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Solar powered evaporative cooled storage structure for storage of fruits and vegetables

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ABSTRACT

A solar powered evaporative cooled storage structure (ECSS) was designed and developed for storage of fresh fruits and vegetables to increase their shelf-life. The structure consists of a solar powered exhaust fan and cooling pump for providing water to the pads. Cooling pads of different materials such as wood shaving, khas and celdec were used. The system works on the principle of a simple desert cooler. The pads are wetted with the help of circulating water through a solar powered pump and an exhaust fan sucks the cool air through the pads of the structure. The areas for the cooling system considered were 2.25 m^2, 4.5 m^2, 6.75 m^2 and 9 m^2 respectively. The results showed that under the no-load condition, the average air cooling efficiency was highest for CELdek at 78.67%, compared to 73.82% for wood wool and 70.75% for khas pad material and the maximum difference in relative humidity (RH) and dry bulb temperature between ambient and inside the cooler was 59% and 14.6°C when these materials were used in all four sides in the ECSS. This environment helped in keeping the vegetables fresh for significantly more time. This is very useful in rural areas where there is shortage of electricity or its supply is erratic for storage of fresh fruits and vegetables.

Key words: Evaporative cooling, Solar energy, Storage of fruits and vegetables

Fruits and vegetables are highly perishable and if not properly handled at their optimum conditions after harvesting or during packaging or transportation; they easily deteriorate and become unsuitable for consumption (Verma and Joshi 2000). As indicated by Kitinoja *et al.* (2010) the world over postharvest losses are estimated at an average of 30-40% in fruit and vegetables before they reach the final consumer. Globally average postharvest losses in general for fresh produce are estimated at 30%. Basediya *et al.* (2013) reported that postharvest losses of fruit and vegetables in India went from 30 to 35%.

As indicated by Choudhury (2006) and Nunes *et al.* (2009), temperature and relative humidity are the two most important environmental factors influencing the quality and the storage life of fresh produce. Jain (2007) incorporates the gas composition surrounding the produce as an environmental factor that directly affects storage life of fruit and vegetables. Proper storage and transport practices of fruit and vegetables include control of temperature and relative humidity, air flow and maintenance of space between containers for satisfactory ventilation (Basediya *et al*. 2013). Maintenance of fresh produce quality requires correct application of optimum temperatures and relative humidity from harvest to the consumer (Paull 1999) and these variables are henceforth a genuine thought of this study.

Deterioration of fruits and vegetables during storage and transportation is generally affected by temperature (Getinet *et al*. 2008, Pathare *et al*. 2012). If the surrounding air temperature is decreased to create storage at optimum levels within four hours, the following are achieved; produce respiration rate is decreased; reduction of water loss from produce; concealment of ethylene production, and significant reduction of the development of microbial activity (Basediya *et al.* 2013).

Cooling has been recognized historically as a cold chain management tool to provide controlled environment for fresh produce (Ngcobo *et al*. 2012). There is therefore, a need to create appropriate cooling facility that is moderate and that compares well with the routine refrigeration system (Basediya *et al*. 2013).

In India hot and dry weather prevails for a noteworthy part of the year. Surrounding hot and dry weather is suitable for efficiently working of the ECSS (Jha and Chopra 2006, Vala and Joshi 2010). Perishable farming produce can be safely stored in ECSS. Evaporative cooling is the simplest and economic method for extending shelf life of fruits and vegetables and can also be used as ripening chamber for banana (Jha 2008, Okunade and Ibrahim 2011).

For regions where plenty of solar radiation is available the solar energy can be harnessed by mounting solar photovoltaic modules to operate the water pump and fan

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of the evaporative cooled system. Study was conducted on Solar PV powered cooling system for potato storage (Eltawil and Samuel 2007, Sharma and Samuel 2015).

In view of the above, a study was conducted to develop a solar powered evaporatively cooled storage structure for storage of fresh fruits and vegetables to increase their shelf-life. Different pad materials were used to evaluate their performance with regard to cooling efficiency of the storage structure. There seems to be success story of using solar energy to power evaporative cooled storage structure and this provides an opportunity to preserve or to extend the shelf-life of fresh produce. This is very useful for farmers in rural areas where electricity is not available or its supply is erratic.

MATERIALS AND METHODS

A theoretical design of the evaporative cooled storage structure (ECSS) was done considering the (a) Storage chamber, (b) Water circulation system and (c) Air circulation system. The theoretical configuration was translated to the actual design used for the development of the ECSS. The design considerations includes, design of evaporative cooler with locally available affordable material and a square or near to square room to ensure most economical and efficient storage as in that surface areas per total volume minimized the construction costs and reduce heat losses. The storage capacity limit of the chamber depends on farmers' requirement. The cooling load incorporates the fresh produce field heat at harvest and the respiratory heat production used to outline cooling load. The ventilation rate (m^3/s) serves to determine and to choose the right fan size. The cooling pad size influences the measure of water flow per unit time. The amount of water flow per unit time will help determine the pump size. Based on the theoretical design, an ECSS was built that will accommodate a maximum of 1 m^3 of storage capacity of fresh produce.

For convenience in operation, loading and unloading of the produce and the other maintenance practices at the field, the height of storage structure was taken as 1.6 m so that it should be easy to enter and work. The floor of the storage cabin was made 20 cm above the floor. The 20 cm gap between the ground and the storage cabin helps to reduce the losses of heat of structure directly through conduction to the ground. It also protects the structure from corrosion due to water accumulated on the ground during rainy season. It is made of 18 gauge MS sheet and supported by 1 inch angle iron. The ms sheet floor of storage cabin makes the bottom of the structure close to reduce the threat of rodents' entry. The total heat load of the structure considering the losses due to conduction, convection, radiation etc. was found as, 52233 kJ/day or 604.5 W, which is equal to 0.155 tonnes of refrigeration or the required ECSS cooling capacity.

The most important aspect of an evaporative air cooling is its water management system. The water distribution network consists of pipe network, a distribution and collection tank and a bottom channel to take the excess water to the tank. Evaporative cooler manufacturers recommend water flow rates to the evaporative cooling pad ranging from 4-6 l/min for each meter length of the distribution pad for coolers up to 1.8 m high. A flow rate of 5 l/min/m of distribution pad surface area for evaporative coolers up to 1.8 m high have been shown to work satisfactorily.

The water distribution system was fitted on the top of this frame and the water was distributed over the upper face of the evaporative pad by a tube, with many holes to drip the water evenly onto the pad face. The pipe was made of PVC, 25 mm in diameter and had 2 mm diameter holes drilled on 50 mm distance along the top of the distribution pipe. Pad was continuously kept wetted. As per the need, considering the frictional losses a 40 l/min underwater cooler pump was used for recirculation of water through the pad.

The water collected by the bottom gutter is returned to a sump from which the water is pumped to the upper distribution pipe or gutter. The gutter is made of 18 gauge GI sheet with the dimension of 10 × 10 cm all along the length of bottom of pad. The sump should have a minimum capacity of 30 l for each square meter area of the distribution pad for coolers in order to hold the water that drains back to the sump when the system stops. As per the availability a plastic water tank of 500 l was used as the sump tank. The water tank was periodically filled.

The selection of the type of pad used in the design was based on porosity, water absorption/evaporation rate of the material, availability, cost and ease of construction. Based on the these requirements three local available materials CELdek pad (50 mm thickness), Wood wool pad (50 mm thickness) and khas khas (*Vetiveria zizanoides*) mat (50 mm thickness) were used.

A negative pressure is needed to be created inside the structure which is a function of the pad and the fan, when this happens, air at a positive pressure rushes into the system through the pad. For proper air circulation, and the best desired airflow pattern, the fan was located at the central position at the top which allows air to be drawn through the pad area which in turn draws the cool air and expel the humidified air out. The axial-flow exhaust fan was fixed at the top of ECSS to control the relative humidity and reduce concentration of carbon dioxide released by stored produce inside the storage structure. The fan has 3 blades with sweep diameter 225 mm with other specifications of fans as 230 V, 48 Watt 50 Hz 1 phase AC and 1300 rpm.

The solar photovoltaic (SPV) system consists of 4 PV solar panels (100 Wp each), one solar inverter (1400 VA) and a battery bank (12V, 2 nos.). With the help of solar inverter DC electricity from the solar panels was converted into AC electricity to operate the fan and pump.

The research work was conducted to evaluate the performance of three types of evaporative cooling pads (CELdek pads, wood wool pads and khas pads) and four different pad areas [2.25 m^2 (pad at one side), 4.5 m^2 (pad at two sides), 6.75 m^2 (pad at three sides] and 9 m^2 (pad at four sides)] for the cooling in evaporative cooled storage structure. Their performance was evaluated based on difference in temperature, relative humidity and cooling efficiency.

RESULTS AND DISCUSSION

Performance of solar photovoltaic (SPV) system

Average solar intensity was measured at surface of solar PV panel and at horizontal surface at 10:00 am, 12:00 pm, 2:00 pm and 4:00 pm during the preliminary experiments. The maximum solar intensity was found as 1070 W/m^2 and 716 W/m^2 at 12:00 pm at the surface of solar panel and at the horizontal surface respectively.

The voltage (V_{oc}) and current (I_{sc}) of battery and inverter were measured at 10:00 am, 12:00 pm, 2:00 pm and 4:00 pm respectively to test the solar PV system performance. The maximum voltage and current of battery were found to be 30.76 V and 15.11 A, while the same for inverter were 31.5 V and 15.56 A respectively at 12:00 pm.

The average value of PV system power measured at battery terminal was found to be 387.1 W at 10:00 am. This value increased to 420.2 W at 12:00 pm and then decreased to 398 W at 2:00 pm and then 313.7 W at 4:00 pm due to decreasing solar radiation as the evening approached. The total energy per day (from 10:00 am to 4:00 pm), given by PV modules to the battery bank was 2.4 kWh (taking 400 W average power during 6 light hours). The consumption of energy per day was observed as 2.212 kWh, which was about 92.16 % of the power supplied by solar PV system.

These results showed that PV system is suitable to supply electricity to cover the load demand without utilizing energy from the electrical grid during the sunny days.

Effect of pad material and pad area on evaporative cooling at no-load

The ECSS was tested with three different pad materials and four distinctive pad areas at no load condition. The temperature and relative humidity values were measured for outside and inside storage atmosphere simultaneously, while the wet bulb temperature values were obtained from psychrometric chart.

There were changes in ambient and storage relative humidity/temperature with respect to change in pad area and pad materials in ECSS (Fig 1-3). The graphs clearly indicates that the difference between ambient and storage temperature increased with increase in the pad area irrespective of pad material. The reason for the above trend is that as the pad area increased the rate of heat transfer also increased due to increased area available for the heat transfer.

The results of ANOVA (Table 1) indicated that there was significance difference among the treatments. The individual effect of the variables, viz. pad area and pad material on air cooling efficiency was significant at 5% level of probability. The maximum air cooling efficiency was obtained by the evaporative cooled storage structure when covered from all sides. It might be due to the fact that with increase in heat transfer area the difference between ambient and storage temperature increased which results in elevated air cooling efficiency.

There was influence of pad area and pad material on air cooling efficiency (Table 2 and 3). It is evident from the results that the CELdek pad material gave maximum performance due to uniform thickness and particle size distribution throughout the surface area. The results indicated the ECSS covered with commercial cellulose pads (CELdek) media from all the four sides performed better.

Effect of different pad area and pad material on temperature and relative humidity

The temperature and relative humidity were recorded for inside and outside the ECSS with different type of evaporative cooling pads and pad areas at different ambient conditions. Each of the experiments was started at 10 am and further readings were taken at 1 pm and 4 pm (Fig 1-3).

The ambient air-dry bulb temperature was 29.5–41.1°C with the average being 35.6°C and the ambient relative humidity was 19–50% with the average being 32% during the 12 days of experiment. The temperature and RH profile indicated that higher the RH of the ambient condition less was the cooling effect in cool chamber. At 10:00 am, the dry bulb temperature difference between ambient and storage structure was low because of high RH while the difference increased at 4:00 pm because of reduction in RH value.

The temperature inside the ECSS reduced and there was an increase in RH value, while the values fluctuated

Table 1 ANOVA

Source	DF	Sum of squares	Mean square	F value	Pr>F
Replication	8	3596.84786	449.60598	8.49	<.0001
Pad material	2	2770.56420	1385.28210	26.17	<.0001
Pad area	3	17878.61732	5959.53911	112.59	<.0001
Error	94	4975.49334	52.93078		
Corrected total	107	29221.52272			

Table 2 Cooling efficiency with different pad area

Pad area	Mean
1 side (2.25 m^2)	40.216^d
2 sides (4.5 m^2)	52.180^c
3 sides (6.75 m^2	64.262^b
4 sides (9 m^2)	74.522^a

*Means with the different letter are significantly different.

Table 3 Cooling efficiency with different pad materials

Pad material	Mean
Wood wool pad	53.160^b
Khas pad	55.384^b
CELdek pad	64.842^a

*Means with the different letter are significantly different.

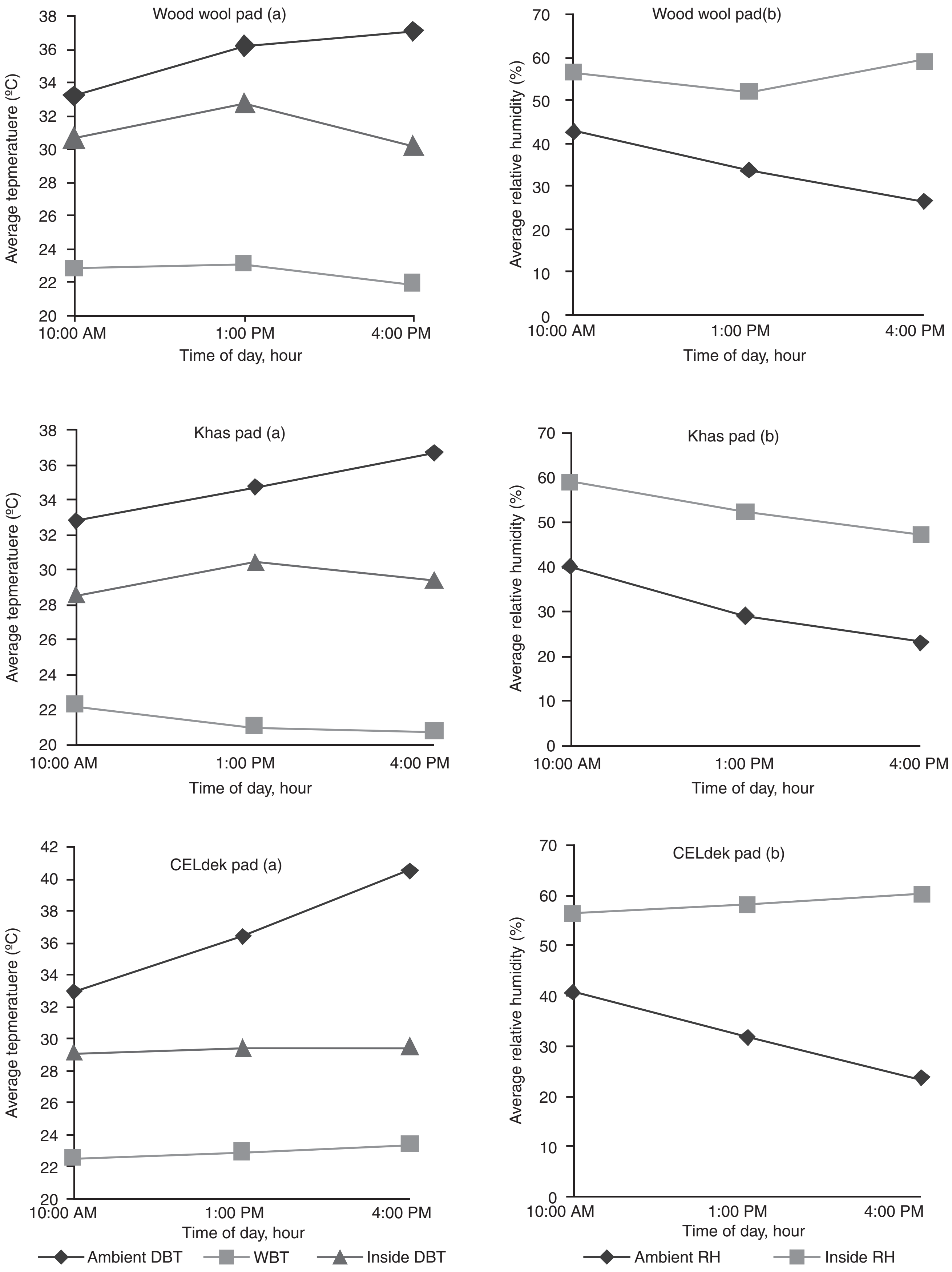

Fig 1 Hourly variation of temperature and relative humidity for ambient and inside the ECSS when pad was used only at one side.

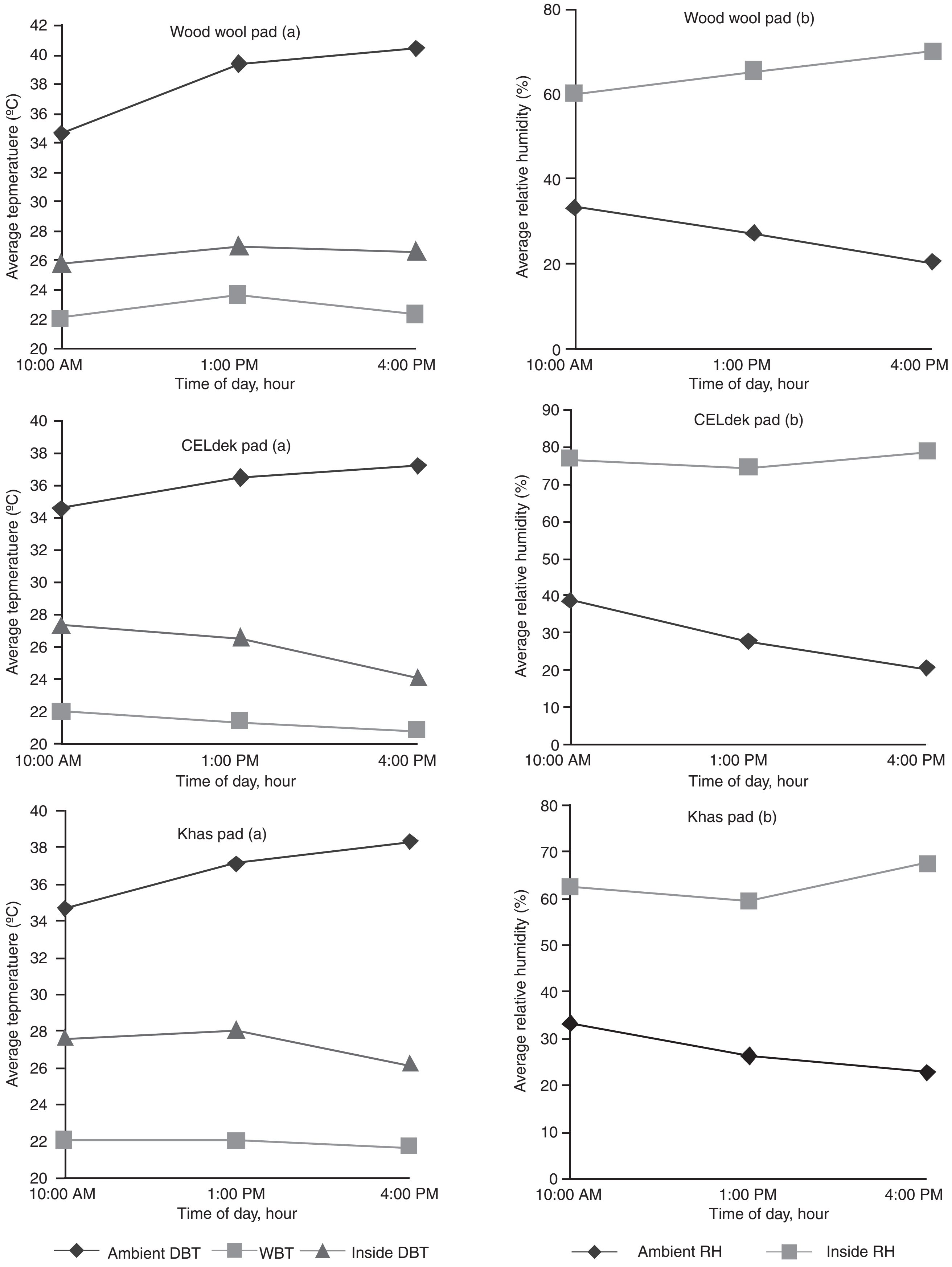

Fig 2 Hourly variation of temperature and relative humidity for ambient and inside the ECSS when pad was used at four sides.

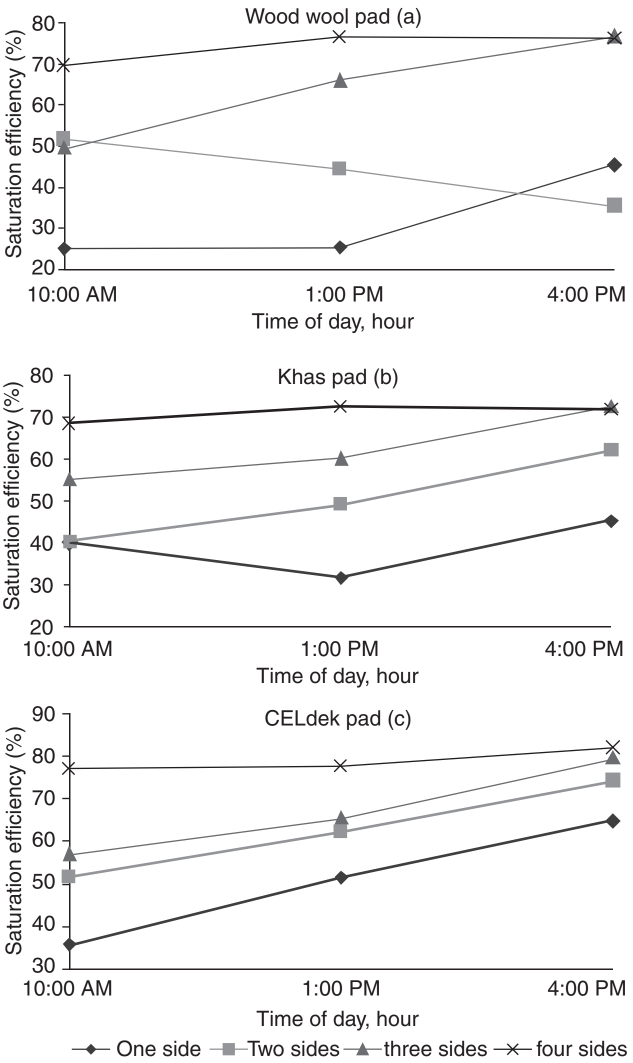

Fig 3 Hourly variation of saturation efficiency for different pad material of the ECSS

Table 4 Effectiveness data of the evaporative cooled structure

Pad material	Pad area	Temperature drop (°C)		Mean cooling efficiency (η %)
		Maximum	Minimum	
Wood wool pad	1 side (2.25 m^2)	6.8	2.5	31.81
	2 sides (4.5 m^2)	5.2	4.4	43.66
	3 sides (6.75 m^2)	11.6	5.5	63.81
	4 sides (9 m^2)	13.8	8.8	73.82
Khas pad	1 side (2.25 m^2)	7.2	4.2	38.91
	2 sides (4.5 m^2)	8.6	3.8	50.25
	3 sides (6.75 m^2)	12.1	7.0	62.56
	4 sides (9 m^2)	10.5	7.2	70.75
CEL dek pad	1 side (2.25 m^2)	11.1	3.8	50.68
	2 sides (4.5 m^2)	10.6	4.2	62.60
	3 sides (6.75 m^2)	13.0	7.2	67.40
	4 sides (9 m^2)	14.5	8.9	78.67

and did not follow any definite pattern under ambient conditions. Temperature and RH difference between ambient and ECSS condition increased with increase in the the pad area. The maximum difference in RH and dry bulb temperature between ambient and inside the cooler was 59% and 14.6°C (Fig 1-3) respectively when CELdek pad was used on all four sides in the ECSS.

Effect of different pad area and pad material on air cooling efficiency

The cooling efficiency at 10:00 am, 1:00 pm and 4:00 pm was calculated. The effect of pad materials and their varying areas on cooling efficiency inside the ECSS is shown in Fig 3. The analysis of variance of the results showed there was a significant difference (P = 0.05) in cooling efficiency amongst three types of evaporative cooling pad materials and four distinctive pad areas (Table 1). Using pad only on one side in ECSS gave the least value of cooling efficiency in each of the pad material.

According to the effect of the pad area on the air cooling efficiency of pad materials showed that there was significant difference on cooling efficiency of ECSS (Table 2). The pad area listed from the average highest efficiency to the lowest as

Four sides[a] > three sides[b] > two sides[c] > one side[d]

According to the effect of the pad materials on the air cooling efficiency of pad materials showed that there was significant difference on cooling efficiency of ECSS (Table 3). The pads listed from the average highest efficiency to the lowest as

CELdek pad[a] > wood wool pad[b] = khas pad[b]

Average cooling efficiency and the maximum and minimum temperature drop was determined during the operating period for different pad materials with various pad areas (Table 4). The 50 mm CELdek pad showed the highest cooling efficiency 81.79% at 4:00 pm when pad was used on four sides in ECSS while the cooling efficiency was found to be minimum 23.67% when wood wool pad was used only at one side in storage structure. It was expected that an evaporative cooling system must have decreased the air temperature to the desired degree with minimum power consumption and expenses. An ideal pad media should have the highest air cooling efficiency. The result indicated the ECSS covered with commercial cellulose pads (CELdek) media from all the four sides as the most suitable.

The study showed that the PV system performed well to operate the system with the solar power during the course of study. There was a significance difference in cooling efficiency between three types of cooling pad materials (CELdek pad, wood wool pad and khas pad) and four distinctive pad areas (2.25 m^2, 4.5 m^2, 6.75 m^2 and 9 m^2). The commercial cellulose pads (CELdek) when used at four sides showed the highest air cooling efficiency (approximately 80%) for 50mm pad thickness. Based on the study the CELdek pad was found as the best pad material compared to the other two local alternative pad materials (khas and wood wool pads). There seems to be success story of using solar energy to power evaporative cooled storage structure and this provides an opportunity to preserve or to extend the shelf life of fresh produce. This is very useful for farmers in rural areas where electricity is not available or its supply is erratic.

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