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PERFORMANCE EVALUATION OF A SUSTAINABLE EVAPORATIVE COOLING SYSTEM USING COOLING PAD BASED ON AGRICULTURAL RESIDUES

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ABSTRACT: The present study evaluates the performance and economic viability of three evaporative cooling pad materials cellulose, rice straw, and palm fiber for small-scale greenhouse applications. The research examined the effects of air velocity (0.5, 1.0, and 1.5 m/s), and water flow rates (3, 5, and 7 L/min.m²) on cooling effect, relative humidity, water consumption, cooling efficiency, energy consumption, and operating costs. Experiments were conducted from July to August 2020, when the ambient temperature peaked at 44.4°C. Among the materials tested, cellulose pads demonstrated the highest cooling efficiency at 81.45% with a thickness of 100 mm, an air velocity of 1 m/s, and a water flow rate of 7 L/min.m². Rice straw followed with a cooling efficiency of 76.26%, and palm fiber recorded 72.57% under the same conditions. While cellulose pads performed best, local materials like rice straw and palm fiber provided acceptable, cost-effective alternatives, with rice straw achieving the lowest operating cost at 1.1 EGP/h, compared to cellulose at 1.21 EGP/h and palm fiber at 1.16 EGP/h for optimal conditions. It can be recommended to use rice straw pads as the most suitable option for small-scale greenhouse operations in developing regions, as they offer an optimal balance between cooling efficiency and cost-effectiveness. In scenarios where maximum cooling efficiency is of paramount importance and budget constraints are less critical, cellulose pads are advised. It is essential that all cooling systems operate at the identified optimal parameters of 100 mm pad thickness and 1 m/s air velocity to maximize efficiency while minimizing resource consumption.

Keywords: Evaporative cooling system, fan and pad, local pads, straw pad, and water flow rate.

INTRODCTION

Greenhouses are extremely important in Egypt's agricultural development and have been widely applied in reclaimed desert areas owing to the perfect growing conditions maintained by these facilities throughout the year. The infrastructure is critical to protecting crops against harsh desert conditions with optimized resource use. In semi-arid countries like Egypt, where temperatures are habitually higher than the optimum mark for crop development, effective cooling can be considered as the basis for successful, productive agriculture. With global warming increasing Earth's temperature and agricultural activities extending to semi-arid regions, temperature control in greenhouses has become a significant challenge. In such semi-arid conditions, cooling systems are a high necessity for maintaining an optimal environment; controlled temperatures increase yields by 20-40% in comparison with uncooled environments **(Chen and Wang 2019)**. Among various cooling methods, the evaporative cooling systems have emerged as predominant with a considerable edge regarding energy efficiency and effectiveness in cooling.

For hot, dry climates, which comprise a large section of the nation, evaporative cooling systems are revolutionary. These systems have two advantages: they use a lot less energy and are less harmful to the environment than

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conventional air conditioners. According **(Elmetenani, et al. 2011)**, their low energy demand makes them perfect for solar power, which is a readily available and sustainable energy source in these regions. They also tell us that if simple direct evaporative air coolers were used in place of half of the conventional cooling devices in the southwest United States, 18 million barrels of oil would be saved annually.

Evaporative cooling systems are based on the adiabatic cooling principle, where air temperature decreases with the evaporation of water. In reality, evaporative cooling systems have proved very efficient in greenhouses, with research showing that they can lower the internal temperature by 10-15°C compared to ambient conditions **(Kittas, et al. 2003)**. The technology mainly comes in two forms: fan-pad systems and fog/mist systems, with the former being more widely used because it is reliable and easy to maintain.

However, conventional evaporative cooling system installation is very costly for small-scale greenhouse operators. Commercially available cooling pads, made mainly from cellulose materials, are one of the major investment costs. This financial burden has influenced the search for alternative solutions that will make the cooling technology affordable to small-scale farmers with a minimal compromise on cooling efficiency.

The importance of low-cost greenhouse development in advancing sustainable agriculture is also highlighted by **(Chen and Wang 2019)**. The study underlines how important it is to have reasonably priced, energy-efficient greenhouse designs that make advantage of renewable energy sources. The authors offer suggestions for improving greenhouse building techniques to boost energy economy and lessen environmental effect.

Recent designs have focused on developing cooling media from locally available farm by-products. These have several advantages: these are readily available, low in cost and offer minimal environmental hazards. Research work carried out by **(Ahmed, et al. 2011)** has demonstrated that agricultural residues materials such as sliced wood pads and Celdek cellulose pads are capable of giving cooling efficiencies comparable to commercial cellulose pads but at a much lower installation cost.

Several studies have reported the technical feasibility of these new materials. For instance, cooling pads made of date palm fiber in the studies conducted by **(Al-Sulaiman 2002)** could achieve a temperature reduction in the range of 4-13°C with cooling efficiencies within the range of 85-92%. On the other hand, rice straw-based cooling media has also given encouraging results; studies reported that its cooling efficiency exceeds 80% under favorable conditions. **(Ahmed, et al. 2011)**.

The cooling media that aids in the evaporation of water is a crucial part of evaporative cooling systems. Traditionally, this cooling medium has been constructed from synthetic or cellulose pad materials, which are pricy, non-biodegradable, and may require regular maintenance. The use of residues materials from agriculture as an alternative cooling media has piqued the interest of experts recently. There are various advantages to this strategy. It encourages sustainability in the environment by making use of garbage that would otherwise be dumped. It may also lower the cost of cooling medium, which would enable smaller producers to use it. Lastly, according to **(Warke and Deshmukh 2017)**, these byproducts might even have natural qualities that increase cooling effectiveness and provide further advantages like improved air quality and illness prevention. Due to the high expense of conventional commercial cooling pads, researchers are looking for more widely available and reasonably priced local alternatives. The goal is to decrease the environmental effect, improve moisture retention, and encourage biodegradability using agricultural byproducts, such as natural fibers containing cellulose **(Ndukwu and Manuwa 2014)**. This quest for substitutes is especially critical for crop production during the off-season, when temperature management is critical. Numerous techniques have been created by researchers to reduce air temperatures and enhance conditions for both plants and livestock. In hot and dry areas, evaporative cooling is considered to be efficient, practical, and financially feasible for greenhouses and poultry buildings since it may successfully reduce temperatures by 4 °C to 13 °C **(Dağtekin, et al. 2009)**. It is imperative to assess the performance of appropriate, locally sourced materials because commercial cooling pads can be costly, particularly for rural agricultural structures **(Chopra and Kumar 2017)**. Numerous investigations have been done on potential evaporative cooling materials, such as date palm fibers (stem), jute, and luffa fibers **(Al-Sulaiman 2002)**.

Additional research looked at straw pads, sliced wood pads, and celdek cellulose pads **(Ahmed, et al. 2011)**. The pads made of sackcloth, jute fiber, and coconut coir **(Alam, et al. 2017)**. Luffa pad with activated carbon foam **(Aziz, et al. 2018)**. Bamboo fiber, coconut coir, khus, and celdek **(Chopra & Kumar, 2017)**. Leaflet, leaf base, bulb, and roots are among the local palm tree "Nakheel" residues **(Almaneea, et al. 2022)**. Despite these substantial researches, there aren't many studies that concentrate on the application of palm fibers and straw pads as wetted pad materials in evaporative cooling systems. Air temperature has a significant impact on greenhouse plant growth, yield, and seedling germination, according to research by **(Abdel-Galil 2010)**. During hot days, increasing the amount of shade (63% and 75%) successfully lowered the temperature but also raised the humidity. These results highlight how crucial it is to weigh the advantages and possible disadvantages of design and environmental management techniques when maximizing greenhouse conditions for productive plant production.

The integration of these alternative cooling media into the greenhouse systems reflects a promising trend for sustainable agriculture in semi-arid regions. Based on the use of local materials and economies of scale with reductions in implementation costs, these works make efficient cooling systems affordable to small farmers, while encouraging environmental sustainability by putting agricultural residues to productive use.

This synthesis of agricultural residues uses and cooling technology addresses not only the economic problems of small-scale greenhouse operators but also contributes to the wider objectives of sustainable agriculture and resources conservation in the semi-arid region. Further development and optimization of such systems will amount to scaling up sustainable greenhouse agriculture in Egypt and other similar climatic regions.

The objective of the present study is to evaluate, comprehensively and comparatively the efficacy of three evaporative cooling pad materials, namely commercial cellulose, rice straw, and palm fiber, for use in small greenhouses in hot and dry environments. The study specifically at finding inexpensive and locally available means of cooling farming settings. The aim of the study was to provide solutions for small-scale farmers in the developing countries where there is little electricity and high heat. In doing so, it sets out to bring about an alternative sustainable low-cost system in comparison with conventional cooling systems. Determine how agricultural residues may give rise to new cooling technologies in order to use resources efficiently, reduce costs, and support year-round cultivation in harsh weather conditions.

MATERIALS AND METHODS

Study Site

The initial experiment was conducted during the summer of 2020 in Awlad Saqr (31°01' N latitude and 31°46' E longitude), Sharqia Governorate, Egypt. The region has a hot, dry, desert climate with average high temperatures of 38.7°C during summer. The experiment was carried out by building a low-cost greenhouse provided with an evaporative cooling system to determine the best coefficients in terms of the type and thickness of the cooling pad, water flow rate and air velocity.

Greenhouse Design and Construction

A Hoop house (Quonset) shape was chosen for the greenhouse with dimensions of 4 m Width and 6 m length and a radius of 2 m. With 3 semicircular brackets distributed every 1.5 m of the length of the greenhouse and longitudinal tensioners along the length of the greenhouse on both sides of the greenhouse and on its top, with a window on the front and back for the cooling pad and fan as shown in Fig. 1.

The axis of the greenhouse was orientated from East to West so that the cooling pad is in the western direction and the fan is in the east direction to reduce solar radiation inside the greenhouse and take advantage of the north-west winds in Egypt. The frame is made of smooth soft steel (mild bar) with a diameter of 8 mm, has a rank of 28/45, the northern and southern sides of the greenhouse are made of two bars of the mild steel with the installation of stands and supports to resist wind load and stresses, the frame is also installed in the ground with cement bases with a depth of 80 cm, Supports were also placed vertically in the middle of each arch, from the ground to the top of the arch, to resist the arch from bending downward. The roof is covered with a single layer of UV-protected polyethylene (200 μm thickness, 90% light transmittance).

Evaporative cooling system

The primary factors influencing the thermal comfort of a plant are temperature and relative humidity, which can be regulated using evaporative cooling systems. Evaporative cooling technology involves the exchange of heat and moisture between air and cooling water. In this study, a direct evaporative cooling (DEC) system was utilized to cool the greenhouse environment during hot summer periods. The direct cooling pad unit was installed on the southern side of the structure, as illustrated in Fig. 2. The greenhouse is equipped with a square fan with a side length of 50 cm shown in Fig. 3, powered by a 220 V motor with an output power of 90 W for the fan to rotate at a rotational speed of 1380 rpm. The fan was strategically positioned on the southern wall, directly across from the air intake, a deliberate decision made during the house's design process

Cooling pad

Initial experiments were conducted to determine the best thickness of the cooling pad, which became clear that the best thickness from an operational and economic standpoint is 100 mm. A commercial cellulose pad was used as a standard pad, and two pads manufactured from local agricultural residues were used (a rice straw pad and a palm fiber pad) due to the permeability of these materials and their ability to absorb water, shown in Figs. 5,6, and 7. They are also made of organic, environmentally friendly agricultural materials that are widely available in Egypt, which achieves a double benefit. Since it is cheap residues for farms compared to commercial cellulose pads, and to help in making beneficial use of agricultural residues, a wooden frame was made for the cooling pad with an area of 1.8x1 m^2 and a thickness of 10 cm and closed on both sides with wide wire mesh for air to pass through it. The wooden frame was pierced at the top with several holes (every 5 cm) to leak water along the length of the pad. The frame was installed in the middle of the northern side of the greenhouse at a height of 0.4 m from the ground, shown in Fig. 4, and opposite it on the other side was the cooling fan at a height of 0.75 cm from the ground.

Water pump and tank

Three different types of pumps were utilized to provide varied water flow rates 3, 5, 7 L/min since the evaporative cooling system depends on the water being distributed to all areas of the machine at a regular and uniform rate. The first pump has two hose clamps and is a G Ganen 4002 type 12V DC freshwater pump. Fig. 6 illustrates a 12 V diaphragm pump self-priming sprayer pump with a pressure switch that can be adjusted to 4.5 l/min 110 PSI for RV campground and marine yacht lawns.

The second pump is shown in Fig. 7, ZQ-7002 model 12V diaphragm water pump, 7-9 L/min, 150 PSI, 12 V DC freshwater pump self-priming sprayer pump with pressure switch adjustable.

The third pump is shown on Fig. 8, Model: EC-B10-10LH, DC 24V 20W, mute brushless water pump submersible impeller centrifugal pump water head 5m 10 L/min rockery circulating pump.

The water tank in this experiment is a cement tank under the cooling pad, its size is 1.8x0.5x0.15 m^3, and water is pumped from it to the pad via a pump and receives the water falling from the pad to pump it again.

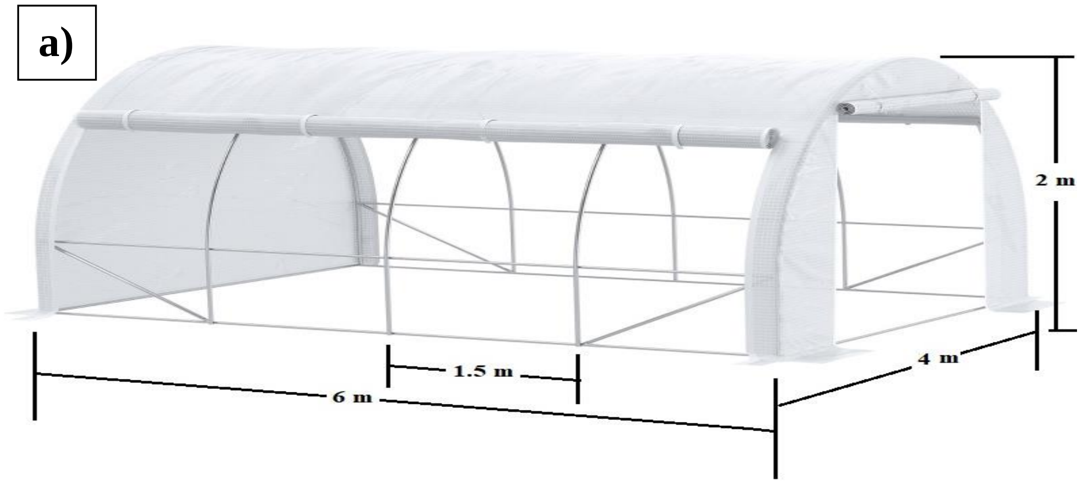
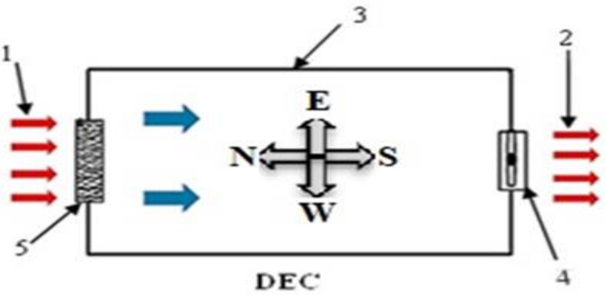


Fig. 1. a) Schematic diagram b) pictorial view of the used single quonset style greenhouse



1. The air entering the greenhouse (hot air) 2. The air coming out of the greenhouse
3. Greenhouse 4. ventilation Fan 5. Cooling pad, 6. Cooling fan.

Fig. 2. A schematic diagram of greenhouse orientation

Fig. 3. Cooling fan used in the experiment

Fig. 4. Rice straw cooling pad is installed in the middle of the northern side of the greenhouse

Fig. 5. The flow of water on the cellulose pad

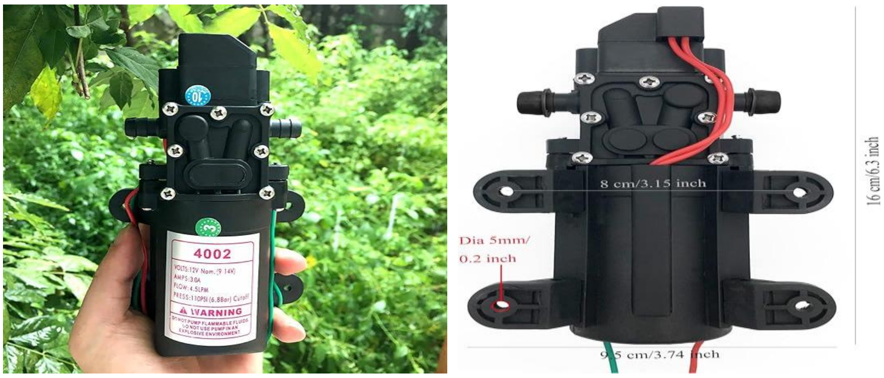


Fig. 6. Water pump model G Ganen 4002

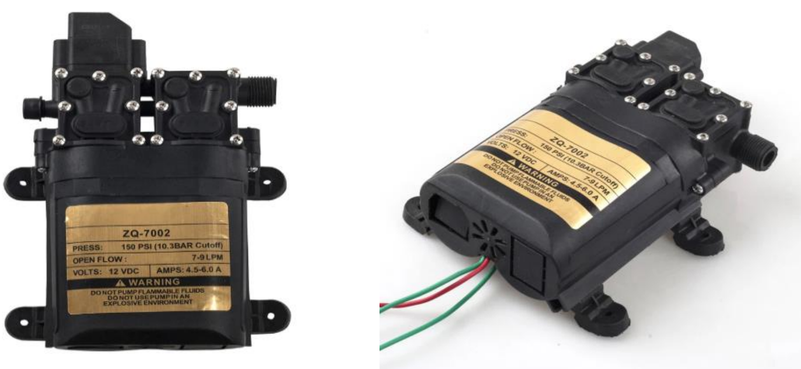


Fig. 7. Water pump model ZQ-7002

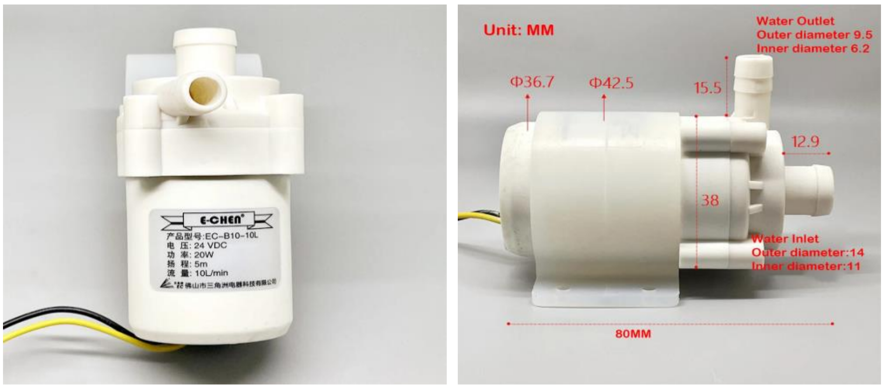


Fig .8. Water pump model EC-B10-10LH

Instrumentation

Throughout the studies, the air's internal and external temperatures were recorded at hourly intervals. Temperature was measured with an accuracy of ± 1 ºC, humidity with an accuracy of ± 3.5%, and air speed with an accuracy of ± 3% using the Tenmars Electronics Company's TM-40 X series. Copper thermocouples with a 0.85 mm diameter were used to measure the water temperatures at the input and outflow. Every thermocouple was immediately linked to a digital millimeter after being calibrated.

The pyranometer was mounted on a horizontal plane at 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, ±2% accuracy, Sensirion).

Methods

The performance evaluation of agricultural residues materials was experimentally done under the following parameters:

- Three different types of cooling pads (cellulose, rice straw and palm fiber).
- Three different water flow rates on the cooling pad (3, 5 and 7) l/min.m^2.
- Three different speeds of air flow through the pad (0.5, 1 and 1.5) m/s.

Measurements

The measurements focused on during the experiment were cooling effect, inside and outside air relative humidity, water consumption, cooling system efficiency, energy consumption and cost calculation.

Pad surface area

The surface area of pad depends on amount of air to be displaced per minute and velocity of air through the (pad_{area}) was determined from the following equation according to **(Liao and Chiu 2002):**

$$pad_{area} = \frac{q_{air}}{v_{air}} \quad \ldots\ldots\ldots\ldots\ldots \textbf{(1)}$$

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.

$$q_{air} = vol_{gh} \times f_{gh} \quad \ldots\ldots\ldots\ldots\ldots \textbf{(2)}$$

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.

Evaporative cooling efficiency

Cooling efficiency depends on ambient temperature, relative humidity, and the wet temperature. The cooling efficiency (ɳ cooling) was determined from the following equation according to , **(ASHRAE 2010):**

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

Where T_{db-out} is the air temperature before the cooling pad at °C, T_{db-evp} is the temperature of the cooled air leaving the cooling pads at °C, and T_{wb-out} is the humidified air temperature before the cooling pad in °C.

Operating cost

Total cost (TC) assessment for different components used of operating systems was analyzed and calculated according to **(Liu, Rasul et al. 2010)**,

$$\mathbf{TC = TFC + TVC} \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

Where TFC is total fixed cost (EGP) and TVC is Total variable cost (EGP).

Electrical energy consumed for cooling system equipment (pcs) per watt. Power consumption includes fan and pump power. The consumed power of ECP was obtained as follows according to **(Sohani and Sayyaadi 2017)**,

$$\mathbf{Pcs = pcs_{fan} + pcs_{pump}} \quad \ldots\ldots\ldots \quad (5)$$

where pcs_{fan} per watt is the power consumption of the fan and is calculated by:

$$\mathbf{pcs_{fan} = W_a\, \eta_{fan}\, C} \quad \ldots\ldots\ldots\ldots \quad (6)$$

$$\mathbf{W_a = Q_{air}\, Pt} \quad \ldots\ldots\ldots \quad (7)$$

$$\mathbf{Q_{air} = Zn\, V_{green}} \quad \ldots\ldots\ldots \quad (8)$$

Where W_a is the air power, W, η_{fan} is the fan efficiency, %, Q_{air} is the volumetric flow rate, m^3/s, Zn is the air change number to be removed from the greenhouse, which is taken as 0.75 times/minute according to **(Joseph 1994)**; V_{green} is the greenhouse volume, m^3 and Pt is the total pressure of the fan, N/m^2

$$\mathbf{Pt = Ps + P\upsilon} \quad \ldots\ldots\ldots\ldots \quad (9)$$

$$\mathbf{P\upsilon = 0.5\, \rho\, \upsilon^2_{air}} \quad \ldots\ldots\ldots\ldots \quad (10)$$

Where Ps is the static pressure, $P\upsilon$ is the kinetic pressure, ρ is the air density, υ_{air} is the air velocity, m/s, C is the safety factor, 1.25 dimensionless.

Present maintenance cost

$$\mathbf{P_M = C_M \left[\frac{((1+i)^{20}-1)}{(i\times(1+i)^{20})}\right]} \quad \ldots\ldots \quad (11)$$

Where P_M= Present maintenance cost (EGP), C_M= Annual maintenance and repairs cost (taken 2% of capital cost) and i = Interest rate (taken 10%).

Cooling effect (Δ T):

The temperature difference between the outside of the greenhouse (T_{ao}) and the inside of the greenhouse (T_{ai}) was used to describe the performance of evaporative cooling systems. The temperature difference between outside and inside the greenhouse (ΔT) was calculated using the following equation:

$$\mathbf{\Delta T = T_{ao} - T_{ai}} \quad \ldots\ldots\ldots \quad (12)$$

Where: Tao: The air stream's outlet dry bulb temperature (°C) and Tai: The air stream's inlet dry bulb temperature (°C) according to **(Abdel-Rahman 2020).**

Consumed energy

A device that measures the amount of electrical energy used by the experimental system. The Engineering Industries Company in Egypt is where this electric meter was acquired.

RESULTS AND DISCUSSION

The climatic conditions of the experimental site

The climate data collected from 1st July to 31 August 2020, between 6 am and 6 pm, provided an overall understanding of the weather conditions affecting the greenhouse. The environmental parameters for the experimental region were represented by solar radiation, ambient temperature, and relative humidity. Data values were collected at regular intervals throughout the day for each month as shown on Fig. 9. The collected data in July and August between 6:00 am and 18:00 pm revealed a progressive rise in solar radiation from the early morning hours until its peak values of 1377 and 1380 w/m^2 at midday. Subsequently, the radiation levels declined. The ambient temperature increased from 27.5 ºC at 6:00 am to reach its peak of 43.25 ºC at 13:00 pm and then declined to 29.3ºC at 6 p.m. The air relative humidity started the day at a high level of 62.7% and steadily decreased until it reached its lowest level of 43.6% at 13:00. It then gradually increased again and reached 54.72% at 18:00.

In August, the recorded data exhibited a similar trend to July in all parameters, with a little elevation in radiation, temperature, and relative humidity. The climatic data indicated a steady rise in solar radiation until its peak value at 1392 w/m^2 at 13:00 pm, followed by a clear declination throughout the rest of the day until dusk. The data collected indicates that the maximum recorded ambient temperature was around 44.4ºC at 13:00 pm, while the lowest relative humidity measurement was about 46.8% at 12:00 pm.

Temperature Reduction and Relative Humidity

Fig.10 shows the effect of varying water flow rates on cooling effect difference between outside and inside the greenhouse and relative humidity under different air velocities and different water flow rates of the Three pads experience. The data collected showed that the behavior of the temperature drop increased steadily throughout the day until 13:00 noon and then decreased later. The opposite also happened for relative humidity, as it started with higher values in the morning and then gradually decreased until it reached 13:00 noon and then returned to increase again, and this It is expected that the hotter the air becomes, the less its ability to saturate with moisture, and this happens largely in the afternoon and later. This trend was revealed by the influence of weather conditions

As for the decrease in temperature, it is clear to us from the results that the lowest decrease in temperature between outside and inside the greenhouse is in the morning, then this decrease increases until it reaches its peak in the afternoon, then it begins to decrease again until 5 pm in all the cooling pads used. This is because the thermal load inside the greenhouse in the morning is low, and the humidity is high, and the air is saturated with water vapor. As for the effect of the type of pad on the temperature reduction, the cellulose pad achieved the best result, followed by rice straw, then palm fiber, with values of 9.46 ºC for cellulose, 7.73 and 6.66 ºC for straw, then palm fiber at 1 pm at an air speed of 1 m/s and a water flow rate of 5 L/min.m^2. As for the effect of air speed, at 1 pm and a water flow rate of 5 L/min.m^2, the cellulose pad achieved a decrease of 7.51, 9.46 and 8.4 ºC at air speeds of 0.5, 1 and 1.5 m/s, respectively. While rice straw achieved 6.56, 7.73 and 7.28 ºC, and palm fiber achieved 5.6, 6.66 and 6.73 ºC, respectively. As for the effect of water flow rate, at 1 pm and air speed of 1 m/s, the cellulose pad achieved a decrease of 8.72, 9.46 and 10.55 ºC at water flow rate of 3, 5 and 7 L/min.m^2 respectively. While rice straw achieved 6.98, 7.73 and 8.40 ºC and palm fiber achieved 5.86, 6.66 and 7.55 ºC respectively.

On the other hand, relative humidity is generally highest in the morning and begins to decrease until noon and after, then begins to increase again, in contrast to temperature. The effect of the type of pad on the relative humidity values, it is clear from the results, as it was noted that the palm fiber pad achieved the highest relative humidity values, followed by rice straw, then cellulose pad, as at 1 pm and an air speed of 1 m/s and a water flow rate of 5 L/min, palm fiber achieved 62.378%, rice straw 60.89 and cellulose 58.91%, while the air speed had an inverse effect on the relative humidity, as the higher the air speed, the lower the relative humidity, as at 1 pm and a 5 L/min.m^2 water flow rate, the cellulose pad achieved a relative humidity of 62.1, 58.91 and 57.72% for speeds of 0.5, 1 and 1.5 m/s respectively, while the rice straw pad achieved 63.35, 60.89 and 59.66%, while the results of palm fiber were 64.89, 62.37 and 61.11% for the same air speeds respectively, Results also clarified the effect of water flow rate on relative humidity through the results, as the water flow rate increases, the relative humidity inside the greenhouse increases. For example, at 1 pm and at an air speed of 1 m/s, the cellulose pad achieved 56.80, 58.91 and 63.40% at flow rates of 3, 5 and 7 L/min.m^2, while the rice straw was 57.72, 60.89 and 63.81%, while the relative humidity using palm fiber was 59.20, 62.37 and 65.50% at the same rates, respectively.

Water consumption and cooling efficiency

Fig.11. shows that the water consumption is lowest in the morning, then rises until it peaks in

the afternoon, and then falls once again until 5 pm for all cooling pads. This is due to a low thermal load, high humidity, and water vapor saturation of the air within the greenhouse in the morning. When it came to the impact of pad type on water consumption, the cellulose pad performed best, followed by rice straw and palm fiber. At 1 pm, with an air speed of 1 m/s and a water flow rate of 5 L/min.m^2, the cellulose pad had a value of 9.00 L/m^2.day, while the straw had values of 8.5 and 8.25 L/m^2.day. Regarding the impact of air speed, the cellulose pad obtained consumption of 8.00, 9.00, and 8.55 L/m^2.day at air speeds of 0.5, 1, and 1.5 m/s, respectively, at 1 pm and a water flow rate of 5 L/min.m^2. In contrast, palm fiber obtained 7.8, 8.25, and 7.82 L/m^2.day, and rice straw obtained 7.90, 8.50, and 8.10 L/m^2.day. Regarding the impact of water flow rate, the cellulose pad obtained consumption of 8.10, 9.00, and 9.8 L/m^2.day at water flow rates of 3, 5, and 7 L/min.m^2 at 1 pm and air speed of 1 m/s, respectively. In contrast, palm fiber produced 7.5, 8.25, and 8.75 L/m^2.day, whereas rice straw produced 7.75, 8.5, and 9.4 L/m^2.day.

In contrast to relative humidity, cooling efficiency is often lowest in the morning and increases until midday and beyond, after which it starts to decline once more. The results clearly show how the kind of pad affected the relative humidity values, with the cellulose pad achieving the greatest values, followed by rice straw and palm fiber pads. There is evidence that shows how pad type affects cooling efficiency, for instance, palm fiber attained 68.4%, rice straw 71.31, and cellulose 77.27% at 1 pm, 1 m/s air speed, and 5 L/min.m^2 water flow rate. Air speed affects cooling efficiency as well. at instance, the cellulose pad demonstrated a cooling efficiency of 72.68, 77.27, and 76.74% at speeds of 0.5, 1, and 1.5 m/s, respectively, at 1 pm and a water flow rate of 5 L/min.m^2, For the same air velocity, the palm fiber values were 63.63, 68.4, and 66.31%, respectively, For the same air velocity, the palm fiber values were 63.63, 68.4, and 66.31%, respectively, but the rice straw pad obtained 66.23, 71.31, and 68.85%. It is evident that Results show that cooling efficiency is influenced by water flow rate; as water flow rate rises, cooling efficiency rises as well. For instance, the cooling efficiency using palm fiber was 63.90, 68.40, and 72.57% at the same rates, while the cellulose pad obtained 73.73, 77.27, and 81.45% at flow rates of 3, 5, and 7 L/min.m^2 at 1 pm and an air speed of 1 m/s. The rice straw achieved 66.81, 71.31, and 76.26% at the same rates

Energy consumption

Energy consumption within the system depends on the duration, speed, and operating capacity of the fan, as well as the water pump and the amount of artificial lighting.

Energy consumption of cellulose pad

Fig.12. showed that the cellulose pad achieved the highest energy consumption rate among the tested pads, followed by palm fiber pad, then rice straw pad. The effect of air speed on energy consumption is clear from the data, as at a water flow rate of 5 L/min.m^2, a speed of 0.5 m/s achieved a consumption of 1.79 kWh, while speeds of 1 and 1.5 m/s achieved a consumption of 1.97 and 2.43 kWh. The effect of water flow rate on energy consumption. At a speed of 1 m/s, a water flow rate of 3 L/min.m^2 achieved a consumption of 1.68 kWh, while a rate of 5 and 7 L/min.m2 achieved a consumption of 1.97 and 2.17 kWh.

While for rice straw pad, the results show the effect of air speed on energy consumption, as it is at a water flow of 5 L/min.m^2 and a speed of 0.5 m/s resulted in a consumption of 1.59 kWh, but speeds of 1 and 1.5 m/s produced consumptions of 1.75 and 2.16 kWh, demonstrating the evident impact of air speed on energy consumption. It was demonstrated how water flow rate affected energy use, a rate of 3 L/min.m^2 produced a consumption of 1.49 kWh at a speed of 1 m/s, but rates of 5 and 7 L/min.m^2 produced consumptions of 1.75 and 1.93 kWh, respectively.

On the other hand, palm fiber pad achieved intermediate results between cellulose and rice straw, as, for example, at an air speed of 0.5 m/s, the energy consumption was 1.71 kWh at a water flow of 5 L/min.m^2, but speeds of 1 and 1.5 m/s produced consumptions of 1.87 and 2.28 kWh, indicating the clear influence of air speed on energy consumption. The impact of water flow rate on energy consumption was illustrated. At a speed of 1 m/s, a rate of 3 L/min.m^2 resulted in a consumption of 1.61 kWh; however, rates of 5 and 7 L/min.m^2 caused consumptions of 1.87 and 2.05 kWh, respectively.

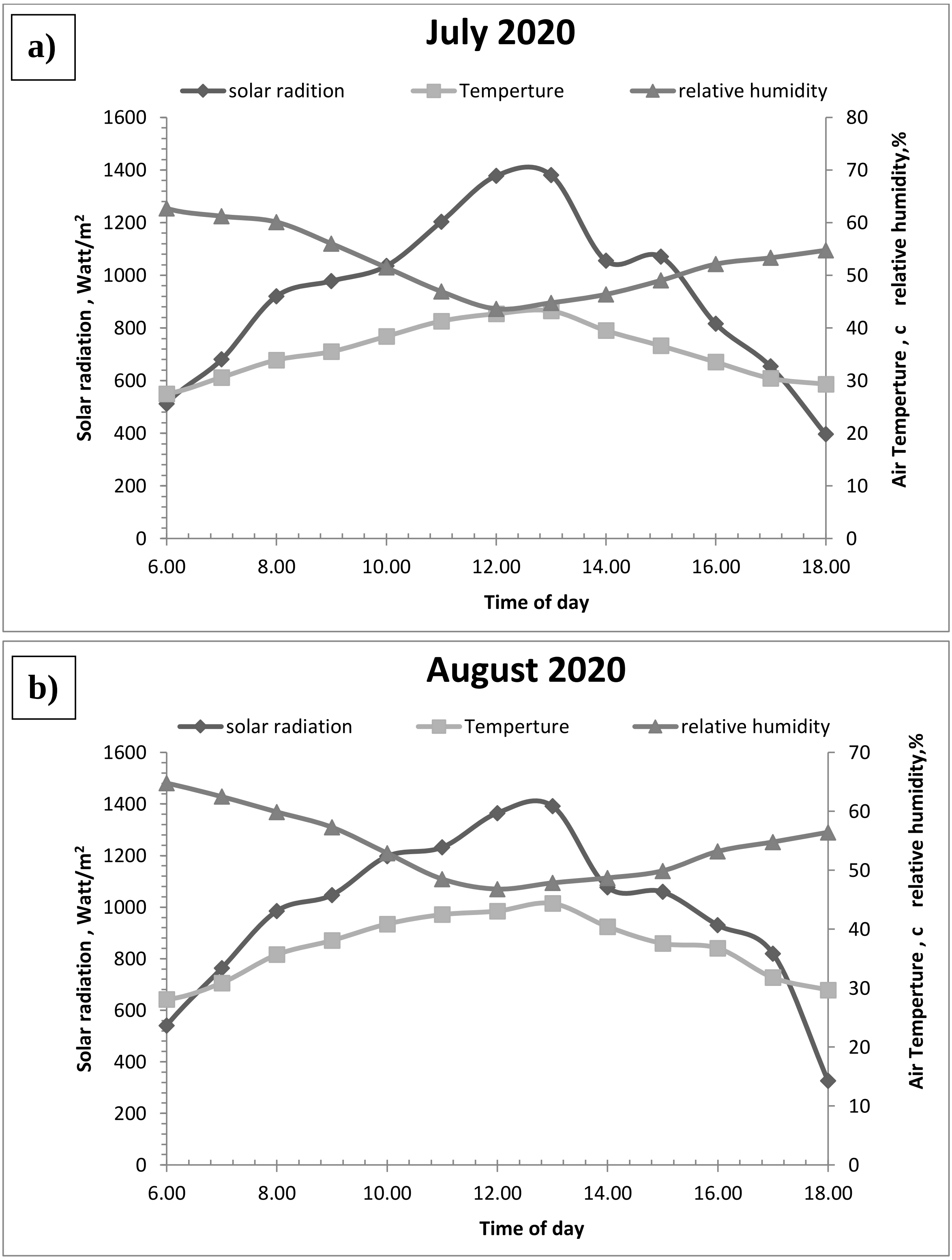


Fig. 9. Climatic conditions such as temperature, solar radiation, and relative humidity of the experimental area outside the greenhouse during a) July 2020 b) August 2020

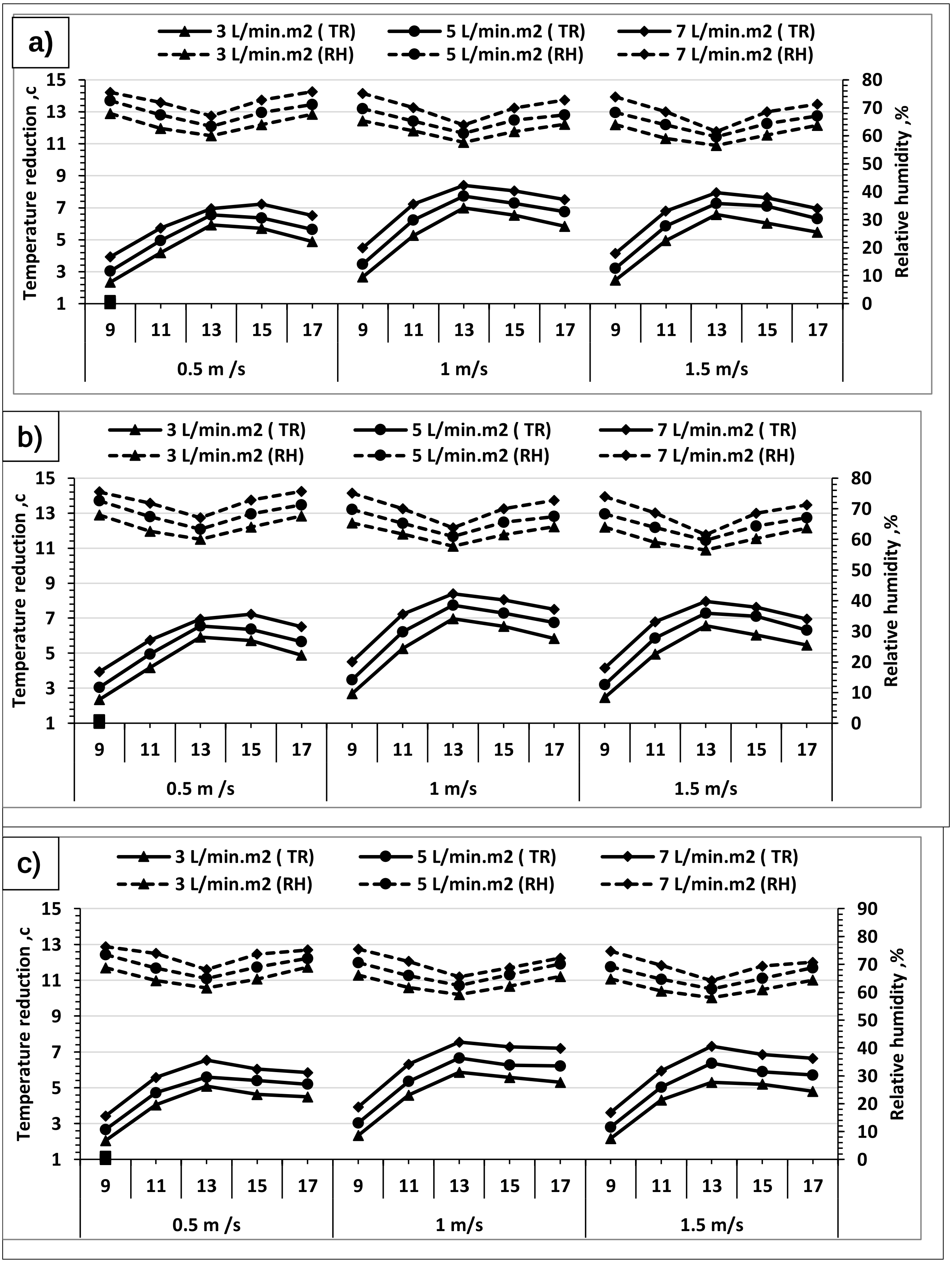


Fig. 10. Variation in temperature and relative humidity during the day depending on the water flow rate and air speed for a) cellulose pad b) rice straw pad c) palm fibers pad

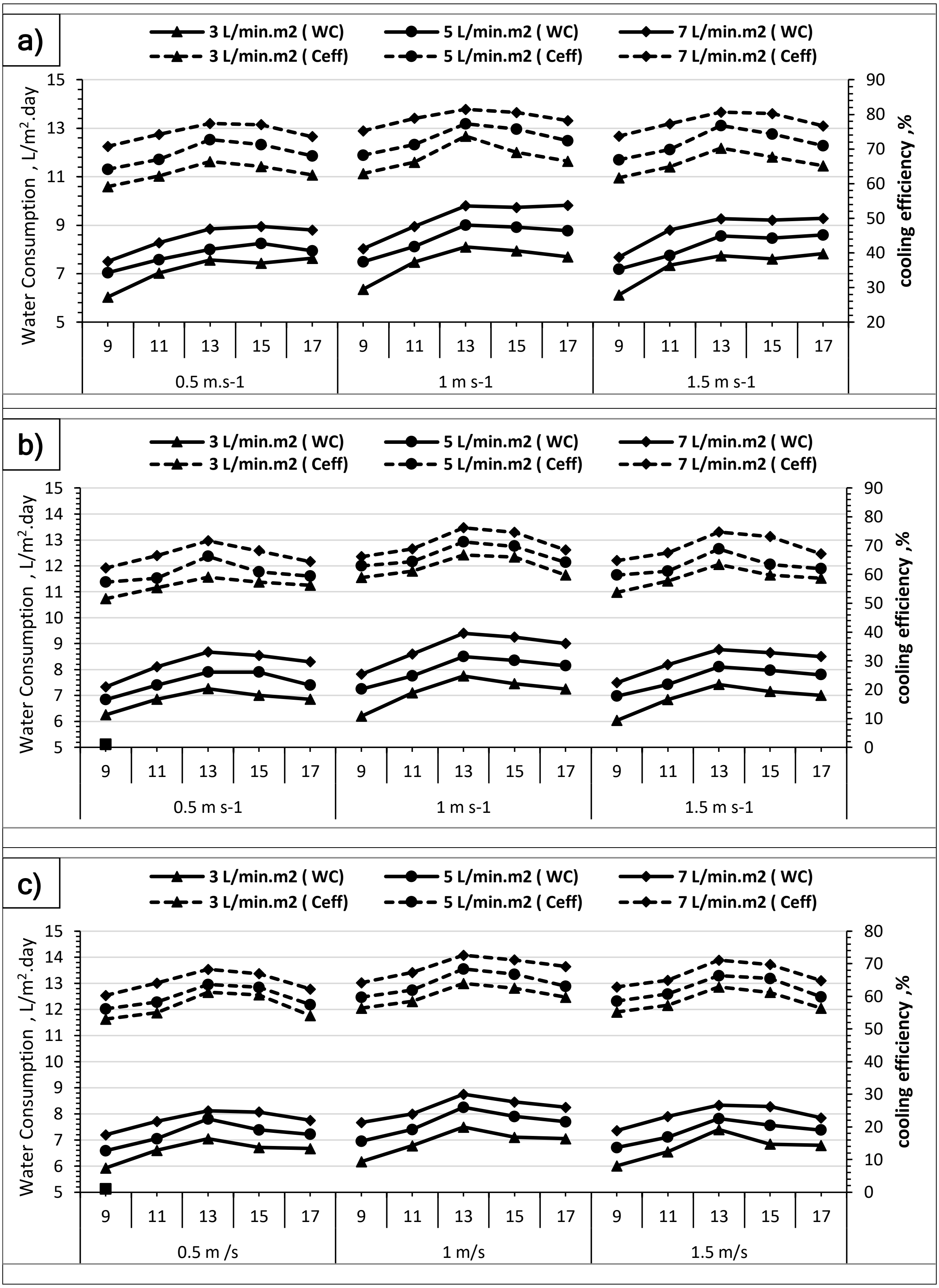


Fig. 11. Variation in water consumption and cooling efficiency during the day depending on the water flow rate and air speed for a) cellulose pad b) rice straw pad c) palm fibers pad

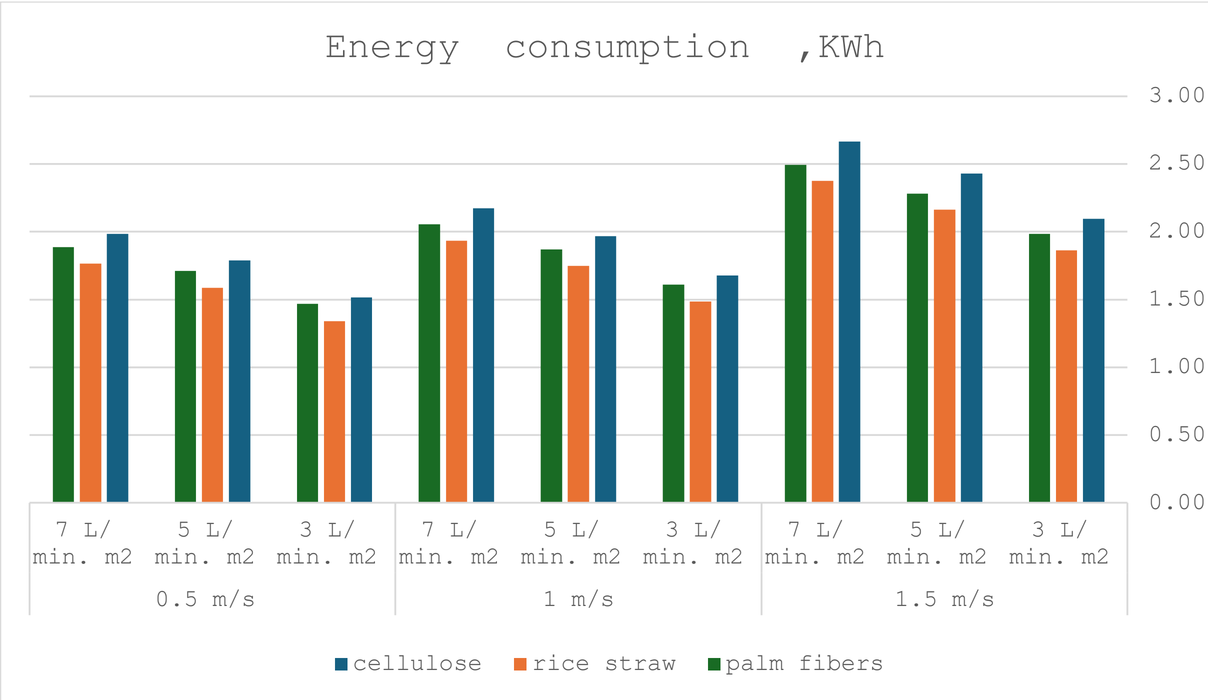


Fig. 12. The effect of pad type, air speed, and water flow rate on energy consumption

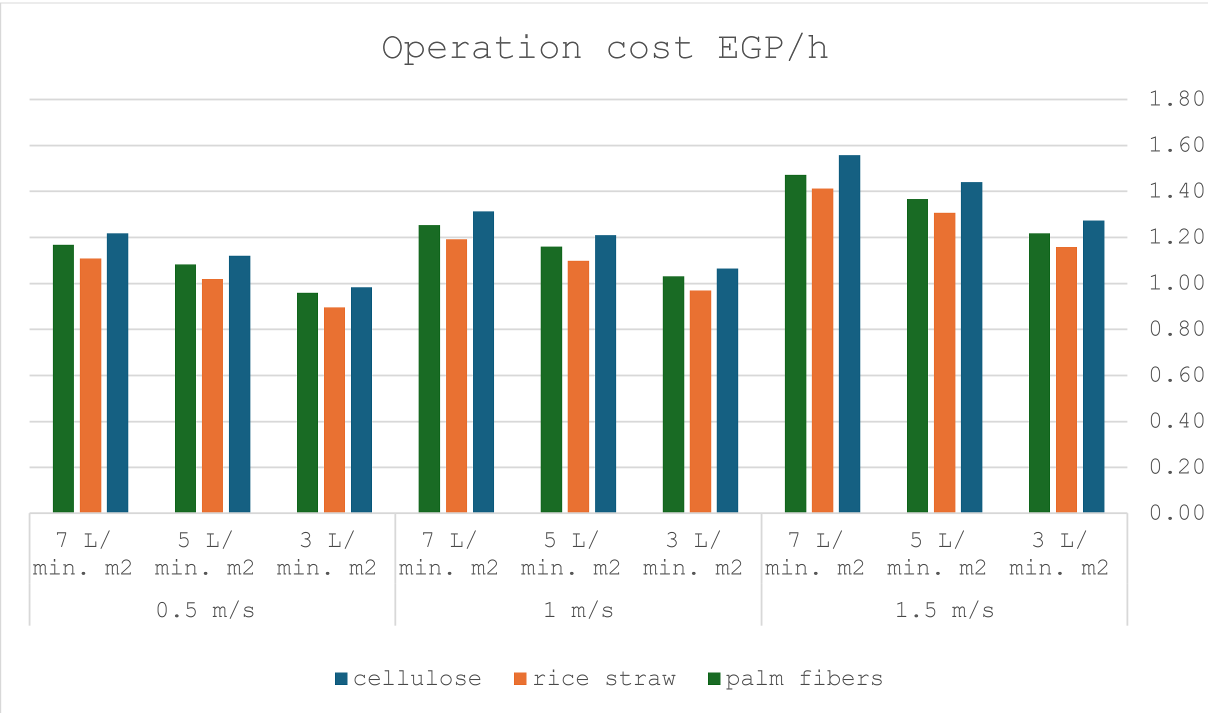


Fig. 13. The effect of pad type, air speed, and water flow rate on operating cost

Operational cost

The total costs depend on the variable costs represented by energy consumption costs as well as the fixed costs represented by construction and installation costs. The operating costs are affected by the capacity of the pump and fan used to achieve the required air velocity and water flow rate, while the construction costs consist of the cost of constructing the structure and cover and purchasing the pumps and fans according to their capacity. The distinguishing factor in the construction costs is the type of pad, as the cost of cellulose pad is higher than using pad made from agricultural residues such as rice straw or palm fiber. The cellulose pad achieved the highest value for operating costs, followed by palm fiber by a small margin, followed by rice straw pad.

Fig.14. shows us the effect of the type of pad, water rate, and air speed on the total operating costs, including fixed costs in a distributed manner. The cellulose pad at a water flow rate of 5 L/min.m^2 and a speed of 0.5 m/s achieved a cost of 1.12 EGP/h, while speeds of 1 and 1.5 m/s achieved a cost of 1.21 and 1.44 EGP/h. The effect of water flow rate on operating cost was shown. At an air speed of 1 m/s, a rate of 3 L/min.m^2 achieved an operating cost of 1.06 EGP/h, while a rate of 5 and 7 L/min.m^2 achieved a cost of 1.21 and 1.31 EGP/h.

While for rice straw pad, the results show the effect of air speed on operating cost, at a water rate of 5 L/min.m^2 and a speed of 0.5 m/s resulted in a cost of 1.02 EGP/h, whereas speeds of 1 and 1.5 m/s produced costs of 1.1 and 1.31 EGP/h. This indicates that air speed has a significant impact on operational costs. It was demonstrated how the water flow rate affected operational costs. Operating costs at a rate of 3 L/min.m^2 at a speed of 1 m/s were 0.97 EGP/h, whereas rates of 5 and 7 L/min.m^2 were 1.1 and 1.19 EGP/h.

On the other hand, the palm leaf pad achieved operating costs of 1.08 EGP/h at an air speed 0.5 m/s was 1.08 EGP/h and a water rate of 5 L/min.m^2, whereas the cost of 1 and 1.5 m/s were 1.16 and 1.37 EGP/h, respectively.

Conclusion

This study conducted an in-depth evaluation of the performance of three evaporative cooling pad materials: cellulose, rice straw, and palm fiber, for small-scale greenhouse applications under the hot and arid conditions of Egypt. The detailed examination of the influence of air velocity, water flow rates, and pad materials on Temperature difference between outside and inside the greenhouse, relative humidity, water consumption, cooling efficiency, energy consumption, and operating costs is presented.

Results showed unequivocally that cellulose pads achieved the highest cooling efficiency, recorded at 81.45%, followed by rice straw at 76.26% and palm fiber at 72.57%. Such results were invariably observed under optimal conditions defined by a pad thickness of 100 mm, an air velocity of 1 m/s, and a water flow rate of 7 L/min.m^2. The study revealed that the temperature decrease was highest at noon time ranging between 6.66°C and 9.46°C depending on the nature of the pad material used.

From an economic point of view, this study shows that locally available agricultural residues materials may be an alternative cooling pad solution. The rice straw pad revealed the lowest operating cost compared to other evaporative pad materials: it was found to be about 1.1 EGP/h, while the operation costs of cellulose pads and palm fiber pads were approximately 1.21 and 1.16 EGP/h, respectively. This is very important for small-scale farmers in developing regions experiencing low-income conditions.

The research showed that for small-scale greenhouse operators, the study provides clear, actionable advice. Those bent on maximum cooling efficiency need to opt for cellulose pads, while those most concerned with economy should give preference to rice straw pads. Whatever the material employed, the thickness of pads must be kept at 100 mm and air velocity at 1 m/s for maximum work efficiency.

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تقييم أداء نظام تبريد تبخيري مستدام في البيوت المحمية بإستخدام وسائد تبريد من المخلفات الزراعية

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تقوم هذه الدراسة بتقييم أداء ثلاثة أنواع من مواد وسائد التبريد التبخيري، وهي السليلوز وقش الأرز وألياف النخيل، ومدى جدواها الاقتصادية في تطبيقات البيوت الزراعية الصغيرة. وتتناول الدراسة تأثير سرعة الهواء (0.5 و1.0 و1.5 متر/ثانية) ومعدل تدفق المياه (3 و5 و7 لتر/دقيقة.م^2) على انخفاض درجة الحرارة، والرطوبة النسبية، واستهلاك المياه، وكفاءة التبريد، واستهلاك الطاقة، وتكاليف التشغيل. أجريت التجارب خلال شهري يوليو وأغسطس 2020، عندما بلغت درجة حرارة الجو ذروتها عند 44.4 درجة مئوية. من بين المواد التي تم اختبارها، أظهرت وسادة السليلوز أعلى كفاءة تبريد بنسبة 81.45%، عند سمك 100 مم، وسرعة هواء 1 متر/ثانية، ومعدل تدفق مياه 7 لتر/دقيقة.م^2. يليها قش الأرز بكفاءة تبريد 76.26%، وألياف النخيل بنسبة 72.57% في نفس الظروف. مع أن وسادة السليلوز كانت الأفضل أداءً، إلا أن المواد المحلية مثل قش الأرز وألياف النخيل توفر بدائل مقبولة من حيث التكلفة، حيث بلغت تكلفة التشغيل لوسادة قش الأرز 1.1 جنيه مصري/ساعة، مقارنةً بـ 1.21 جنيه مصري/ساعة للسليلوز و1.16 جنيه مصري/ساعة لألياف النخيل في الظروف المثلى .

توصي الدراسة بإستخدام وسادة قش الأرز كبديل جيد للبيوت الزراعية الصغيرة في المناطق النامية، لما توفره من توازن مثالي بين كفاءة التبريد وتكلفة التشغيل. أما في الحالات التي يكون فيها تحقيق أعلى كفاءة تبريد أمرًا بالغ الأهمية، مع مرونة في الميزانية، فيمكن استخدام وسادة السليلوز. من الضروري تشغيل جميع أنظمة التبريد وفق المعايير المثلى المحددة (سمك 100 مم وسرعة هواء 1 متر/ثانية) لتعظيم الكفاءة وتقليل استهلاك الموارد. سيفيد هذا البحث بشكل كبير المزارعين الصغار الذين يبحثون عن طرق تبريد فعالة منخفضة التكلفة لزراعة المحاصيل في البيوت الزراعية.

الكلمات المفتاحية: التبريد التبخيرى – المروحة والوسادة – وسائد تبريد محلية – قش الأرز.

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