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Determination of Performance of Different Pad Materials and Energy Consumption Values of Direct Evaporative Cooler

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Abstract: The purpose of this study is to determine the performances of luffa and greenhouse shading netting (which can be used as alternatives to commercial cellulose pads, that are popular for cooling greenhouses), the contribution of external shading to the evaporative cooling performance, and the energy consumption of the direct evaporative cooler. In this experiment, eight different applications were evaluated: natural ventilation (NV), natural ventilation combined with external shading net (NV + ESN), cellulose pad (CP), cellulose pad combined with external shading net (CP + ESN), luffa pad (LP), luffa pad combined with external shading net (LP + ESN), shading net pad (SNP), and shading net pad combined with external shading net (SNP + ESN). The cooling efficiencies of CP, CP + ESN, LP, LP + ESN, SNP, and SNP + ESN were found to be 37.6%, 45.0%, 38.9%, 41.2%, 24.4%, 29.1%, respectively. Moreover, their cooling capacities were 2.6 kW, 3.0 kW, 2.8 kW, 3.0 kW, 1.7 kW, 2.0 kW, respectively. The system water consumption values were 2.9, 3.1, 2.8, 3.2, 2.4, 2.4 l h^{-1}, respectively. The performance coefficients of the system were determined to be 10.2, 12.1, 11.3, 11.9, 6.6, 7.8. The system's electricity consumption per unit area was 0.15 kWh m^{-2}. As a result of the study, it was determined that commercially used cellulose pads have advantages over luffa and shading net materials. However, luffa pads can be a good alternative to cellulose pads, considering their local availability, initial cost, cooling efficiency, and capacity.

Keywords: evaporative cooling; alternative materials; cooling efficiency; cooling capacity; coefficient of performance

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1. Introduction

Greenhouses are structures that protect crops from adverse climatic conditions and provide a suitable indoor environment for crop production throughout the year [1]. These structures have advantages over open-field cultivation. This is because, in the greenhouse, growing conditions can be better observed and controlled. This significantly improves out-of-season crop production and increases crop yields [2]. However, during the hot season, the heat input into the greenhouse causes the internal temperature to increase and exceed the optimum value [3]. In greenhouses, the greenhouse effect caused by the absorption of solar radiation causes the internal temperature to be higher than the external temperature. In this case, plants and products may dry out, and their production may decrease due to high evaporation rates caused by high indoor temperatures [4]. Greenhouse plants generally adapt to temperatures between 17 and 27 °C [5]. Above these temperature values, plant development continues, and flowering occurs; however, pollen germination worsens. Even if the pollen tube occurs, it cannot extend sufficiently, and since fertilization does not occur, the flower falls off, and the yield decreases with the formation of parthenocarpic small fruits [6]. In regions with unfavorable climatic conditions for crop production, it is necessary to reduce the indoor greenhouse air temperature or regulate the temperature to be closer to the outdoor temperature during the summer months for successful crop production [7]. Several methods can cool the greenhouse environment to grow plants in more suitable conditions. Although natural ventilation is generally considered the first step as it is a cheaper and simpler process, it is generally insufficient for removing excess energy from the interior on sunny summer days [8]. Environmental protection requirements also force creators and suppliers of ventilation technologies to adopt a cost-effective approach to energy supply processes in the greenhouse complex [9,10]. Evaporative cooling technology can be used as a replacement for the conventional vapor compression cooling system [11]. Conventional air conditioning systems using a vapor compression cycle are uneconomical due to high electricity consumption. Evaporative cooling by means of evaporative coolers is therefore one of the best and most economical solutions [12]. Spring–summer temperatures are typically high in the Mediterranean basin, making evaporative cooling systems necessary for a suitable growing environment [4,13]. One of the most effective solutions for maintaining optimum climatic conditions in a greenhouse is using evaporative cooling systems. This system's basic principle is converting sensible heat into latent heat. The water required for this process is added directly to the greenhouse environment by misting or wet pads. Evaporative cooling both reduces the temperature and vapor pressure deficit and ensures that the greenhouse internal air temperature is lower than the external air temperature [14–16]. The fan-pad cooling system, which is widely used in greenhouses, is the most effective direct evaporative cooling system [17]. Fan-pad cooling systems reduce the heat load of the indoor environment by converting the sensible heat in the air into latent heat, and provide the indoor conditions necessary for plant growth [18]. The use of evaporative cooling is one of the passive cooling methods that can contribute to the reduction in the energy consumption of buildings [19]. In addition, to overcome the high electrical energy consumption of space cooling, evaporative cooling has been found to be the best and most cost-effective solution [20]. Increasingly hotter and longer summers and the frequency and duration of heat waves worldwide are the main factors causing a significant increase in energy demand for cooling and air conditioning. With cooling demand and energy prices rising rapidly worldwide, the need to develop highly efficient cooling equipment is also increasing [21]. The performance of a direct evaporative cooler is greatly influenced by the efficiency of the cooling pads. When analyzing the performance of a direct evaporative cooler, the cooling efficiency and the humidity of the pad are two important factors to consider [22]. Both of these factors are highly dependent on the type of cooling pad in use. The cooling efficiency of the systems depends on the type of material used in the pad, the surface area of the pad, the thickness of the pad, its porosity, the size of the holes, the flow rate of the air passing through the pad, and the provision of good humidification by creating a large surface area. It is also influenced by many factors, such as the ability to hold moisture for a long time, the ability to evaporate, the maximum wet surface area, the amount of water used, the local availability, and the cost [23–26].

Furthermore, the high cost of commonly used cellulose pads limits the applications of this technology in small- or medium-scale agro-industrial production systems. This was a reason to research alternative materials that can produce pads at a cost much lower than cellulose pads [27,28]. These materials can lead to energy savings, increase thermal values and extend the life of the equipment [29]. Additionally, Chaomuang et al. [30] suggest that hybrid systems, combining evaporative cooling with a water chiller or desiccant dehumidifier should be investigated to improve the performance of organic-waste-based cooling pads. The use of air conditioning technology is associated with an increase in electricity consumption. This, in turn, requires the development of more energy-efficient cooling solutions [31]. Evaporative cooling systems are more expensive because they use more energy and water than traditional natural ventilation and crop transpiration methods.

However, it can compensate for the extra cost as it contributes to increasing earliness, quality, and yield by cooling the internal environment during periods when temperatures are very high. Therefore, growers can extend the growing season, plant earlier, and change the periods of maximum production [32].

In Turkey, one of the world's major greenhouse growing centers, the high temperature and vapor pressure deficits between June and July harm greenhouse crops. During these periods, especially in some regions where greenhouse cultivation is intensive, greenhouses are left empty, and no production takes place. In order to cool the greenhouses during these months and make the indoor climate suitable for crop production, evaporative cooling methods have to be used. However, the use of evaporative cooling in low- and medium-technology greenhouses is limited due to the high cost of evaporative cooling materials imported from abroad, energy requirements, and lack of knowledge about its use. In Turkish greenhouses, growers widely use shade nets to shade the greenhouses. At the same time, farmers also grow pumpkin fiber. The farmers' knowledge of these two materials, the porous structure of the materials, and the high water retention capacity of pumpkin fiber are among the important characteristics of these materials. However, it is important to understand the effects of these materials as pad materials on indoor climate parameters and to determine their performance through field applications to determine their usability as cooling pads. In addition, due to high energy costs, determining the amount of energy consumed is essential for manufacturers. This study aimed to determine the performance of materials (luffa and shading net) that can be used as alternatives to commercial pads used in cooling greenhouses, the contribution of external shading to evaporative cooling performance, and the energy consumption required for evaporative cooling.

2. Materials and Methods

2.1. Experimental Site Description

The study was conducted between July and August in the high tunnel greenhouse at Kırşehir Ahi Evran University (39°08′02″ N 34°07′08″ E, 1082 m above sea level). Long-term (1930–2023) climate values in the study area in July and August are shown in Table 1 [33].

Table 1. Long-year climate parameters of the study area.

Climatic Data	June	July	August
Monthly minimum temperature (°C)	2.6	5.1	5.0
Monthly average temperature (°C)	19.7	23.1	23.0
Monthly maximum temperature (°C)	36.2	40.2	40.5
Average number of days with maximum temperature 30 °C and above	5.61	15.20	16.03
Average number of days with maximum temperature 25 °C and above	19.29	28.94	28.93
Monthly minimum relative humidity average (%)	19.4	16.5	16.8
Monthly average relative humidity (%)	54.2	47.6	47.6
Monthly maximum relative humidity average (%)	91.5	85.6	85.8
Monthly average wind speed (m s^{-1})	2.5	3.3	3.1
Monthly average sunshine time (hours)	10.8	12.0	11.5
Monthly average global solar radiation (cal cm^{-2})	553.5	565.4	508.9

It is seen that the monthly maximum temperature values in July and August, when evaporative cooling is required in the study area, are around 40 °C. In addition, it is seen that the mean number of days when the maximum temperature is 30 °C and above in the study area is 15–16 days for July and August. The monthly average relative humidity is 47.6%. Accordingly, considering the increasing temperature and low relative humidity in the outdoor environment of the study area and the temperature increases in the greenhouse, it can be seen that the need for evaporative cooling is necessary for plant production in July and August.

2.2. Experimental Design

In the study, the floor area of the greenhouse in the north–south direction is 3 × 5 m, and the height is 2 m. The greenhouse is covered with 360-micron thick UV + IR + EVA-added polyethylene plastic.

A direct evaporative cooler was used to cool the greenhouse's indoor environment. The components of the direct evaporative cooler are pad media, electrical fan, water tank, floater, water supply, and a distribution pipe and electrical pump. In the direct evaporative cooling system, the water drips from the top of the distribution bath through small holes over the pads. On the distribution bath, the diameter of each hole is distributed uniformly (0.5 × 1 cm). Unevaporated water falls directly back into the reservoir bath under the pads and is recirculated. The direct evaporative cooler is designed to be open on three sides to allow dry air to come into contact with the material and to have an air outlet on one side. An electrical fan draws hot and dry air from outside through the gaps between the pad material. Some of the water evaporates into the air stream as the outdoor air passes over the wetted surface of the pad. Thus, heat is removed from the air and the air exits the pad at a lower temperature and with a higher humidity. In this system, the amount of water evaporated was recorded between 09:00 and 17:00, when the system was operated, and the total amount of water consumed was determined. Figure 1 shows the direct evaporative cooling system and its components.

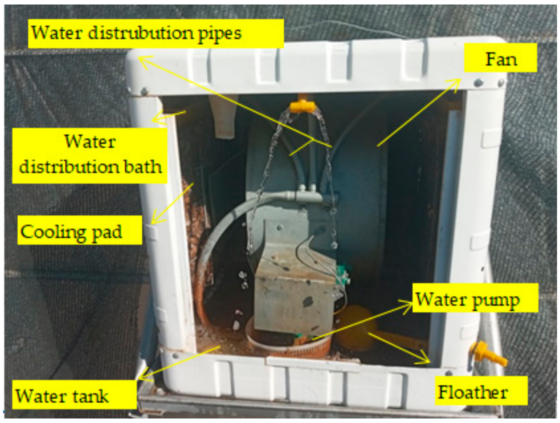


Figure 1. Direct evaporative cooling system and the components of the system.

In the direct evaporative cooler, a 35 × 35 × 3.5 cm thick cellulose pad, a luffa pad, and shading net pad materials were used as pad materials (Figure 2). Cooling pads were tested at inlet air velocities of 2.0 m s^{-1}. The density of the celdek pad was about 25.9 kg m^{-3}, that of the luffa pad was about 19.0 kg m^{-3}, and that of the shading net pad was about 13.6 kg m^{-3}.

(**a**) (**b**) (**c**)

Figure 2. The testing materials: (**a**) cellulose pad; (**b**) luffa pad; (**c**) shading net pad.

Eight different applications were conducted to determine the performance of the pad materials used and to investigate its effect on the greenhouse internal environment (Table 2). In the natural ventilation and natural ventilation + external shading net applications, the greenhouse window and door are left open. The ventilation opening ratio in the greenhouse is 11% of the floor area.

Table 2. Applications for cooling in the greenhouse.

Abbreviations	Applications
NV	Natural ventilation
NV + ESN	Natural ventilation combined with external shading net
CP	Cellulose pad
CP + ESN	Cellulose pad combined with external shading net
LP	Luffa pad
LP + ESN	Luffa pad combined with external shading net
SNP	Shading net pad
SNP + ESN	Shading net pad combined with external shading net

2.3. Measurement and Observation

Measurements were made every 30 min inside and outside the greenhouse between 09:00 and 17:00, when the temperature rises during the day, to determine the system performance and its effects on the internal environment of the greenhouse. The technical features of the measuring devices used in the study are shown in Table 3.

Table 3. The specifications of the measuring instruments.

Sensor Type	Sensor Model	Sensor Accuracy	Specification Range
Temperature	Onset HOBO U12	±0.35 °C	−20 °C to +70 °C
Relative humidity	Onset HOBO U12	±2.5%	5% to 95%
Wind speed	Benetech Anemometer GM816	±5%	0–30 m s^{-1}
Solar radiation	Apogee pyranometer sensor	5%	0–1750 W m^{-2}
Electricity consumption	TT Technic PMG-1	±2–5%	1–3680 W

2.4. Performance Parameter

An important parameter to describe the cooling performance is the difference between the indoor and outdoor temperatures. According to this, the cooling effect of the system is calculated using Equation (1) [12,34].

$$\Delta T = T_{\text{in}} - T_{\text{o}} \tag{1}$$

where ΔT is the cooling effect (°C), T_{in} is the indoor air temperature (°C), and T_{o} is the outside air temperature (°C).

The system's cooling efficiency was determined with the help of Equation (2) [35–38].

$$\eta = \frac{[T_{\text{o}} - T_{\text{in}}]}{[T_{\text{o}} - T_{\text{db}}]} \times 100 \tag{2}$$

where η is the cooling efficiency (%), T_{o} is the outside air temperature (°C), T_{in} is the indoor air temperature (°C), and T_{db} is the dry bulb temperature of the outside air (°C).

The cooling capacity of the evaporative cooling pad was determined with Equation (3) [38,39].

$$Q_{\text{c}} = M_{\text{a}} \times C_{\text{pa}} \times [T_{\text{o}} - T_{\text{in}}] \times 3.6 \tag{3}$$

where Q_{c} is the cooling capacity (kJ h^{-1}), T_{o} is the dry bulb temperature of the outside air (°C), T_{in} is the dry bulb temperature of the air leaving the pad (°C), M_{a} is the mass flow rate of the air (kg s^{-1}), and C_{pa} is the air-specific heat (J kg^{-1} $°C^{-1}$).

The water consumption rate, which is a function of the air's specific humidity and the air's mass flow rate, was calculated with Equation (4) [38,39].

$$Q_{\omega} = M_a\,[\omega_o - \omega_i] \times 3600 \tag{4}$$

where Q_{ω} is the water consumption rate (kg h^{-1}), M_a is the mass flow rate of air (kg s^{-1}), ω_i is the specific humidity of the outdoor air before entering the pad (kg kg^{-1}), and ω_o is the specific humidity of the outdoor air after leaving the pad (kg kg^{-1}).

The ratio of cooling capacity to total electrical power consumption is expressed as the coefficient of performance (COP) and is given by Equation (5) [12,29].

$$COP = \frac{Q_C}{W_{fan} + W_{pump}} \tag{5}$$

where Q_c is the cooling capacity (kWh) and W_{fan} and W_{pump} are the electrical power consumption of the fan and the pump (kWh).

Sensible heat transfer occurs depending on the temperature difference between the indoor and outdoor environments in the greenhouse. Sensible heat transfer (*SHT*) is related to the density and specific heat of the air carrier fluid. The sensible heat transfer per greenhouse floor area was calculated using Equation (6) [37]:

$$SHT = \left[\left(\frac{VR}{A_g}\right) . \, \rho \, . \, C_{pa} \, . \, (T_o - T_{in})\right] \tag{6}$$

where *SHT* is the sensible heat transfer (W m^{-2}), *VR* is the ventilation efficiency (m^3 s^{-1}), A_g is the greenhouse floor area (m^2), ρ is the density of air (kg m^{-3}), C_{pa} is the specific heat at constant pressure (J kg^{-1} °C^{-1}), T_i is the temperature of the greenhouse air (°C), and T_o is the temperature of the outdoor air (°C).

The amount of latent heat that must be removed from the greenhouse environment (latent heat transfer) varies depending on the temperature, the ventilation efficiency, the relative humidity, and the air movement over the vegetation. Heat transfer in the form of latent heat depends on the latent heat of vaporization and the density of the air. Latent heat transfer (*LHT*) can be calculated using Equation (7), according to the specific humidity difference between the greenhouse indoor environment and the outdoor environment [37].

$$LHT = \left[\left(\frac{VR}{A_g}\right) . \, \rho \, . \, h_{fg} \, . \, (\omega_o - \omega_i)\right] \tag{7}$$

where *LHT* is the latent heat transfer (W m^{-2}), h_{fg} is the latent heat of evaporation (J kg^{-1}), ω_i is the specific humidity of greenhouse air (kg kg^{-1}), and ω_o is the specific humidity of outdoor air (kg kg^{-1})

The ratio of sensible to latent heat transfer is defined as the Bowen ratio (β) and was calculated using Equation (8) [37]:

$$\beta = \left(\frac{SHT}{LHT}\right) \tag{8}$$

Vapor pressure deficit (*VPD*) values in the greenhouse interior environment were calculated using Equations (9) and (10).

$$SVP = 610.78 \times 2.71828^{\left(\frac{T}{T+273} \times 17.2694\right)} \tag{9}$$

$$VPD = SVP \times \left(1 - \frac{RH}{100}\right) \tag{10}$$

where *SVP* is the saturation vapor pressure, *VPD* is the vapor pressure deficit (kPa), *T* is the temperature (°C), and *RH* is the relative humidity (%).

3. Results and Discussion

3.1. Natural Ventilation and Natural Ventilation + External Shading Net Applications

In the study, external and internal climate parameters measured in natural ventilation and natural ventilation + external shading net applications are given in Table 4.

Table 4. External and internal climate parameters measured in natural ventilation and shading net applications.

Applications	Measurement	Temperature, °C		Relative Humidity, %		Solar Radiation, W m^{-2}		VPD, kPa	
		Out	In	Out	In	Out	In	Out	In
NV	Max.	28.7	40.7	48.4	40.8	1018.0	848.3	2.9	6.0
	Mean	24.4	36.1	34.3	27.9	847.9	630.9	2.1	4.5
	Min.	17.5	27.3	24.5	21.1	530.8	419.3	1.0	2.1
NV + ESN	Max.	30.0	40.8	43.2	38.6	1001.0	475.1	3.0	5.9
	Mean	28.0	38.3	33.7	28.8	825.3	361.1	2.5	4.9
	Min.	22.8	32.6	27.6	23.6	516.3	235.1	1.6	3.0

Natural ventilation was first applied to reduce high indoor temperature values. On the day when natural ventilation was applied, the average ΔT (indoor–outdoor) temperature difference was measured to be 11.8 °C, and the relative humidity value ΔRH was measured to be 6.4% lower on average. While the outdoor VPD value is 2.1 kPa, the indoor VPD value is determined to be 4.5 kPa. In NV application, ΔSR decreased by an average of 26.0% due to the cover material. High radiation values coming into the greenhouse increase the temperature in the indoor environment. Increasing temperature values dried the ambient air and caused low relative humidity. As a result, the NV application could not make the indoor temperature, relative humidity, or VPD values suitable for plant cultivation on the trial days. Therefore, NV + ESN application was made to reduce the solar radiation reaching the greenhouse interior environment and make it suitable for plant cultivation. Accordingly, on the day of the NV + ESN application, the average ΔT temperature difference was measured as 10.3 °C, and the relative humidity values ΔRH were measured as 4.85% lower on average. While the outdoor VPD value was 2.5 kPa, the indoor VPD value was determined to be 4.9 kPa. In the NV + ESN application, ΔSR decreased by an average of 44.0% with the help of a cover material and an external shading net.

In regions with high solar radiation intensity, high ventilation rates are not sufficient to reduce greenhouse temperature. Since high solar intensity causes heat stress on plants, shading net systems are used in greenhouses [40]. Although the shading net causes decreases in different indoor and outdoor temperatures and increases in the relative humidity, as can be seen in Table 4, these values are quite high in terms of plant growth. Similarly, in the study conducted by [26] in a high tunnel greenhouse, ΔT = 12.63 °C and ΔRH = 4.88% were found on a day of NV application. The NV + ESN application led to values of ΔT = 9.48 °C and ΔRH = 4.24%. In this study, similar to the NV application, increasing outdoor radiation values caused the temperatures in the greenhouse interior to increase and, accordingly, the relative humidity values to decrease. The application of the shading net has led to a decrease in indoor temperatures. However, in this application, the indoor temperature and relative humidity values could not be kept within the optimum values required for plant cultivation. Plants grown in greenhouses have adapted to temperature values of 17–27 °C. In addition, the desired indoor relative humidity value is around 80% [41]. Grange and Hand [42] stated that humidity rates between 1.0 kPa and 1.2 kPa VPD have little effect on the physiology and development of horticultural plants. Moreover, low humidity levels will cause plant water stress and reduce growth, while higher levels may promote disease and cause growth and development disorders. Barker [43] stated that in the range of 0.5–0.8 kPa vapor pressure deficit values are optimal for most greenhouse crops and will prevent yield loses due to fruit shrinkage and fungal diseases. In this study, a high vapor pressure deficit occurred in the indoor environment due to increasing temperature and decreasing relative humidity. Increasing the relative humidity values in the indoor environment in order to reduce the increasing VPD values will be important for plant cultivation. In findings, as can be seen from both applications, indoor temperature, relative humidity, and vapor pressure deficit values are above the optimum values required for plant cultivation. It is clear that, in the summer months, when NV and NV + ESN applications are made, high temperature and low relative humidity values will negatively affect the flower set, yield, and development parameters of the plants to be grown. For this reason, the necessity of evaporative cooling systems that reduce the indoor air temperature value and increase the indoor air relative humidity values during the trial months emerges.

3.2. Evaporative Cooling Applications

3.2.1. Cellulose Pad and Cellulose Pad + External Shading Net Applications

The external and internal climate parameters measured in the cellulose pad and cellulose pad + external shading net applications are given in Table 5.

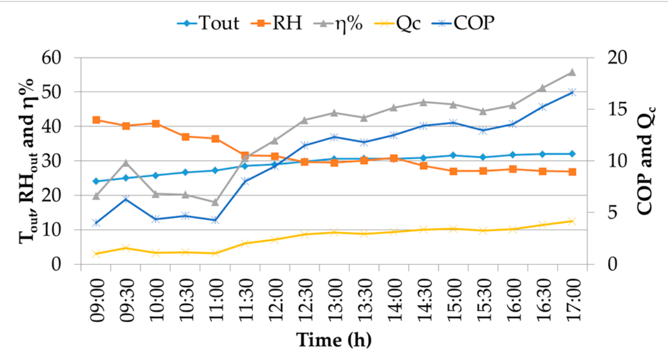
Table 5. External and internal climate parameters measured in cellulose pad and cellulose pad + external shading net applications.

Applications	Measurements	T_{out}, °C	RH_{out}, %	T_{in}, °C	RH_{in}, %	VPD_{in}, kPa	VPD_{out}, kPa	Cooling Effect, °C	Cooling Efficiency, %
CP	Max.	24.1	26.9	21.8	52.6	3.5	1.5	2.1	18.0
	Mean	29.3	32.0	23.8	59.4	2.8	1.2	5.5	37.6
	Min.	32.0	42.0	25.0	64.8	1.7	1.0	8.9	55.8
CP + ESN	Max.	25.6	27.3	21.3	52.6	3.5	1.5	1.1	10.2
	Mean	30.0	32.0	23.4	63.3	2.9	1.1	6.6	45.0
	Min.	32.0	43.5	25.0	75.0	1.9	0.6	10.1	66.0

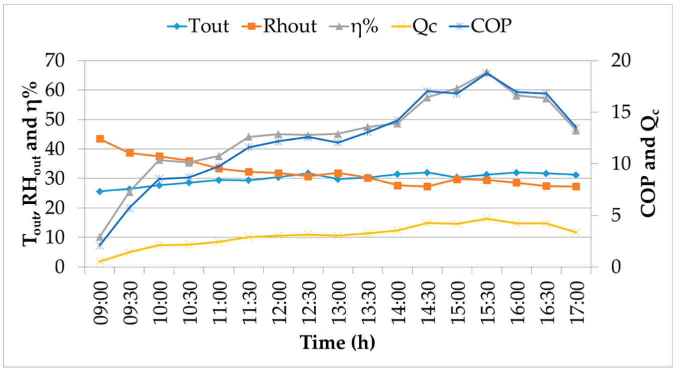
In the CP application, the outdoor solar radiation was determined to be 820.9 W m^{-2} on average, between 511.4 and 991.3 W m^{-2}. The indoor solar radiation value was measured as 574.6 W m^{-2} on average, between 373.3 and 765.9 W m^{-2}. In the CP + ESN application, the outdoor solar radiation value was 771.3 W m^{-2}, on average, between 196.3 and 1010.7 W m^{-2}. On average, the indoor solar radiation value was 314.9 W m^{-2}, between 82.4 and 453.2 W m^{-2}. In the CP application, the solar radiation rate reaching the greenhouse environment was determined to be 70.0%. In the CP + ESN application, the solar radiation rate reaching the greenhouse environment was 40.8%.

As shown in Table 5, the cooling effect in the CP application was 5.5 °C and for the CP + ESN application it was 6.6 °C. In a study on the cooling effect, Gunhan et al. [44] reported that, for the 5 cm pad thickness and four different air speeds (0.6, 1.0, 1.3, and 1.6 m s^{-1}), the cooling effects were found to be 4.97 °C, 4.69 °C, 3.91 °C, and 3.99 °C, respectively. Shivpuje et al. [45] found that the average dry bulb temperature of the air entering the cooling pad varied between 32 °C and 36 °C, and the air exit temperature from the cooling system was between 27 °C and 29 °C. Vala et al. [46] stated that, with a 10 cm thick Celdek pad, the average cooling effect was 8 °C. These results align with previous findings in the literature. Moreover, it has been determined that indoor temperature values can be brought to values suitable for plant cultivation with CP (23.8 °C) and CP + ESN (23.4 °C) applications. This is because of the additional moisture introduced into the greenhouse through the direct evaporative cooling process. Increasing the relative humidity in the indoor environment increased the cooling effect by decreasing the temperatures. At the same time, by using external shading in the CP + ESN application, the solar radiation reaching the interior was reduced, and the cooling effect was higher than that of the CP application. However, since shading nets will reduce the light reaching the indoor environment, the plants' light needs should also be considered.

Variations of some performance parameters with time are given in Figure 3a for the CP application and in Figure 3b for the CP + ESN application.



(**a**)



(**b**)

Figure 3. Variations in performance parameters the CP and CP + ESN pads with time: (**a**) CP; (**b**) CP + ESN.

In the CP application, the indoor relative humidity values were 27.4% higher on average than those in the external environment. The CP + ESN application's indoor relative humidity values were 31.3% higher than those of the external environment. According to this, in the CP application, the outdoor VPD value was 2.8 kPa and the indoor VPD value was determined to be 1.2 kPa. In the CP + ESN application, while the outdoor VPD value was 2.9 kPa, the indoor VPD value was determined to be 1.1 kPa. In a study on relative humidity, Gunhan et al. [44] reported that, for a 5 cm pad thickness and four different air speeds (0.6, 1.0, 1.3, and 1.6 m s^{-1}), the relative humidity differences were 37.21%, 33.58%, 28.83%, and 27.38%, respectively. Shivpuje et al. [45] found that the average relative humidity of the air entering the cooling pad varied between 42.1% and 48.2%, and the relative humidity at the exit was between 65.4% and 78.7%. The results of our study are in line with previous findings in the literature. Under conditions of increasing outdoor temperature values, relative humidity values decreased in the outdoor environment (Figure 3a,b). In this case, the dry air entering the pad took in more moisture, causing the relative humidity values in the indoor environment to increase. In addition, increasing the relative humidity contributed to the decrease in VPD values. Increasing the relative humidity and decreasing VPD values in the CP and CP + ESN applications made the greenhouse indoor environment suitable for plant cultivation. However, due to the external shading net used in the CP + ESN application, the indoor conditions were more suitable than those of the CP application.

In the study, the cooling efficiency of the CP application was determined to be 37.6% on average, between 18.0 and 55.8%. The cooling efficiency of the CP + ESN was determined to be 45.0% on average, between 10.2% and 66.0%. Accordingly, it has been observed that the cooling efficiency of the CP + ESN application is higher than that of the CP application. The results showed that the external shading net positively increased the evaporative cooling efficiency. Figure 3a,b show that the decreasing relative humidity values in the outdoor environment increased the cooling efficiency. This is because the decreasing temperatures inside the greenhouse increased the difference between the indoor and outdoor temperatures. As the temperature difference increased, the indoor temperatures approached the outdoor wet bulb temperature and the cooling efficiency increased. In a study on cooling efficiency, Gunhan et al. [44] calculated the evaporation saturation efficiency to be 46.1% for a pad thickness of 5 cm. Vala et al. [46] stated that, with a 10 cm thick Celdek pad, the saturation efficiency ranged between 90.70 to 57.14%. Franco et al. [32] reported that the saturation efficiency for a cellulose pad was between 70% and 64%. The results revealed that the cooling efficiency was higher than the results of [44] showed, where the pad thickness was similar, but lower than the results of [32,46], where pad thickness was thinner. Mishra et al. [47] reported that an increase in the thickness of the pad also increased the cooling efficiency. For this reason, in this study, the resulting differences depended on the external climate (incoming radiation, outdoor relative humidity, etc.) and the pad thickness.

The cooling capacity for the CP application was calculated to be Qc = 9221.5 kJ h^{-1} (2.6 kW) and the COP value was calculated to be 10.2. The cooling capacity for the CP + ESN application was calculated to be Qc = 10895.5 kJ h^{-1} (3.0 kW) and the COP value was 12.1. In our study, the cooling capacity and COP values were found to be higher in the CP + ESN application than in the CP application. The increasing temperature values in the greenhouse indoor environment lead to the availability of the high heat of vaporization. This results in evaporation and cools the indoor environment. A large temperature difference is obtained when cooling causes the internal temperature of the greenhouse to fall below the ambient temperature, resulting in a high cooling capacity [47]. In our study, the decrease in greenhouse temperature values in the CP + ESN application ($\Delta T = 6.6$ °C) compared to the CP application ($\Delta T = 5.5$ °C) increased the cooling capacity and the COP. Accordingly, the cooling capacity and the COP values increased in the CP + ESN application. Also, Figure 3a,b indicate that lower outdoor relative humidity leads to enhanced evaporation, leading to a higher cooling capacity and a higher COP. Shivpuje et al. [45] found that the system's cooling capacity varies between 0.7 and 1.1 kW, and the highest COP value in the system is determined to be 19.5. Vala et al. [46] calculated the cooling capacity to be 2717 kJ h^{-1} with a 10 cm thick Celdek pad. Chaomuang et al. [30] reported that, at the four different air velocities (0.5, 1.0, 1.5, and 2.0 m s^{-1}), the cooling capacity for the CP was 0.3–0.6 kW and the COP value was around 2.2–4.5. In addition, the cooling capacity shows a direct relationship not only with temperature drop but also with flow rate. Maurya et al. [38] reported that increasing air velocities increased the cooling capacity. Doğramacı et al. [29] stated that, as the air speed increased up to a certain value, the COP value and the cooling capacity increased. Compared to the findings of studies conducted by other researchers, the cooling capacities found in this study were lower than those found in [45] and higher than those found in [30]. This study's cooling capacities increased due to the high air velocity, which was 2 m s^{-1}. The increasing cooling capacity increased the COP value. At the same time, the cooling effect occurring in the greenhouse contributed to the increase in these values.

In the CP application, the water consumption capacity was calculated to be $Q\omega$ = 26.5 L day^{-1} (2.9 L h^{-1}). In the CP + ESN application, the water consumption capacity was $Q\omega$ = 27.8 L day^{-1} (3.1 L h^{-1}). There was a difference of 4% for the CP application and 5% for the CP + ESN application between the amount of water added to the system (between 09:00 and 17:00) and the calculated daily water consumption. It was determined that this was caused by losses and leaks in the system. According to the obtained results, water consumption in the CP + ESN application was higher than that in the CP application. Low relative humidity in the outdoor environment allows the evaporative cooler to evaporate more water and consume more water. At the same time, the excess amount of evaporated water contributes to an increase in cooling capacity. The water consumed in the CP + ESN application also increased the cooling capacity compared to the CP application. Vala et al. [46] stated that the average water evaporation with a 10 cm thick Celdek pad was 4.31 L h^{-1}. Nikolaou et al. [48] measured the daily water required for fan-pad evaporative cooling under Mediterranean conditions in a greenhouse that was growing cucumbers; they found that up to 3 L of water was used per m^2 of greenhouse floor area. Franco et al. [32] reported that the water consumption per unit for cellulose pad varies between 1.8 L h^{-1} and 2.62 L h^{-1}. This study determined that 1.8 L was necessary per m^2 greenhouse floor area for the CP application, and 1.9 L was needed per m^2 greenhouse floor area for the CP + ESN application. These results align with previous findings in the literature. In addition, due to the water shortage in regions with a Mediterranean climate, water consumption per unit area is as important as the cooling of greenhouses. This is because determining the amount of water consumed for cooling will also affect the feasibility of evaporative cooling applications in water-limited areas.

Fan-pad cooling systems reduce heat loads by converting sensible heat in the air to latent heat; this creates a more suitable indoor climate for plant growth [18]. The changes in sensible and latent heat transfer per floor area in the greenhouse, depending on time, are given in Figure 4a for the CP application and in Figure 4b for the CP + ESN application.

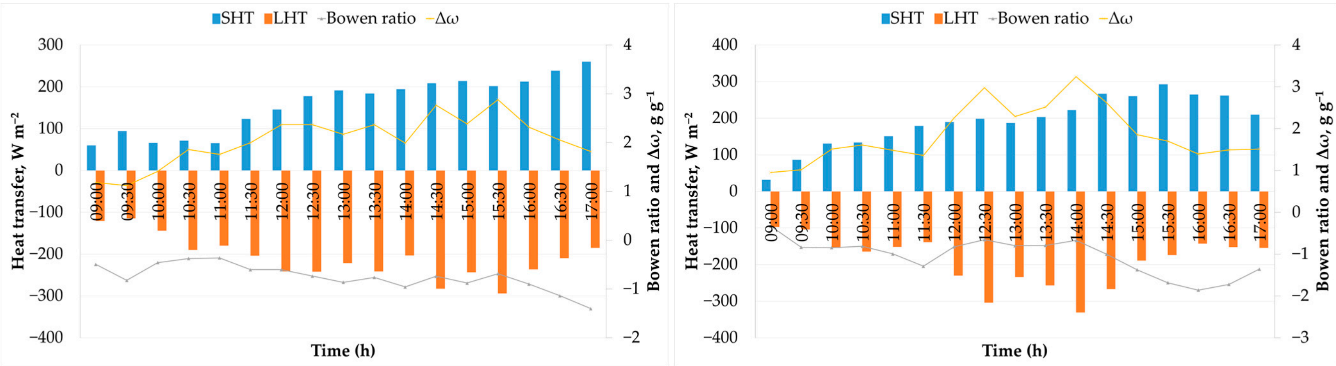


Figure 4. Variation in the sensible and latent heat transfer as a function of time: (**a**) cellulose ped; (**b**) cellulose pad + external shading net.

As seen in Figure 4a in the CP application, SHT was found to be 159.5 W m^{-2} on average, between 59.9 and 260.1 W m^{-2}. LHT was −209.1 W m^{-2} on average, between −114.4 W m^{-2} and −294.1 W m^{-2}. The Bowen ratio was found to be −0.8 on average, between −0.4 and −1.4. The difference in specific humidity was 2.1 g g^{-1} on average, between 1.1 and 2.9 g g^{-1}. As seen in Figure 4b, in the CP + ESN application, SHT achieved 192.4 W m^{-2} on average, between 31.6 and 292.8 W m^{-2}. LHT was found to be −191.0 W m^{-2} on average, between −97.2 and −331.1 W m^{-2}. The average Bowen ratio was found to be −1.1 between −0.3 and −1.9. The difference in specific humidity was 1.87 g g^{-1} on average, between 1.0 and 3.2 g g^{-1}. In CP and CP + ESN applications, while SHT increased due to the temperature difference (ΔT) increase between the outdoor and indoor areas of the greenhouse, LHT increased due to the increase in the specific humidity difference between the greenhouse environment and the outdoor air (Figure 4a,b). In addition, the Bowen ratio increased depending on the increase in the specific humidity difference. In their studies, researchers have reported that sensible heat transfer in the greenhouse increases linearly with the temperature difference, and the latent heat transfer increases linearly with the specific humidity difference. At the same time, it was determined that SHT was higher than LHT when the cooling system was operating in the greenhouse [37,49,50]. Similarly, in the CP and CP + ESN applications, we determined that SHT increased linearly with the temperature difference and LHT with the specific humidity difference; additionally, it was found that SHT was higher than LHT when the systems were operating in the greenhouse. Öztürk [37] stated that SHT was higher than LHT when the β values were considered in the greenhouse trial. A value of β (−) indicates that the air temperature inside the greenhouse is lower than the outdoor air temperature and that the specific humidity is higher than that of the outside environment. Moreover, although SHT occurs towards the vegetation in the greenhouse, LHT occurs from the vegetation under these conditions. Similar to the previous study, in the CP and CP + ESN applications, we determined that LHT was higher than SHT when the cooling system was operating in the greenhouse. However, this increase was greater in the CP + ESN application, and the greenhouse indoor environment became more suitable for plant cultivation.

3.2.2. Luffa Pad and Luffa Pad + External Shading Net Applications

The external and internal climate parameters measured in the luffa pad and the luffa pad + shading net applications are given in Table 6.

Table 6. External and internal climate parameters measured in luffa pad and luffa pad + external shading net applications.

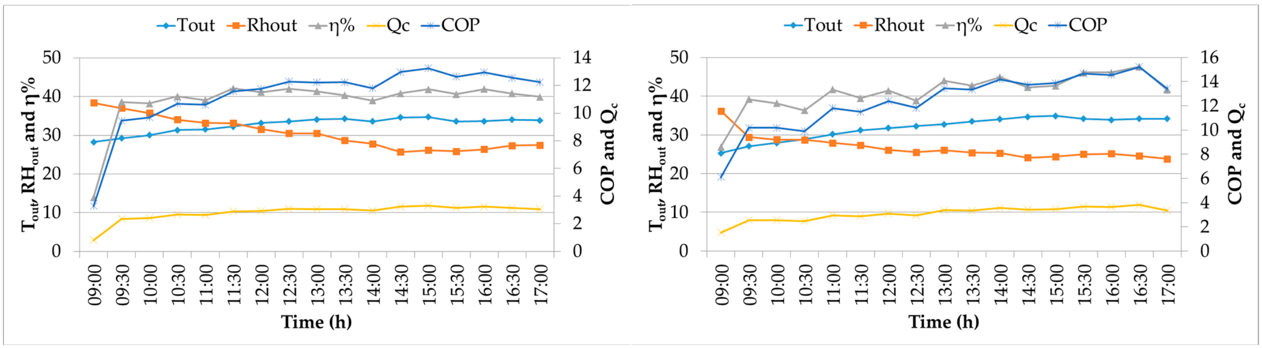
Applications	Measurements	T_{out}, °C	RH_{out}, %	T_{in}, °C	RH_{in}, %	VPD_{in}, kPa	VPD_{out}, kPa	Cooling Effect, °C	Cooling Efficiency, %
LP	Max.	28.3	25.7	24.2	49.6	4.1	1.8	1.7	14.0
	Mean	32.7	30.6	26.6	55.7	3.5	1.5	6.1	38.9
	Min.	34.7	38.4	27.6	62.7	2.4	1.1	7.2	42.1
LP + ESN	Max.	25.3	23.8	21.7	45.6	4.2	1.9	3.2	26.9
	Mean	31.8	26.7	25.2	51.6	3.5	1.6	6.6	41.2
	Min.	34.9	36.2	27.4	56.6	2.1	1.2	8.2	47.6

In the LP application, the outdoor solar radiation value was determined to be 778.3 W m^{-2}, between 475.1 and 947.7 W m^{-2} on average. The indoor solar radiation value was measured to be 571.3 W m^{-2}, between 356.3 and 746.5 W m^{-2} on average. In the LP + ESN application, the outdoor solar radiation value was 789.3 W m^{-2} on average, between 494.4 and 969.5 W m^{-2}. On average, the indoor solar radiation value was 336.8 W m^{-2}, between 215.7 and 426.6 W m^{-2}. In the LP application, the solar radiation rate of the solar radiation reaching the greenhouse environment was determined to be 73.4%. In the LP + ESN application, the solar radiation rate reaching the greenhouse environment was found to be 42.7%.

As shown in Table 6, the cooling effect in the LP application was 6.1 °C; for the LP + ESN application, it was determined to be 6.6 °C. Accordingly, it has been observed that the cooling effect of the LP + ESN application is higher than that of the LP application. This result showed that the shading net positively increased the evaporative cooling effect. Moreover, it has been determined that the indoor temperature values can be brought to values that are suitable for plant cultivation with the LP (26.6 °C) and LP + ESN (25.2 °C) applications. In a study on the cooling effect, Ahmadu et al. [11] reported that, in applications with luffa fiber—charcoal pad maximum cooling effect of 11 °C was found for the application without dehumidification pad; a charcoal pad maximum cooling effect of 10 °C was found for the application with dehumidification pad. Mishra et al. [47] reported that, for the luffa pad, the cooling effect for a 3 cm pad was in the range of 10.3 to 9 °C at an air speed of 0.5–1.5 m s^{-1}. The cooling effect was found in the range of 10.8 to 9.9 °C for 5 cm luffa pads and in the range of 11.5 to 9.9 °C for 7 cm luffa pads. The findings obtained in the study were lower than the results of the previous findings. Mishra et al. [47] reported that, as the air velocity increases, the exit air temperature increases; this can be due to the decrease in contact time at the air–water interface. In line with previous studies, the low cooling effect in this study could be explained by the reduced contact time of the air entering the pad with the water due to the high air speed.

In the study, variations in some performance parameters with time are given in Figure 5a for the LP application and Figure 5b for the LP + ESN application.

In the LP application, the indoor relative humidity values were 25.1% higher on average than outdoor ones. In the LP + ESN application, the indoor relative humidity values were 24.9% higher than those of the external environment. According to this, while in the LP application, the outdoor VPD value was 3.5 kPa, the indoor VPD value was determined to be 1.5 kPa. In the LP + ESN application, while the outdoor VPD value was 3.5 kPa, the indoor VPD value was determined to be 1.6 kPa. The increasing temperature values in the outdoor area of the greenhouse decreased the relative humidity values in the outdoor environment (Figure 5a,b). In this case, the dry air entering the pad took in more moisture, causing the relative humidity values in the indoor environment to increase. In addition, increasing relative humidity values in the indoor environment contributed to the decrease in VPD values. In addition, due to the external shading net used in the LP + ESN application, the indoor conditions were more suitable than those in the LP application. Increasing the relative humidity and decreasing the VPD values in the CP and CP + ESN applications made the greenhouse indoor environment suitable for plant cultivation. In a study on the indoor relative humidity effect, Ahmadu et al. [11] reported that, when using luffa fiber with charcoal pad (15 cm width), the relative humidity ranged from 45% to 85% without dehumidification pad and from 46% to 49% with dehumidification pad. The lower relative humidity obtained in this study was due to the thinner pad thickness. The decrease in air–water contact has reduced the relative humidity values that reach the indoor environment. In addition, even though the relative humidity values are close compared to the CP and CP + ESN applications, the insertion of CPs into the pad at a certain angle increased the water–air contact. For this reason, the relative humidity values increased in the CP and CP + ESN applications compared to the LP and LP + ESN applications.



(**a**) (**b**)

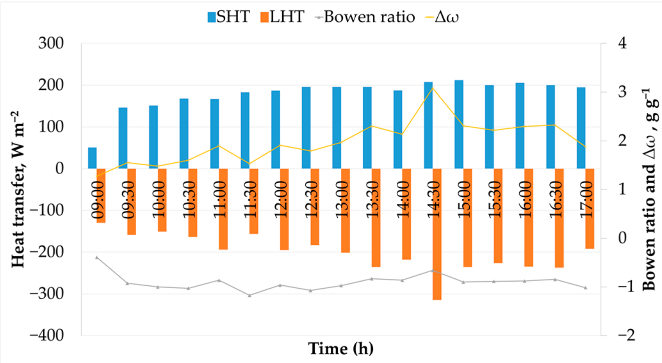
Figure 5. Variations of performance parameters the LP and LP + ESN pads with time (**a**) LP; (**b**) LP + ESN.

In the LP application, the cooling efficiency was calculated to be 38.9% on average, between 14.0 and 42.1%. The cooling efficiency of the LP + ESN pad was calculated to be 41.2% on average, between 26.9% and 47.6%. Figure 5a,b show that the decreasing relative humidity values in the outdoor environment increased the cooling efficiency. Accordingly, it has been observed that the cooling efficiency of the LP + ESN application is higher than that of the LP application. These results showed that the ESN application positively increased the evaporative cooling efficiency. In studies conducted by researchers, Al-Sulaiman [12] selected palm fibers (stem), jute, and luffa as wet pads in evaporative cooling; as a comparison, they used a commonly used commercial wet pad. The study calculated the average cooling efficiencies to be 62.1% for jute, 55.1% for luffa fiber, 49.9% for the commonly used commercial pad, and 38.9% for palm fiber. It was also reported that luffa pad has an advantage over other fibers. In a study comparing luffa and zizanoid, Kesevan [51] reported that the cooling efficiency of the loofah pad was 58% at a pad thickness of 4 cm. de Oliveira et al. [52] reported that, for a 15 cm pad width, the cooling efficiencies were 77.3% (luffa pad) and 84.5% (commercial pad). Mishra et al. [47] reported that, for the luffa pad, the cooling efficiency for a 3 cm pad varied in the range of 59.2% to 51.7% for air velocities between 0.5 and 1.5 m s^{-1}. For the 5 cm pad, ranges between 60.6% and 55.6% were found; for the 7 cm thick pad, values in the range of 65.9% to 56.8% were found. Compared with previous findings, the cooling efficiency was found to be lower than those found by [47,52]. This is because the thickness of the pad and the air speed were low. Therefore, different thicknesses, water flow rates, and air flow rates for loofah pads must be investigated.

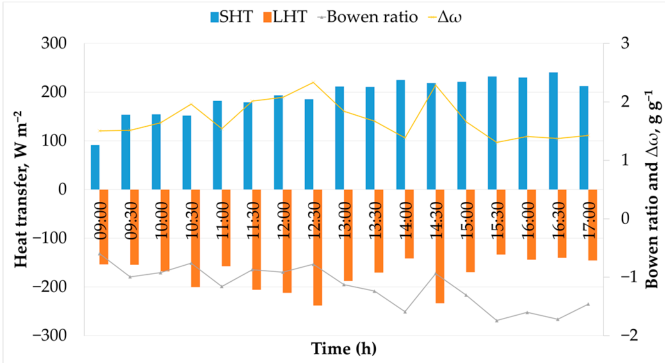
In the LP application system, the cooling capacity was calculated to be Qc = 10174.9 kJ h^{-1} (2.8 kW); meanwhile, in the LP + ESN application, the system cooling capacity was calculated to be Qc = 10740.4 kJ h^{-1} (3.0 kW). In this study, while the COP value in the system was calculated to be 11.3 for the LP application, that of the LP + ESP application was calculated to be 11.9. Moreover, the cooling capacity was higher in the LP + ESN application than in the LP application. This is due to the decrease in the greenhouse temperature values in the LP + ESN application (ΔT = 6.6 °C) compared to those of the LP application (ΔT = 6.1 °C), which had increased cooling capacity and COP. Also, Figure 5a,b indicate that lower outdoor relative humidity leads to enhanced evaporation, leading to a higher cooling capacity and a higher COP. The study conducted by Ahmadu et al. [11] studied two methods: luffa fiber + charcoal (without dehumidification) and luffa fiber + charcoal (with dehumidification). A maximum cooling capacity of 3.84 kW and a COP of 16.1 were recorded by the system without the dehumidifying pad. When the system was operating with the dehumidifying pad, a cooling capacity of 3.2 kW and a COP value of 13.4 were also recorded. Mishra et al. [47] reported that, for the 3 cm luffa pad the cooling capacity between 455 and 1203 W for air velocities between 0.5 and 1.5 m s^{-1}. Moreover, for the 5 cm pad, ranges between 478 and 1323 W were found; for the 7 cm thick pad, ranges between 508 and 1340 W were found. The researchers also reported that, for the luffa pad, the COP values found for the 3 cm pad were 4.13, 6.55, and 8.18 at air speeds of 0.5, 1.0, and 1.5 m s^{-1}, respectively. The COP values for the 5 cm pad were 4.26, 6.97, and 8.48; for the 7 cm pad, these were 4.34, 7.01, and 8.53. According to Mishra et al. [47], the cooling capacity for a given pad increases as the air velocity increases. However, the air's cooling effect is reduced at high air velocities. This is because the contact time between air and water decreases at a high velocity, reducing the rate of water evaporation. But increasing the mass flow rate at higher speeds increases the cooling capacity. In addition, the cooling capacity increases by increasing the pad thickness for the same air speed. Compared with previous findings, the thinner pad thickness (3.5 cm) reduced the cooling capacity in this study. However, increasing air speed (2 m s^{-1}) increased the cooling capacity.

In the LP application, the water consumption capacity was calculated to be $Q\omega$ = 25.2 L day^{-1} (2.8 L h^{-1}). In the LP + ESN application, the water consumption capacity was $Q\omega$ = 29.0 L day^{-1} (3.2 L h^{-1}). There was a difference of 4% for the LP and LP + ESN applications between the amount of water added to the system between 09:00 and 17:00 and the calculated daily water consumption. It was determined that this was caused by losses and leaks in the system. According to the obtained results, the water consumption in the LP + ESN application was higher than that in the LP application. Low relative humidity in the outdoor environment allowed the evaporative cooler to evaporate more water and consume more water. At the same time, the excess evaporated water contributes to an increase in cooling capacity. The water consumed in the LP + ESN application also increased the cooling capacity compared to the LP application. Ahmadu et al. [11] reported that, in the application with luffa fiber and a charcoal pad, the total water consumed was 0.99 l h^{-1} for the condition without dehumidification; this was 1.08 l h^{-1} with dehumidification. Mishra et al. [47] reported that, for the luffa pad, the water consumption for a 3 cm pad varied in a range of 0.353 to 0.930 g s^{-1} for air velocities of 0.5 to 1.5 m s^{-1}. Also, they found that, for the 5 cm pad, these values varied in a range of 0.374 to 1.262 g s^{-1}; for the 7 cm thick pad, the range was 0.418 to 1.406 g s^{-1}. The researchers also stated that, with increasing air speed, the rate at which water evaporates is increased. The water consumption in the our study was higher than that reported in the literature. This is because the higher air velocity used in this study also increased the evaporation rate, leading to increased water consumption. Given the water scarcity in the eastern Mediterranean and the necessity of reducing energy consumption in greenhouses, greenhouse cooling continues to be an economic and technical challenge [53]. This study determined a water consumption value of 1.7 L per m^2 of greenhouse floor area for the LP application and 1.9 L per m^2 for the LP + ESN application. In this case, greenhouse enterprises need to consider water consumption amounts and energy consumption for evaporative cooling.

The change in sensible and latent heat transfer per floor area in the greenhouse, depending on time, is given in Figure 6a for the LP application and in Figure 6b for the LP + ESN application from this study.



(**a**)



(**b**)

Figure 6. Variation in the sensible and latent heat transfer as a function of time: (**a**) luffa pad; (**b**) luffa pad + external shading net.

As seen in Figure 6a, for the LP application, SHT was 179.5 W m^{-2} on average, between 50.7 and 212.1 W m^{-2}. LHT was found to be −201.5 W m^{-2} on average, between −129.6 W m^{-2} and −314.9 W m^{-2}. The Bowen ratio was −0.9 on average, between −0.4 and −1.2. The difference in specific humidity achieved 2.0 g g^{-1} on average, between 1.3 and 3.1 g g^{-1}. In the LP + ESN application, as seen in Figure 6b, SHT was determined to be 193.9 W m^{-2} on average, between 91.6 and 240.9 W m^{-2}. LHT was found to be −173.9 W m^{-2} on average, between −133.4 W m^{-2} and −238.4 W m^{-2}. The Bowen ratio was −1.2 on average, between −0.6 and −1.7. The difference in specific humidity was 1.7 g g^{-1} on average, between 1.3 and 2.3 g g^{-1}. In the LP and LP + ESN applications, SHT increased due to the increase in the temperature difference (ΔT) between the outdoor and indoor areas of the greenhouse; meanwhile, LHT increased due to the increase in the specific humidity difference between the greenhouse environment and the outdoor air (Figure 6a,b). Similar to the CP and CP + ESN applications, the LP and LP + ESN applications also determined that LHT was higher than SHT when the cooling system was operating in the greenhouse. However, this increase was greater in the LP + ESN application and the greenhouse indoor environment became more suitable for plant cultivation.

3.2.3. Shading Net Pad and Shading Net Pad + External Shading Net Application

The external and internal climate parameters measured for the shading net pad and shading net pad + external shading net applications are given in Table 7.

Table 7. External and internal climate parameters measured in shading net pad and shading net pad + external shading net applications.

Applications	Measurements	T_{out}, °C	RH_{out}, %	T_{in}, °C	RH_{in}, %	VPD_{in}, kPa	VPD_{out}, kPa	Cooling Effect, °C	Cooling Efficiency, %
SNP	Max.	26.6	26.5	25.6	37.4	3.8	2.5	0.4	4.2
	Mean	31.4	34.8	27.8	47.3	3.1	2.0	3.6	24.4
	Min.	33.7	50.3	29.5	55.7	1.7	1.5	5.3	31.7
SNP + ESN	Max.	26.1	27.4	23.9	42.0	3.7	2.2	0.1	0.7
	Mean	31.1	31.8	26.7	50.1	3.1	1.8	4.4	29.1
	Min.	33.6	39.9	28.1	56.6	2.0	1.3	6.3	38.5

In the SNP application, the outdoor solar radiation value was determined to be 791.7 W m^{-2} on average, between 479.9 and 1051.9 W m^{-2}. The indoor solar radiation value was determined to be 559.9 W m^{-2} on average, between 198.7 and 795.0 W m^{-2}. In the SNP + ESN application, the outdoor solar radiation value was 639.9 W m^{-2} on average, between 123.6 and 957.4 W m^{-2}. The indoor solar radiation value was 257.6 W m^{-2} on average, between 46.1 and 424.2 W m^{-2}. In the SNP application, the solar radiation rate reaching the greenhouse environment was determined to be 70.7%. In the SNP + ESN application, the solar radiation rate reaching the greenhouse environment was found to be 40.3%.

As shown in Table 7, the cooling effect in the SNP application was 3.6 °C; for the SNP + ESN application, this was determined to be 4.4 °C. Accordingly, it has been observed that the cooling effect of the SNP + ESN application is higher than that of the SNP application. The results showed that the shading net positively increased the evaporative cooling effect. In a study on the cooling effect, Gunhan et al. [44] reported that, for a 5 cm pad thickness and four different air speeds (0.6, 1.0, 1.3, and 1.6 m s^{-1}), the cooling effects were found to be 2.67, 1.92, 1.72, 1.96 °C, respectively. The cooling effect obtained here was higher than those of previous findings. However, it was lower than those of the CP, CP + ESN, LP, and LP + ESN applications. SNP's low water retention capacity reduced the relative humidity values transferred to the indoor environment. Therefore, the cooling effect on the indoor environment decreased.

In the study, variations of some performance parameters with time are given in Figure 7a for the SNP application and Figure 7b for the SNP + ESN application.

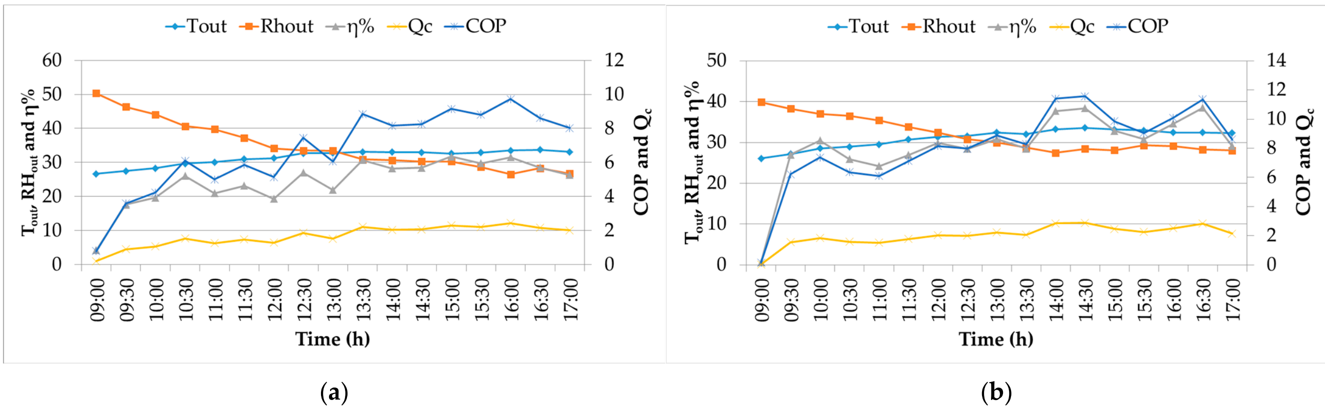


Figure 7. Variations of performance parameters the SNP and SNP + ESN pads with time (**a**) SNP; (**b**) SNP + ESN.

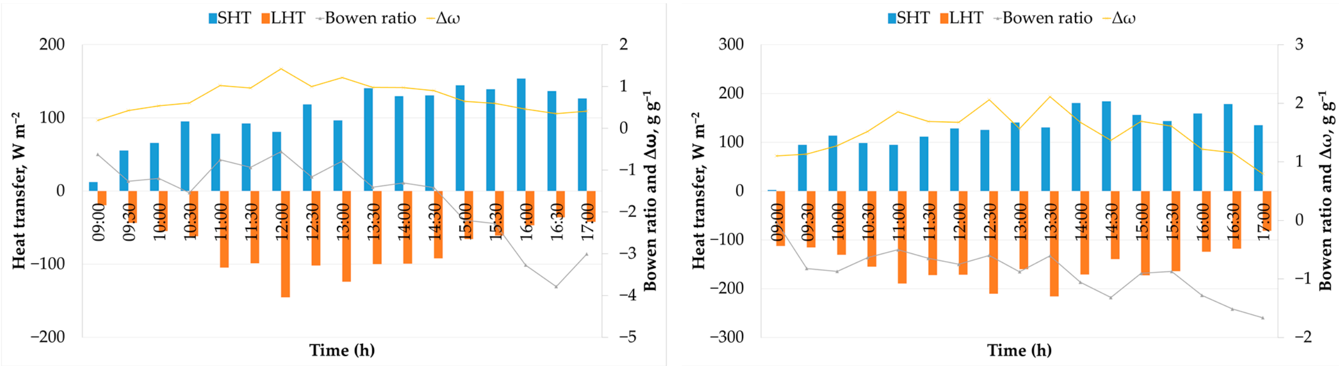
In the SNP application, the indoor relative humidity values were 12.5% higher on average than those in the outdoor environment. SNP + ESN application indoor relative humidity values were 18.2% higher than those of the external environment. According to this, in the SNP application, the outdoor VPD value is 3.1 kPa; meanwhile, the indoor VPD value is determined to be 2.0 kPa. In the SNP + ESN application, while the outdoor VPD value is 3.1 kPa, the indoor VPD value is determined to be 1.8 kPa. The increasing temperature values in the outdoor area of the greenhouse led to decreased relative humidity values in the outdoor environment (Figure 7a,b). In this case, the dry air entering the pad took in more moisture, causing the relative humidity values in the indoor environment to increase. In addition, the increasing relative humidity values in the indoor environment contributed to the decrease in the VPD values. Moreover, due to the external shading net used in the SNP + ESN application, the indoor conditions were more suitable than those of the SNP application. However, in both applications, the relative humidity was lower than that of the CP, CP + ESN, LP, and LP + ESN applications. In a study on the performance of Celdek pads, Gunhan et al. [44] reported that, for the 5 cm pad thickness and four different air speeds (0.6, 1.0, 1.3, and 1.6 m s^{-1}), the relative humidity differences were found to be 17.82%, 12.54%, 11.54%, and 12.29%, respectively. These results align with the previous findings in the literature. The indoor relative humidity values could not be increased due to the low evaporation rate in the SNP and SNP + ESN applications.

In the SNP application, the cooling efficiency was calculated to be 24.0% on average, between 4.2 and 31.7%. The cooling efficiency of the SNP + ESN application was calculated to be 28.0% on average, between 0.7% and 38.5%. Figure 7a,b show that the decreasing relative humidity values in the outdoor environment increased the cooling efficiency. Accordingly, it has been observed that the cooling efficiency of the SNP + ESN application is higher than that of the SNP application. At the same time, the ESN application positively increased the evaporative cooling efficiency. However, in both applications, the cooling efficiency was lower than that of the CP, CP + ESN, LP, LP + ESN applications. In a study on the cooling efficiency of Celdek pads, Gunhan et al. [44] calculated the evaporation saturation efficiency as 25.2% for a 5 cm pad thickness. Also, they reported that the shading net has a low saturation efficiency level. However, it was reported that the cooling efficiency of the pad with 0.6 ms^{-1} wind speed and 15 cm shading net pad was 51.3% and could be considered as alternative pad materials instead of CELdek pad. The cooling efficiency obtained in this study was near with the researcher for 3 cm pad thickness. Since evaporative cooling efficiency depends on the relative humidity of the outdoor environment and the velocity of the air passing through the pad, the results small vary. For SNP applications, cooling efficiency can be increased by increasing pad thickness and selecting low air velocities.

In the SNP application, the system cooling capacity was calculated to be Qc = 5922.8 kj h^{-1} (1.7 kW); in the SNP + ESN application, the system cooling capacity was calculated to be Qc = 7038.4 kJ h^{-1} (2.0 kW). In this study, while the COP value in the system was calculated to be 6.6 for the SNP application, that in the SNP + ESP application was calculated to be 7.8. Also, Figure 7a,b indicate that lower outdoor relative humidity leads to enhanced evaporation, leading to a higher cooling capacity and a higher COP. But, in both applications, the cooling capacity was lower than that in the CP, CP + ESN, LP, and LP + ESN applications. Moreover, the decrease in greenhouse temperature values in the SNP + ESN application (ΔT = 4.4 °C) compared to that in the SNP application (ΔT = 3.6 °C) increased the cooling capacity and the COP. Accordingly, the cooling capacity and COP values increased in the SNP + ESN application compared to the SNP. However, in both applications, lower cooling capacity and COP values were obtained compared to those of the CP, CP + ESN, LP, and LP + ESN applications due to the low cooling effect.

In the SNP application, the water consumption capacity was calculated to be Qω = 21.6 L day^{-1} (2.4 L h^{-1}). In the SNP + ESN application, the water consumption capacity was Qω = 21.9 L day^{-1} (2.4 L h^{-1}). There was a difference of 4% for the SNP and SNP + ESN applications between the amount of water added to the system (between 09:00 and 17:00) and the calculated daily water consumption. It was determined that this was caused by losses and leaks in the system. Furthermore, it was determined that 1.4 L was used per m^2 of greenhouse floor area in SNP and 1.5 L was used per m^2 for greenhouse floor area in SNP + ESN. According to the obtained results, the water consumption in the SNP + ESN application was nearly to that in the SNP application. Compared to the CP, CP + ESN, LP, and LP + ESN applications, the water consumption was lower in the SNP and SNP + ESN applications. Accordingly, the cooling effect, relative humidity, cooling efficiency, and cooling capacity values were lower. The shading net material's low water-holding capacity was important for this. According to the obtained results, compared to the other applications, the indoor environment of the greenhouse could not be brought to the appropriate temperature or relative humidity values for plant growth.

The changes in the sensible and latent heat transfers per floor area in the greenhouse, depending on time, are given in Figure 8a for the SNP application and in Figure 8b for the SNP + ESN application.



(**a**) (**b**)

Figure 8. Variation in the sensible and latent heat transfer as a function of time: (**a**) shading net pad; (**b**) shading net pad + external shading net.

As seen in Figure 8a, in the SNP application, SHT was found to be 105.7 W m^{-2} on average, between 12.1 and 153.8 W m^{-2}. LHT was −76.3 W m^{-2} on average, between −19.4 W m^{-2} and −145.3 W m^{-2}. The average Bowen ratio was −0.8, between −0.4 and −1.6. The difference in specific humidity was 0.75 g g^{-1} on average, between 0.2 and 1.4 g g^{-1}. In the SNP + ESN application, as seen in Figure 8b, SHT was found to be 128.1 W m^{-2} on average, between 2.40 and 183.7 W m^{-2}. LHT was −153.1 W m^{-2} on average, between −81.3 W m^{-2} and −215.7 W m^{-2}. The average Bowen ratio was found to be −0.9, between −0.02 and −1.7. The difference in specific humidity was 1.5 g g^{-1} on average, between 0.8 and 2.1 g g^{-1}. In the SNP and SNP + ESN applications, SHT increased due to the increase in the temperature difference (ΔT) between the greenhouse outdoor and indoor; meanwhile, LHT increased due to the increase in the specific humidity difference between the greenhouse environment and the outdoor air (Figure 8a,b). According to other applications (CP, CP + ESN, LP, and LP + ESN), the SNP and SNP + ESN applications showed higher LHT than SHT when the cooling system was operating in the greenhouse. However, in the SNP and SNP + ESN applications, the LHT values were lower than those in other applications (CP, CP + ESN, LP, and LP + ESN) due to the low evaporation effect of the pads. For this reason, the greenhouse indoor environment was unsuitable for plant growth in the SNP and SNP + ESN applications.

3.3. Energy Consumption for Evaporative System

Mediterranean countries, which have a high productivity potential due to high solar radiation levels all year round, also face disadvantages such as severe water scarcity, high air temperature, and low relative humidity levels [54]. The optimal plant growth environment of greenhouses can be maintained through extensive cooling and ventilation systems [55]. Although evaporation systems are considered a cooling solution due to the low energy required for their operation, their actual energy requirements must be analyzed [56]. In view of water scarcity in the Eastern Mediterranean and the need to reduce consumption of energy in greenhouses, greenhouse cooling continues to be an economic and technical challenge [53]. Çalışır et al. [57] compared systems of direct evaporative cooling and a vapor compression cooling. Under the same conditions, it was found that the power consumption of the split air conditioner was 1.64 kW and that of the direct evaporative cooler was 0.52 kW. If the systems operated for 1000 h, then the total annual cooling cost would be TL 295.2 per year for the split air conditioner and TL 93.6 per year for the evaporative cooling system. Accordingly, the difference in the annual energy consumption of the two units compared was found to be 1120 kWh. The researchers also stated that, given the increasing demand for electricity during the cooling season and the increase in CO_2 emissions caused by this demand, using these systems in any environment where thermal comfort can be achieved with direct evaporative cooling will provide great economic and environmental benefits. In this study, the instantaneous electricity consumption of the system is 0.25 kWh. The average electricity consumption for 9 h between 09:00 and 17:00 during the day corresponds to 2.25 kWh. Accordingly, the electricity consumption per unit area was found to be 0.15 kWh m^{-2}. In Turkey, kWh of electricity is USD 0.12. In our study, the amount of energy consumed for evaporative cooling was lower than that found in the study conducted by the researcher. Considering factors such as the energy consumption of the cooler unit used for cooling and the area it will cool, the obtained results are similar. In Turkey, vegetable prices decrease after May due to open-field cultivation. Therefore, this high cost required for cooling in greenhouses should be evaluated by producers, taking many factors into account, such as the product grown, the market price, and the water consumed by cooling processes.

4. Conclusions

In the study, the cooling effects (ΔT) in the NV and NV + ESN applications were determined to be 11.8 °C and 10.3 °C; these are higher than the indoor temperature. In the evaporative applications, the cooling effect was determined to be lower than the outdoor temperature. Accordingly, in the CP, CP + ESN, LP, LP + ESN, SNP, and SNP + ESN applications, the cooling effects were calculated to be 5.5 °C, 6.6 °C, 6.1 °C, 6.6 °C, 3.6 °C, and 4.4 °C. The indoor relative humidity values were determined to be 27.9%, 28.8%, 59.4%, 63.3%, 55.7%, 51.6%, 47.3%, and 50.1%. When the applications are compared, the indoor temperatures in the NV and NV + ESN applications increased with the increasing radiation values. Accordingly, the indoor temperature values were higher than those of the outdoor environment. In evaporative cooling applications, the indoor temperature values were lower than the outdoor temperatures. This is because the environment is cooled by providing moisture to the indoor environment with evaporative applications. In addition, the humidity given to the greenhouse environment contributes to reducing the vapor pressure deficit by increasing the relative humidity in the indoor environment.

The cooling efficiencies of the applications (CP, CP + ESN, LP, LP + ESN, SNP, and SNP + ESN) were calculated to be 37.6, 45.0, 38.9, 41.2, 24.4, and 29.1%, respectively. The cooling capacities were calculated as 2.6, 3.0, 2.8, 3.0, 1.7, and 2.0 kW and COPs 10.2, 12.1, 11.3, 11.9, 6.6, and 7.8. Water consumption values were determined to be 2.9, 3.1, 2.8, 3.2, 2.4, 2.4, and l h^{-1}. When a performance comparison was made between the applications, the cooling efficiencies and cooling capacities of the SNP and SNP + ESN applications were lower than those of other applications. The LP and LP + ESN applications showed similar characteristics to the CP and CP + ESN applications with regard to cooling efficiency and capacity. It has been determined that the production season can be extended to July and August with the CP, CP + ESN, LP, and LP + ESN applications by making the indoor climate conditions suitable for plant cultivation. In addition, reducing the relative humidity values of the air entering the cooler directly by the dehumidification method will significantly increase the cooling efficiency. The study calculated electricity consumption per unit area as 0.15 kWh m^{-2}. In the present day, where energy costs are high, providing the electricity needed for evaporative coolers directly from solar energy will reduce electricity cost. It is very important to consider the performance of cooling applications and the amount of water they consume in areas where water is limited. The study concluded that locally available luffa could be a good alternative to commercial cellulose pads among the pad materials tested. However, more studies are needed to investigate different water flow rates and pad thicknesses.

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