more moisture, (2). The largest differences in relative humidity with and without shading occur during mid-afternoon (13:00-15:00). At 3 mins fan stopping, the difference is 1.4% at 13:00 up to 2.1% at 15:00. At 8 mins fan stopping, the difference is 1.5% at 13:00 up to 2.8% at 15:00, (27). For every type of pad, the relative humidity rose in tandem with an increase in the fan stopping period. Humidity for rice straw pads varied from 57% to 71% after three minutes of halting. After five minutes, it rose to 65.4–75% and, after eight minutes, 68.3–79%. Before the fans started ventilation, the prolonged fan resting period allowed for more evaporation and moisture buildup inside the greenhouse. (24). The addition of shading increased the relative humidity by 5-12% for each pad type and fan stopping period. This is likely because shading decreased the temperature, allowing moisture to accumulate more readily in the cooler air.

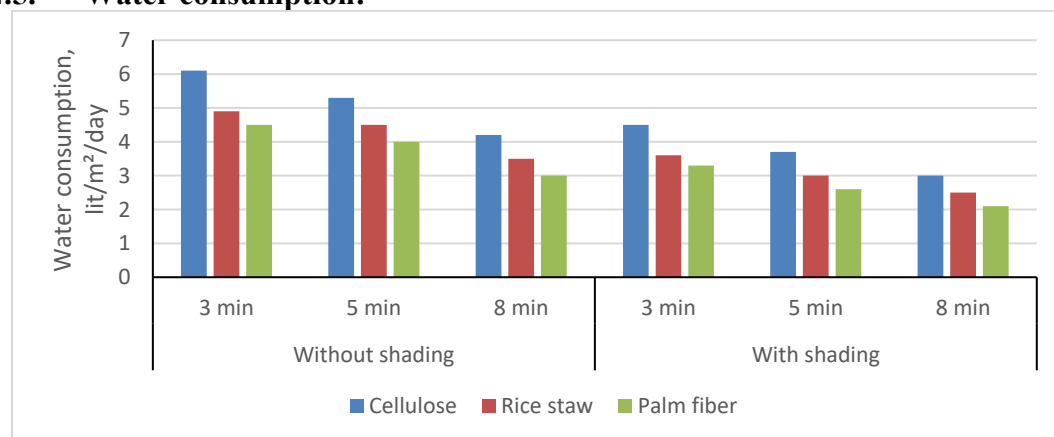
As shown in table 1, Palm fiber pads led to significantly ( $p \leq 0.01$ ) higher RH at 68.100% than rice straw at 66.233% and cellulose at 59.250%. RH increased significantly from 59.583% at 3 min, to 65.667% at 5 min, up to 68.333% at 8 minutes ( $p \leq 0.01$ ). Shading significantly ( $p \leq 0.01$ ) increased RH to 67.133% over no shading at 61.922%.

Interactions: Significant interactions between all main effects of pad type, stopping period, and shading (all  $p \leq 0.01$ ). This indicates complex interdependent relationships between these factors in impacting relative humidity. For instance, adding shading increased relative humidity more for the palm fiber pads (from 61.767% without shading to 68.1% with shading) compared to the smaller RH increase for cellulose pads with shading (from 56.900% to 59.250%).

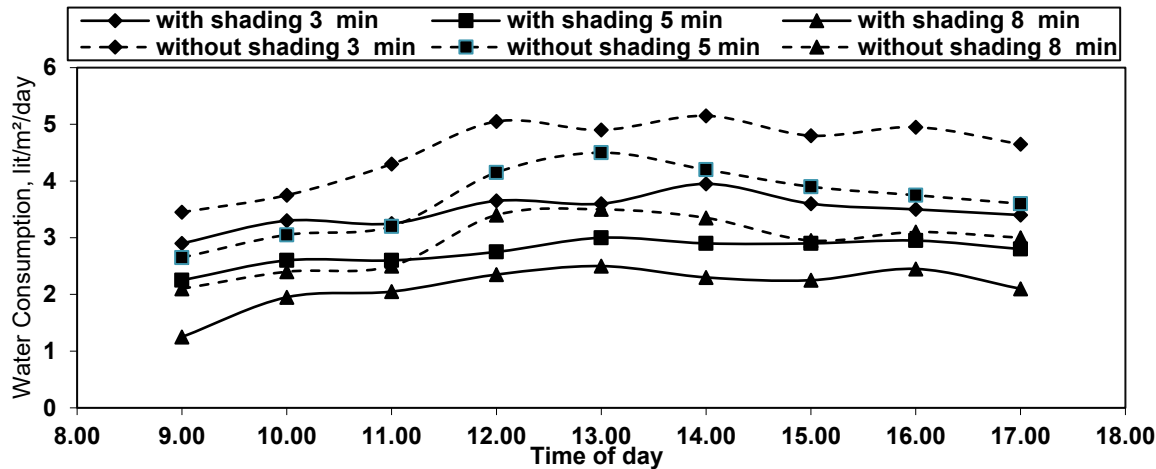
The ANOVA revealed highly significant main effects of pads materials, stopping periods, and shading on relative humidity ( $p \leq 0.01$ ), indicating these factors strongly influence humidity levels. Additionally, all interaction effects were statistically significant, suggesting combinations of pads materials, stopping periods, and shading have varying impacts on humidity. Stopping periods exhibited the largest F-statistics, meaning this factor accounted for the most variability in the response.

In summary, the greenhouse's highest relative humidity levels were achieved with the palm fibers cooling pad and prolonged fan halting periods. Shading added a marginally higher amount. While higher humidity is necessary for plant growth and transpiration, many crops may be more susceptible to fungal infections at levels exceeding 70%. Based on the unique requirements of each crop and the surrounding climate, the best pad material, fan schedule, and shading strategy should be chosen.

#### 4.5. Water consumption:



**Fig. 13. Effect of Pad material and stopping period on water consumption with and without shading at 1 pm.**



**Fig. 14. Water consumption versus time of day at different fan stopping periods with and without shading for rice straw pad material.**

The data indicates that both shading and increasing fan stopping periods significantly reduce evaporative cooling water consumption, especially during hot afternoon conditions. For example, from 12-1pm with 8-minute stops, shading reduced use from 4.1 to 2.92 lit/m<sup>2</sup>/day (28.78% reduction). But with 3-minute stops, it reduced use from 6 to 4.6 lit/m<sup>2</sup>/day (34.14% reduction). Using these strategies together provides the best water savings., (28).

Without shade, the fan stopping time for all pad materials rose from three to eight minutes, resulting in an increase in water usage. The most water-consuming materials were cellulose pads, which were followed by rice straw and palm fibers pads. On the other hand, shade significantly decreased the amount of water used for all pad materials and fan stop times. For instance, compared to unshaded settings, shading reduced water consumption by 30.2% for cellulose pads, 33.34% for rice straw pads, and 38.1% for palm fibers pads during a 5-minute halting period. The reduced water consumption with shading is likely because shading decreases ambient air temperature around the evaporative cooler, reducing the saturation drop and evaporative demand. The lower evaporation rate results in less water consumption to maintain the cooling effect., (24).

As shown in table 1, Cellulose pads consumed significantly ( $p \leq 0.01$ ) more water at 4.4667 lit/m<sup>2</sup>/day, versus 3.6667 lit/m<sup>2</sup>/day for rice straw and 3.25 lit/m<sup>2</sup>/day for palm fiber. Lower stopping times led to significantly ( $p \leq 0.01$ ) higher consumption, from 3.05 lit/m<sup>2</sup>/day at 8 minutes to 3.85 lit/m<sup>2</sup>/day at 5 minutes and up to 4.4833 lit/m<sup>2</sup>/day at 3 minutes. No shading had significantly ( $p \leq 0.01$ ) higher consumption at 4.44 liters versus with shading at 3.1444 liters.

Interactions: Significant interactions found between pad type and stopping period ( $p \leq 0.01$ ) as well as between pad type and shading ( $p \leq 0.01$ ). Water consumption increased more substantially for cellulose pads (by 1.1167 liter) versus palm fiber pads (0.5167-liter increase) when going from 8 min to 3 min stopping times. Similarly, not having shading led to a higher water consumption increase for cellulose pads (1.3056 liter) versus palm fiber pads (0.8056 liter).

The analysis of variance revealed that pads materials, stopping periods, and shading all had highly significant main effects on water consumption (all  $p \leq 0.01$ ), indicating that varying these factors substantially impacted the mean water consumption. Overall, ANOVA provides strong statistical evidence that pads materials, stopping periods, shading, and their interactions significantly influence water consumption under the conditions tested.

In summary, the results indicate that shading and selecting pad materials with suitable properties can substantially reduce water consumption in evaporative coolers, while still providing efficient cooling. Lower fan stopping periods also increase water consumption.



#### 4.6. Vapor Pressure Drop (VPD):

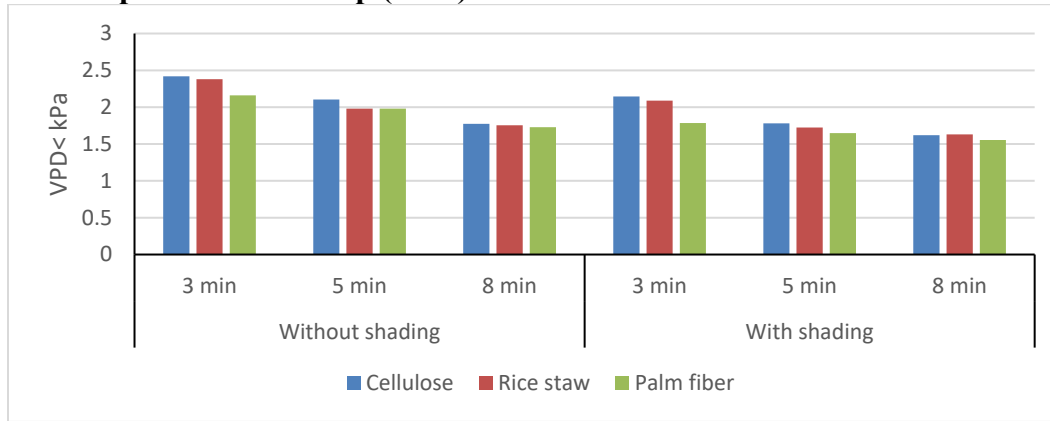


Fig. 15. Effect of Pad material and stopping period on VPD with and without shading at 1 pm.

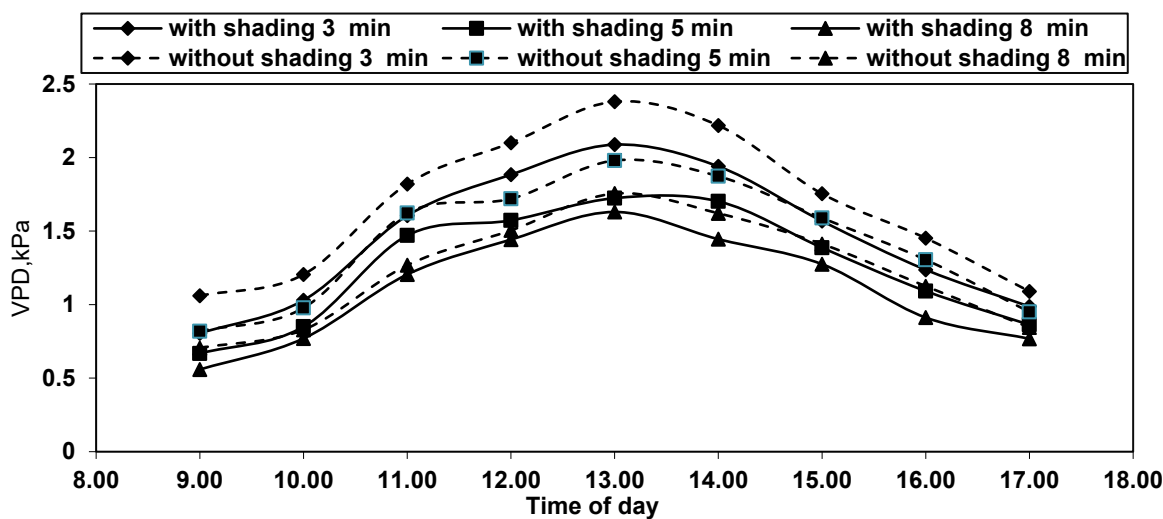


Fig. 16. VPD versus time of day at different fan stopping periods with and without shading for rice straw pad material.

The results show that (VPD) decreases with increasing fan stopping period for all pad materials and shading conditions. For no shading, VPD decreased from 2.42 to 1.775 kPa for cellulose, 2.38 to 1.755 kPa for rice straw, and 2.16 to 1.728 kPa for palm fibers as fan stopping increased from 3 to 8 minutes. With shading, VPD decreased from 2.145 to 1.619 kPa for cellulose, 2.088 to 1.63 kPa for rice straw, and 1.784 to 1.554 kPa for palm fibers, (29).

When cellulose pads were compared to other pad materials, they showed the highest VPD, followed by rice straw and palm fibers. Comparing cellulose to rice straw and palm fibers, the former had a VPD of 2.38 kPa and the latter 2.16 kPa during a 3-minute fan halting period without shadowing. Greater evaporation and consequent humidification are made possible by cellulose's more porous structure and larger surface area. Because they are more compact, palm fibers pads evaporate less water and have less of an effect on VPD. according to (30).

VPD was greatly decreased by shading all pad materials and fan stopping times. Shading reduced the VPD average for cellulose from 2.16 without shading to 1.784 kPa with shading, for rice straw from 2.38 to 2.088 kPa, and for palm fibers from 2.42 to 2.145 kPa with shading during a 3-minute fan stopping time. Shading reduces plant transpiration and fibers warmth by obstructing direct sunlight. As a result, the greenhouse's VPDs are reduced, and less moisture is extracted from the air. The longer fan stopping periods were associated with the greatest reduction in VPD with shade.

As shown in table 1, Cellulose pads resulted in significantly ( $p \leq 0.01$ ) higher VPD at 1.9741 kPa compared to 1.9322 kPa for rice straw and 1.8098 kPa for palm fiber pads. Longer stopping periods



significantly ( $p \leq 0.01$ ) decreased VPD from 2.1696 kPa at 3 mins to 1.6769 kPa at 8 mins. No shading led to significantly ( $p \leq 0.01$ ) higher VPD at 2.0362 kPa versus with shading at 1.7745 kPa.

Interactions: Significant interactions found between pad type and stopping period ( $p \leq 0.01$ ), stopping period and shading ( $p \leq 0.01$ ), and pad type, stopping period, and shading ( $p \geq 0.05$ ).

The three-way interaction between pad type, stopping period, and shading on VPD was not significant ( $p \geq 0.05$ ). This suggests the two-way interactions described above better explain the interdependent effects on VPD rather than the combination of all three factors.

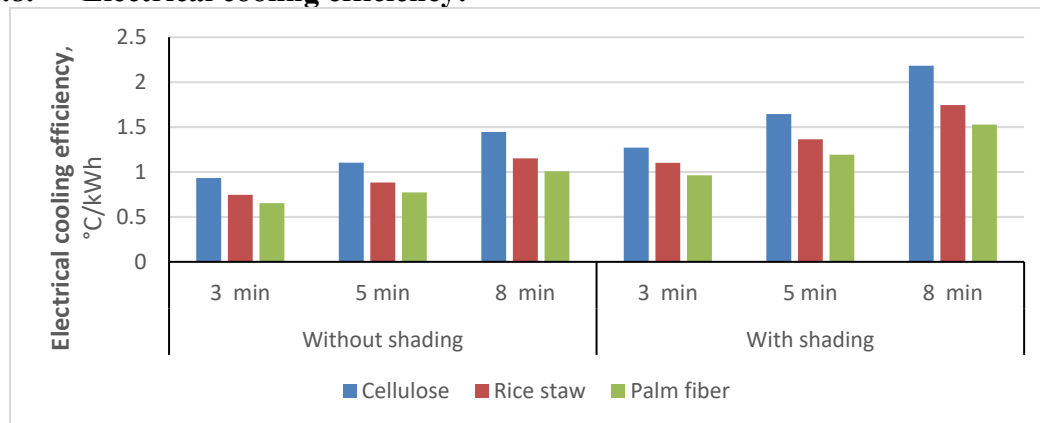
The Analysis of Variance (ANOVA) table for the measurement VPD (Vapor Pressure Drop) was examined. The table revealed significant sources of variation in the data. Specifically, the factors "Pad materials," "stopping periods," and "Shading" demonstrated highly significant effects on VPD, with F-statistics on the order of  $1E+12$  to  $1E+11$  and  $p \leq 0.01$ , indicating their strong influence on the observed variation.

In summary, increasing fan stopping period, using more porous pad materials like cellulose, and implementing shading can all help reduce vapor pressure drop inside greenhouses. Lowering the VPD creates a more favorable environment for plant growth and production. Further testing could examine the interactions between these factors and optimize conditions for specific crops.

#### 4.7. Energy consumption:

Energy consumption according to the devices and equations mentioned above is constant for each off period where the power is forced to be off and on by a timer, and the energy consumption values are determined based on the capacity of the cooling fans and water pump and the actual operating time of the system (on and off periods). A 3-minute off period achieved an energy consumption of 9.44 kWh/day, while a 5-minute off period achieved 6.75 kWh/day, and an 8-minute off period achieved 4.72 kWh/day. This is logical because the energy consumption per hour is 2.95 kWh for the pump and cooling fans, and a 3-minute off period achieves 3.2 actual operating hours per day, while a 5-minute off period achieves 2.29 hours of operation per day, and an 8-minute off period achieves 1.6 hours of operation per day.

#### 4.8. Electrical cooling efficiency:



**Fig. 17. Effect of Pad material and stopping period on electrical cooling efficiency with and without shading at 1 pm.**

Electrical cooling efficiency is the ratio of temperature drop to energy consumption. The higher the value of the efficiency index, the higher the cooling efficiency and energy consumption. Figure.16, shows that the cellulose pad achieved the highest electrical cooling efficiency, followed by rice straw and then palm fiber. The longer the stop period, the higher the electrical cooling efficiency. Without shading, the cellulose pad recorded an electrical cooling efficiency of 0.93, 1.1, and 1.4 °C/kWh, respectively, at system stop periods of 3, 5, and 8 minutes. On the other hand, the presence of shading increases electrical cooling efficiency. When shaded, the rice straw pad recorded 1.1, 1.36, and 1.7 °C/kWh at stop periods of 3, 5, and 8 minutes, respectively. This is explained by the fact that when the



system's downtime increases from 3 to 5 and 8 minutes, the actual daily operating hours decrease and energy consumption decreases. However, this decrease in energy consumption does not correspond to a decrease in cooling capacity. This is because the temperature was measured three times: at the beginning, middle, and end of the downtime period, and the average of the three measurements was taken. Since the average temperature decrease was significant relative to energy consumption, the results are shown in the following figure.

In summary, we see that the electrical cooling efficiency index is not the only indicator for choosing the pad type, downtime duration, and shading type. Furthermore, using rice straw padding with a shading system and a 3-minute downtime period achieves reliable and effective cooling and electrical cooling efficiency compared to commercial cellulose pads, which can achieve excellent results during downtimes of 3 minutes and acceptable results up to 5 minutes.

#### 4.9. Crop production parameters:

Stem length and diameter and leaves number and width:

The results obtained for stem length and diameter under different treatments are shown in Table 2. The analysis of variance of the results showed that there were significant differences ( $P = 0.05$ ) in stem length and diameter between the treatments. It was found that the stem length and diameters (96 and 1.44 cm, respectively) under the conditions of the greenhouse cooled by straw pads were the lowest compared to the other greenhouses, which could be attributed to increased relative humidity and reduced temperature. This result is in line with the findings of (26) who indicated that a high relative humidity may cause weakening of the growth of a crop.

Table 2: Stem length and diameter and leaves number and width inside and outside the greenhouses.

Treatment	Length of stem (cm)	Stem diameter (cm)	Leaves number	Leaves width (cm)
Straw pads	96.0 c	1.44 d	30 c	5.5 c
cellulose pads	175.5 b	2.50 c	55 b	7.8 b
Palm fibers pads	210.5 a	3.80 b	75 a	10.4 a
Outside	20.0 d	5.10 a	9 d	3.0 d
SE±	0.43	0.35	0.45	0.70
CV%	13.42	21.23	11.66	12.43

Note: Means in the same column(s) followed by the same letters(s) are not significantly different according to Duncan's Multiple Range Test.

#### 5. Conclusion

- Experiments were conducted to evaluate three types of evaporative cooling pads (cellulose, rice straw, and palm fiber) in greenhouses, with and without shade, and at three fan-off intervals (3, 5, and 8 minutes).
- Temperature, humidity, water usage, vapor pressure drop, cooling efficiency, energy consumption, and electrical cooling efficiency were measured hourly from 9 am to 5 pm daily.
- Shading, pad type, and fan-on/off significantly affected temperature reduction.
- Cellulose pad achieved the best results in most measurements except water consumption, followed by rice straw pad, while palm fiber pad performed the worst.
- The rice straw pad achieved cooling efficiency of 61–71.5% under shade, and 57–62.5% without shade.
- The rice straw pad achieved good electrical cooling efficiency, ranging from 1.1-1.75 °C/kWh, in shaded mode, and was the most energy-efficient alternative to commercial cellulose.
- 50% shading achieved excellent results in reducing the thermal load, reducing system operation times, and helping the alternative pads maintain suitable greenhouse conditions in Egyptian conditions.
- System operation times varied, but the best results were achieved with 3-minute off periods without shade and 5-minute off periods with shade.



- The rice straw pad achieved a cooling temperature of 10.4 °C, 62% humidity, 71.5% cooling efficiency, and a water consumption of 3.5 lit/m<sup>2</sup>/day.
- We recommend using the rice straw pad as an alternative to agricultural waste with 50% shade and a 2-minute on/5-minute off period, or without shade and a 3-minute off period.

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