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DETERMINATION OF COOLING EFFICIENCY AND WATER USE FOR FAN AND PAD SYSTEMS IN A MEDITERRANEAN CLIMATE

Sedat BOYACI [1], Atılgan ATILGAN [2]

ABSTRACT

In regions with Mediterranean climates, high indoor temperatures, particularly during the summer months due to high solar radiation, limit plant growth in greenhouses. Due to the inadequacy of natural ventilation and shading practices commonly used to reduce indoor temperatures during these months, evaporative systems have become widely used in recent years. However, in regions where water is scarce, the high water volumes required for evaporative cooling are an issue that greenhouse operators should not overlook. The aim of this study was to determine the cooling effect, relative humidity effect, cooling efficiency, and water consumption of fan and pad cooling systems under Mediterranean climate conditions. For this purpose, measurements were taken in a Gothic-roofed greenhouse between June and September, when temperatures are high. The pad area used in the greenhouse was 7.5 m^2, the water flow rate was 10 L per minute per meter of pad, and the air change rate was 0.066 $m^3m^{-2}s^{-1}$. The average cooling effect, relative humidity effect, cooling efficiency, and water consumption in June were determined as 7.9 °C, 19.4%, 60.7%, and 9.82 $L{\cdot}m^{-2}$, respectively. In July, these figures were 5.6°C, 21.9%, 52.1%, and 9.73 $L{\cdot}m^{-2}$, respectively; in August, 5.4°C, 14.5%, 50.9%, and 10.2 $L{\cdot}m^{-2}$; and in September, 7.1°C, 21.2%, 55.3%, and 11.1 $L{\cdot}m^{-2}$. The study results indicate that while the fan pad system is successful in reducing greenhouse temperatures, it also results in high water consumption. Therefore, it was concluded that studies on different water flow rates and ventilation rates to reduce water consumption are necessary.

Keywords: *greenhouse, evaporative systems, fan pad, cooling efficiency, water consumption*

INTRODUCTION

Greenhouses are structures designed to improve the quality of produce by protecting out-of-season crops from adverse weather conditions outdoors (Dehbi et al., 2017). In hot climates, greenhouses

[1] *Kırşehir Ahi Evran University, Türkiye*
[2] *Alanya Alaaddin Keykubat University, Türkiye*

are specifically designed for agricultural production during the cold and temperate periods of the year. However, high summer temperatures negatively impact the growth of cultivated crops (Callejón-Ferre et al., 2009). In arid and semiarid regions, summer temperatures are characterized by daytime temperatures that can exceed 40 °C and relative humidity levels below 30% (Al-Helal et al., 2004). In Mediterranean countries, greenhouses experience high temperatures (T>35°C) and vapor pressure deficits (VPD>3 kPa) during the summer months. These conditions contribute to a decline in the quality and quantity of greenhouse produce. Therefore, various methods can be used to lower the air temperature inside the greenhouse during the hottest times of the year to allow plants to grow under more favorable conditions (Baille, 1999). Evaporative cooling systems are a common method for reducing indoor temperatures in greenhouses (Atılgan and Öz, 2007; Cámara-Zapata et al., 2020). This method is generally more efficient in areas where the air temperature is high and the relative humidity is low (Dzivama et al., 1999). Evaporative cooling is based on the principle that water absorbs heat from the air as it evaporates, lowering its temperature. These systems depend on mechanically supplying water and converting sensible heat into latent heat from the evaporating water. Throughout the process, the total heat (enthalpy) of the air remains constant (Arbel et al., 1999; Al-Ismaili and Jayasuriya, 2016). Researchers have determined that by using the fan pad system, which is one of the evaporative methods, the indoor air temperature can be reduced by 5-15°C compared to the outdoor environment and the system efficiency is approximately 80% (Kittas et al., 2003; Daives 2005; Fuchs et al., 2006; Boyacı, 2019). This feature of evaporative cooling in greenhouses allows plants to be grown during seasons when temperatures are not conducive to plant growth. Furthermore, the increased humidity inside the greenhouse due to evaporation reduces crop evapotranspiration by 60-80%, resulting in significant water savings. This is why they are gaining popularity because they significantly reduce irrigation water requirements compared to open-field farming (Fernandes et al., 2003). Johannes et al. (2009) found that water consumption of tomato plants using EVAP (PE film-covered, evaporatively cooled greenhouse: fan and pad cooling system) and NET (net-covered, naturally and mechanically ventilated greenhouse) cooling systems was 1.2 $L \cdot day^{-1}$ per plant in the fan-pad system and 1.8 $L \cdot day^{-1}$ in the net system. The fan-pad system was found to reduce evaporative loss from the plant. With these advantages, evaporative cooling systems are currently the technology used to provide cooling to greenhouses in arid regions where greenhouses are generally ventilated (Hegazy et al., 2022). However, this technology consumes large amounts of water, which is undesirable in water-scarce regions (Al-Ismaili and Jayasuriya, 2016; Montero, 2006). The amount of water required for evaporative cooling in greenhouses is much greater than that required for irrigation (Al-Mulla, 2006). In terms of total water consumption, greenhouses in arid climates are water-intensive. Therefore, fan-pad evaporative cooling systems do not solve the problem of water scarcity due to their high demand for cooling water (Al-Ismaili and Jayasuriya, 2006). Rising temperatures and irregular precipitation patterns, caused by climate change, are making the use of water increasingly important. This situation causes the sustainability of many productive irrigated areas to be threatened due to limited water resources. This threatened particularly evident in areas that rely on groundwater resources for irrigation, especially in greenhouses in the Mediterranean Basin (Sánchez et al., 2025). The development and sustainability of agriculture in arid countries around the world is constrained by two factors: high temperatures and water scarcity (Al-Ismaili and Jayasuriya, 2006). Therefore, understanding the amount of water used for cooling greenhouses is as crucial as knowing how to cool them. In regions with water constraints, excessive water consumption in evaporative cooling applications will impact the system's viability. For this purpose, indoor temperature changes, system efficiency, and monthly changes in water requirements per unit area were determined using a fan-pad cooling system in a region with a Mediterranean climate. The study results will provide insights into the use of fan-pad systems in regions with water constraints.

MATERIALS AND METHODS

The present study was conducted between June to September in the gothic type greenhouse in Türkiye with Mediterranean climate region. Long years (1930–2024) climatic datas in the study area from June to September are given in Table 1 (MGM, 2024).

Table 1. Long years climatic parameters of the experiment area.

Climatic Data	June	July	August	September
Mean temperature [°C]	25.0	28.3	28.5	25.0
Mean highest temperature [°C]	32.0	35.8	36.2	32.7
Mean lowest temperature [°C]	18,8	22.2	22.3	18.5
Mean relative humidity [%]	49.5	51.4	52.7	49.8
Mean sunshine duration [hours]	10.0	10.5	9.8	8.7

In the study area, monthly mean highest temperatures between June and September exceed the optimum upper limit of 30°C for plant cultivation. Monthly mean relative humidity ranges from 49 to 52.7%. Therefore, considering the temperature and relative humidity values outside the experiment area and the temperature increases inside the greenhouse, evaporative cooling is required for plant production between June and September.

The study was conducted in a 150 m² (7.5 m x 20 m) floor area plastic greenhouse with a Gothic roof. 7.5 m² of Celdek pad material was used on the short north-facing wall of the greenhouse. The pads were placed 50 cm high on the greenhouse floor. A 1.1 kW fan was placed on the short south-facing wall of the greenhouse. The fan flow rate was 36,000 m³/h. The amount of water delivered to the pads in the fan-pad system was 10 L per minute per meter of pad (ASAE, 1994).

In the study, one-hour temperature and relative humidity measurements were taken to determine the effects of the cooling system on the greenhouse's indoor environment. The Onset HOBO U12 temperature (Accuracy: ±0.35°C, Specification Range: −20°C to +70°C) and relative humidity (Accuracy: 2.5%, Specification Range: 5% to 95%) device was used for indoor and outdoor measurements. A flow meter was used to determine water consumption.

The difference between indoor and outdoor temperature and relative humidity values was determined using Equation 1 and Equation 2.

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

$$\Delta RH = RH_{\text{in}} - RH_{\text{out}} \tag{2}$$

where;

- ΔT is the temperature effect (°C),
- T_{in} and T_{out} are the indoor and outdoor air temperature (°C),
- ΔRH is the relative humidity effect (%),
- RH_{in} and RH_{out} are the indoor and outdoor relative humidity (%).

The cooling efficiency of the system was determined using Equation (3) (ASAE, 1995)

$$CE = \frac{T_{\text{out}} - T_{\text{in}}}{T_{\text{out}} - T_{\text{wb}}} \times 100 \tag{3}$$

where;

- *CE* is the cooling efficiency (%)
- T_{wb} is the wet bulb temperature of the outdoor air (°C).

RESULTS AND DISCUSSION

Temperature and Relative Humidity Changes in the Fan Pad System

The monthly changes in the average temperature and relative humidity values measured indoors and outdoors between the hours when the systems are operated and the monthly changes in the indoor-outdoor temperature difference depending on the outdoor relative humidity are shown in Figure 1 to Figure 4.

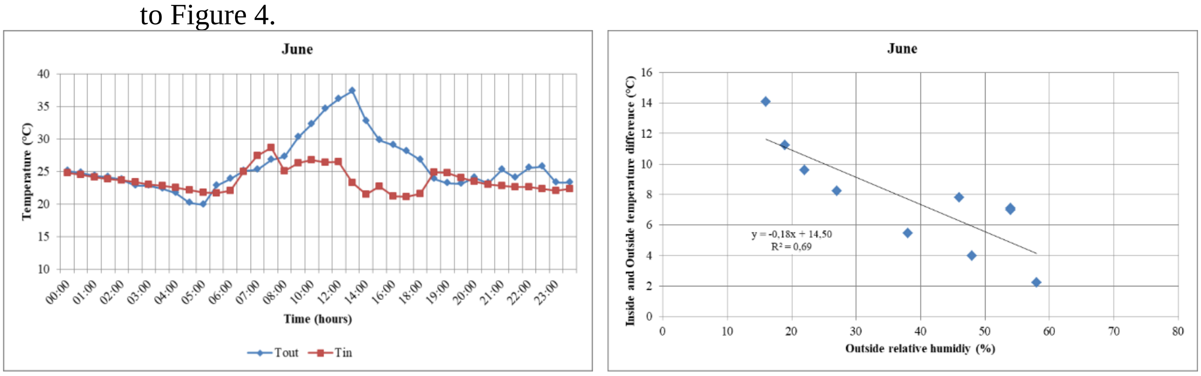

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Figure 1. In the greenhouse in June, (A) changes in indoor - outdoor temperature and relative humidity, (B) indoor-outdoor temperature difference depending on outdoor relative humidity.

Outdoor temperature values measured in June were found to be 31.9 °C on average between 28.1 and 37.4 °C. Relative humidity values varied as 38.2% between 16 and 58%. Indoor temperature values were found to be 24.0 °C on average between 21.1 and 26.6 °C, and relative humidity was 57.6% between 48 and 65%. Accordingly, the average cooling effect (ΔT) was found to be 7.9 °C between 3.2 and 13.1 °C, and the humidity effect (ΔRH) was found to be 19.4% between 4 and 32%. With increasing outdoor relative humidity, the outdoor-indoor temperature difference began to decrease. Accordingly, it was observed that cooling applications worked more effectively as the outdoor relative humidity value decreased during the day.

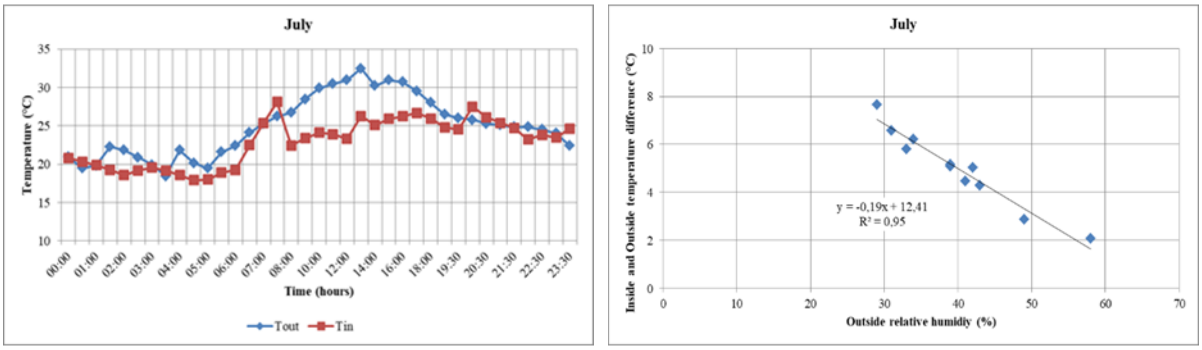

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Figure 2. In the greenhouse in July, (A) changes in indoor - outdoor temperature and relative humidity, (B) indoor-outdoor temperature difference depending on outdoor relative humidity.

Outdoor temperature values measured in July ranged from 28.0–32.5 °C, with an average of 30.0 °C. Relative humidity values varied between 29–58% and were 39.8%. Indoor temperature values ranged from 23.3–25.7 °C, with an average of 24.4 °C, and relative humidity between 50–73% and 61.7%. Accordingly, the average cooling effect was found to be 5.6 °C between 3.1–7.7 °C, and the humidity effect was found to be 21.9 °C between 13–32%. With an increase in outdoor relative humidity, the outdoor-indoor temperature difference began to decrease. Consequently, cooling applications were observed to be more effective as the outdoor relative humidity value decreased during the day.

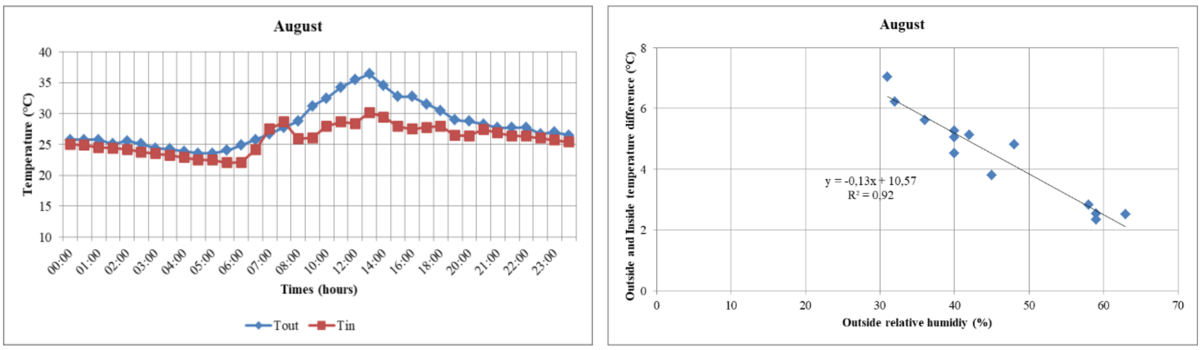

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Figure 3. In the greenhouse in August, (A) changes in indoor - outdoor temperature and relative humidity, (B) indoor-outdoor temperature difference depending on outdoor relative humidity.

Outdoor temperature values measured in August were found to be between 28.7 and 36.4 °C, with an average of 32.5 °C. Relative humidity values varied between 31 and 63% and were 44.5%. Indoor temperature values were found to be between 25.1 and 29.2 °C, with an average of 27.1 °C, and relative humidity between 52 and 68% and 59.0%. Accordingly, the average cooling effect was found to be 5.4 °C between 1.8 and 8.1 °C, and the humidity effect was found to be 14.5% between 2 and 23%. The increased indoor temperatures in August were maintained within suitable levels for plant growth thanks to the evaporative effect of the fan pad system.

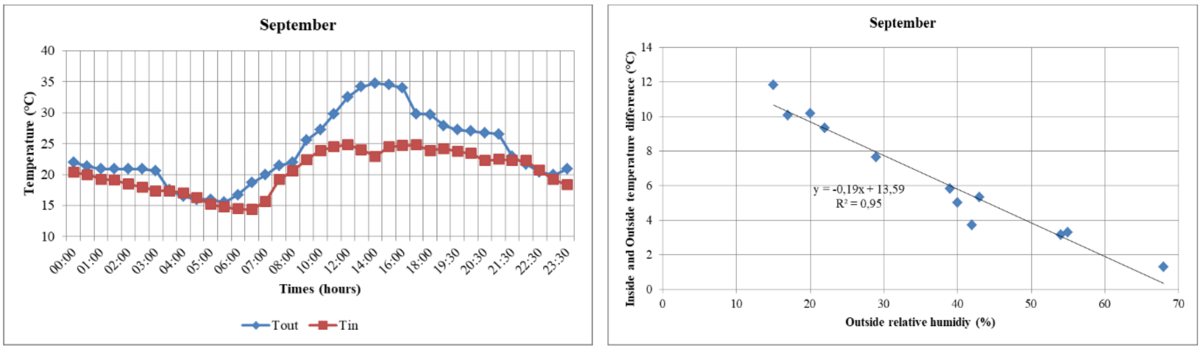

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Figure 4. In the greenhouse in September, (A) changes in indoor - outdoor temperature and relative humidity, (B) indoor-outdoor temperature difference depending on outdoor relative humidity.

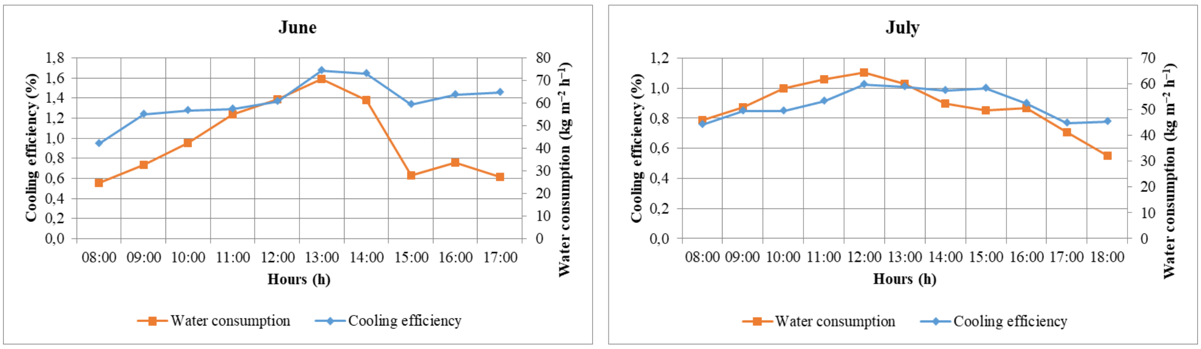
Outdoor temperature values measured in September were found to be 31.2°C on average between 28-34.7 °C. Relative humidity values varied between 15-68% and averaged 36.6%. Indoor temperature values were found to be 24.2 °C on average between 23.0-25.0 °C, and relative humidity was 57.7% on average between 50-75%. Accordingly, the average cooling effect was 7.1 °C between 3.4-11.8 °C and the humidity effect was 21.2% between 7-41%. High outdoor temperatures and the greenhouse effect increased indoor temperatures. However, the high indoor temperatures and low relative humidity values could be mitigated with a fan-pad cooling system.

Plant species grown in greenhouses require different optimum growth temperatures during each growth phase. Increasing or decreasing these temperatures directly impacts plant yield and quality parameters. In temperate climates, on clear, sunny days, due to the high amount of heat energy gained from solar radiation in the greenhouse, indoor temperatures can exceed the optimum temperature required by the plant. This increase impacts plant production and marketable fruit quality. During these periods, a cooling method should be used to control the increase in greenhouse temperature. The goal of greenhouse cultivation is to increase the efficiency of the equipment used, extend the export and production seasons, and increase yield and profitability. However, some cooling methods used to reduce interior temperatures in Mediterranean climate regions (mostly ventilation and shading) are insufficient to provide the desired interior conditions during the summer months (Sapounas et al., 2007). In studies conducted by researchers with a fan pad system, indoor temperatures could be reduced between 5-15 °C and the system efficiency varied between 40-80% (Arbel et al., 1999; Al-Amri, 2000; Kittas et al., 2001; Kittas et al., 2003; Daives 2005; Fuchs et al., 2006; Oz et al., 2009; Boyacı, 2019). Dayıoğlu and Silleli (2015) found that the hourly average temperature and relative humidity values varied between 20-27 °C and 50%-68%, respectively, with the fan-pad system. It was determined that the average temperature inside the greenhouse was 24.5 ºC when the outside air temperature was 31.4 ºC. The average cooling effect and cooling efficiency values for the fan-pad system were determined as 6.96 ºC and 76.8%, respectively. In addition, the achieved outdoor and indoor temperature difference increased due to the decrease in the relative humidity of the outdoor air. In a study conducted by Boyacı (2019), it was reported that the fan-pad system reached the highest outdoor-indoor temperature difference of 12.85 °C when the outdoor relative humidity was 16% and the lowest value of 2.01 °C when the outdoor relative humidity was 58%, and that the system was affected by the outdoor relative humidity values. The cooling effectiveness of a fan-pad system, an evaporative cooling method, depends on the relative humidity of the outdoor environment. Therefore, the higher the outdoor relative humidity, the lower the cooling effectiveness of the fan-pad system (Kumar et al., 2009). The indoor-outdoor temperature and relative humidity differences obtained in this study are consistent with the researchers' values. It was also determined that the indoor-outdoor temperature difference was affected by outdoor relative humidity values, and that decreasing outdoor relative humidity values increased the system's cooling and efficiency.

Determination of Cooling Efficiency and Water Consumption

The relationship between the cooling efficiency and water consumption of the fan pad system according to months is given in Figure 5.

In June, cooling efficiency was found to be 60.7% on average, ranging from 42–74.4%. Water consumption was 1.0 kg $m^{-2} \cdot h^{-1}$ on average, ranging from 0.6–1.6. Daily water consumption was 9.82 $L \cdot m^{-2}$ and a total of 1473 L. In July, cooling efficiency was found to be 52.1% on average, ranging from 44.3–59.7%. Water consumption was 0.9 kg $m^{-2} \cdot h^{-1}$ on average, ranging from 0.6–1.1. Daily water consumption was 9.73 $L \cdot m^{-2}$ and a total of 1459 L. In August, cooling efficiency was found to be 50.9% on average, ranging from 26.4–61.0%. Water consumption was 0.9 $kg \cdot m^{-2} \cdot h^{-1}$ on average, ranging from 0.5–1.2. Daily water consumption was 10.2 L m^{-2} and a total of 1523 L. In September, cooling efficiency was found to be 55.3% on average, ranging from 33.4% to 70.0%. Water consumption was 1.0 $kg \cdot m^{-2} \cdot h^{-1}$, ranging from 0.4% to 1.5%. Daily water consumption was 11.1 $L \cdot m^{-2}$ and a total of 11659 L.



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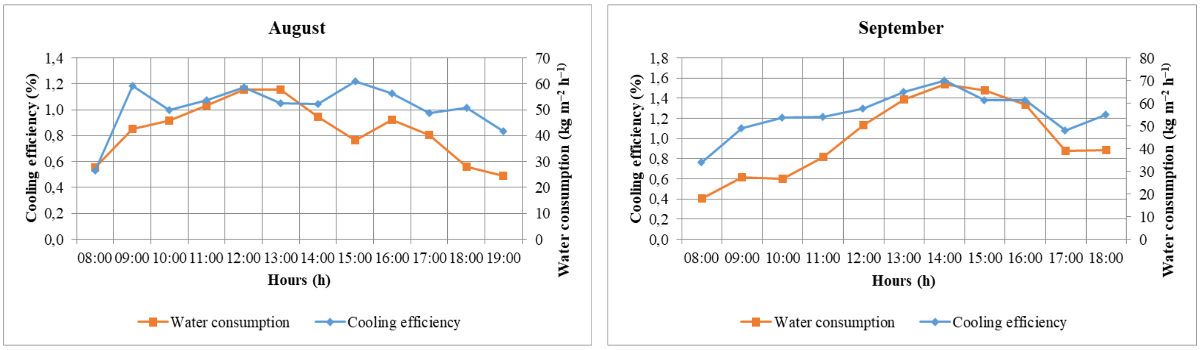

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Figure 5. Change in cooling efficiency and water consumption in the fan pad system (A) water consumption and cooling efficiency in June, (B) water consumption and cooling efficiency in July, (C) water consumption and cooling efficiency in August, (D) water consumption and cooling efficiency in September.

Fresh vegetable production in greenhouses located in arid regions generally takes place in greenhouses with evaporative cooling applications during the warm months of the year. However, during this period, the amount of water used for indoor cooling can exceed the amount of water used for irrigation of plants (Tsafaras et al., 2021). Fadel et al. (2014) stated that in arid climate conditions, the amount of water used in the fan and pad system accounts for 58.0% of the total water consumption in the greenhouse. Al-Mulla (2006) reported that it accounts for 67% of the gross greenhouse water consumption. Sustainable solutions are needed to overcome the impacts of environmental constraints on food production. Sustainable solutions in regions with harsh climates should combine efficient cooling technologies with smart water management and energy optimization (Muhie, 2022; Trepanier and Gosselin, (2024). In studies on water consumption of the fan pad system, Sabeh et al. (2006) reported that the air exchange rate in a greenhouse where tomatoes were grown affected water use. The average water usage of the fan-pad system was found to be 0.145, 0.182, 0.265, 0.325 and 0.387 $g \cdot m^{-2} \cdot s^{-1}$ for air exchange rates in the greenhouse of 0.017, 0.037, 0.051, 0.067 and 0.079 $m^3 \cdot m^{-2} \cdot s^{-1}$, respectively. It was noted that increased cooling efficiency also increased water consumption. Furthermore, considering 100% drainage recovery, the water consumption of the fan-pad cooling system (14.8 $L \cdot m^{-2} \cdot day^{-1}$) was higher than that of the tomato irrigation system (8.9 $L \cdot m^{-2} \cdot day^{-1}$). Sabeh et al. (2007) compared greenhouses where tomatoes were grown and fan-pad and high-pressure fogging were used. The total daily water usage of the fan pad was 3.2, 6.4, 8.5, and 10.3 $L \cdot m^{-2}$ for ventilation rates of 0.016, 0.034, 0.047, 0.061 $m^3 \cdot m^{-2}\ s^{-1}$, respectively. Total daily water use by the high-pressure-fog system was 7.9, 7.4, and 9.3 $L \cdot m^{-2}$ for fan ventilation rates of 0.01, 0.016, 0.034 $m^3 \cdot m^{-2}\ s^{-1}$, respectively. Total greenhouse water use efficiency was calculated using hydroponic irrigation (4.5 $L \cdot m^{-2}$) and evaporative cooling water consumption. Tsafaras et al. (2021) found that the contribution of evaporative cooling to total water consumption varied daily throughout the year based on weather conditions. Notably, daily water usage for irrigation ranged from 2 $L \cdot m^{-2}$ during the darker period to 5–6 $L \cdot m^{-2}$ during the summer. The amount of water used for evaporative cooling ranged from zero in winter to 35 $L \cdot m^{-2}$ and 20 $L \cdot m^{-2}$ in the plastic tunnel and Venlo-type greenhouse, respectively, during the summer. In this study, the amount of water consumed at a ventilation rate of 0.067 $m^3 \cdot m^{-2} \cdot s^{-1}$ for the fan pad system showed similar characteristics to those reported by Sabeh et al. (2006) and Sabeh et al. (2007). However, due to climatic conditions, it was lower than the values reported by Tsafaras et al. (2021). Additionally, increasing the amount of evaporated water reduced indoor greenhouse temperatures. However, increasing the amount of water consumed to cool the indoor environment is a significant problem in water-scarce areas. Therefore, considering water consumption as well as cooling effectiveness in evaporative cooling applications is crucial. Because the amount of water consumed in a fan pad system used in situations where temperatures do not permit plant growth can exceed the daily water consumption of plants.

CONCLUSION

The results of the study presented here indicate that indoor temperatures can be reduced with fan-pad cooling systems during periods when high temperatures in greenhouses in regions with Mediterranean climates inhibit plant growth. Evaporative cooling systems are cooling methods that consume less energy and provide adequate indoor thermal comfort. This method, based on the principle of converting sensible heat into latent heat, is based on the conversion of water vapor into sensible heat. However, the large amount of water evaporated due to outdoor climate conditions is a limiting factor in water-constrained regions. However, measures to increase cooling efficiency and reduce water consumption include: (1) checking airtightness in different areas of the greenhouse, (2) selecting fans of appropriate capacity to ensure the correct amount of air exchange in the greenhouse, (3) considering the manufacturer's recommendations, as the amount of water evaporated from the pad varies depending on the pad material, (4) checking appropriate water flow rates, (5) checking system connections to reduce water circulation losses, (6) ensuring the reuse of water recovered from drainage, and (7) managing greenhouse air conditioning with automated systems, if possible. These measures will not only increase system efficiency but also contribute to reducing the amount of water consumed.

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Corresponding Author: Sedat Boyacı
ORCID: 0000-0001-9356-1736
e-mail: sedat.boyaci@ahievran.edu.tr

Department of Biosystems Engineering
Faculty of Agriculture
Kırşehir Ahi Evran University
40100-Kırşehir, Türkiye

Atılgan Atılgan
ORCID: 0000-0003-2391-0317

Department of Biosystems Engineering
Engineering Faculty
Alanya Alaaddin Keykubat University
07425, Antalya, Türkiye

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