



Research paper

Intelligent greenhouse design decreases water use for evaporative cooling in arid regions

I. Tsafaras^{a,*}, J.B. Campen^a, C. Stanghellini^a, H.F. de Zwart^a, W. Voogt^a, K. Scheffers^a,
A. Al Harbi^b, K. Al Assaf^c

^a Wageningen University and Research, Business Unit Greenhouse Horticulture, P.O. Box 644, 6700 AP Wageningen, Netherlands

^b King Saud University, Riyadh, Kingdom of Saudi Arabia

^c SABIC Sustainable Agricultural Centre (Estidamah), King Saud University, Riyadh, Kingdom of Saudi Arabia



ARTICLE INFO

Handling editor: Dr Z Xiyang

Keywords:

Evaporative cooling
Water use efficiency
Greenhouse design
Pad and fan
Water saving
Greenhouse climate simulation

ABSTRACT

Production of vegetables for fresh consumption in arid regions usually takes place in greenhouses with evaporative cooling during the warm months of the year. In this period, water use for cooling easily exceeds irrigation water use. The purpose of this paper is to investigate how far water use for evaporative cooling can be lowered by adapting design elements of the greenhouse and the evaporative cooling system. In a greenhouse trial in a desert environment, in Riyadh (KSA), two different greenhouses: one traditional and one modified, both equipped with a pad and fan system, have been compared in terms of productivity and water use with main focus on water use for cooling. The modified greenhouse design resulted in about 14% higher fresh weight production and more than 40% water saving was achieved on evaporative cooling. The climate and water use data recorded during the trial were used to validate a greenhouse climate simulation model including pad and fan cooling. Then, we used the validated model in a scenario study and we quantified the effect of each one of three design elements on use of cooling water. It was shown that the extracted air temperature has a major influence on water use for cooling. Increasing the extracted air temperature with 4 K resulted in about 27% saving in water use for cooling. The latter was done by repositioning of the exhaust fans in order to take advantage of the vertical air temperature gradient in the greenhouse. Additionally, a 5% higher cooling efficiency of the pad wall could yield an extra 12% water saving for evaporative cooling. Finally, the greenhouse cover-to-ground area ratio was also found to affect the water use for cooling. In summary, we have shown that there is much scope for saving on water use for evaporative cooling by improving design of greenhouses and of the cooling system, and that a good greenhouse climate model can be a useful tool in this process. The findings of the current research provide clear guidelines for the construction of more water efficient evaporatively cooled greenhouses.

1. Introduction

Fresh vegetable production needs to be increased in the upcoming years to ensure a healthy diet for everybody (Krishna Bahadur et al., 2018). Although plentiful solar radiation would seem to provide semi-arid and arid regions with great potential for agricultural operations, it is the high temperature which does not, as it typically rises above optimal values. This is the case for most of Saudi Arabia, with an average yearly sun radiation sum of 7.6 GJ m⁻² and mean monthly maximum temperatures between 39 °C and 46 °C for at least 5 months each year. When such values occur, relative humidity does not exceed 20%, being less than 10% during the day, particularly in the central

region of the country (Al-Helal et al., 2004). This is the reason why vegetable production in Saudi Arabia takes place in greenhouses equipped with evaporative cooling, usually pad and fan systems (Al-Helal et al., 2004, 2007). Of course the dry climate of the country ensures a large effect: under the aforementioned typical weather conditions an evaporative cooling system can reduce the air temperature by more than 20 K while increasing the humidity, thus creating a favorable climate for vegetable production. Evaporative cooling has been shown to deliver conditions more favorable than natural (or even forced) ventilation also in less dry conditions than deserts, for instance the island of Cyprus (Nikolaou et al., 2019).

However, evaporative cooling is attained at the expense of large

* Corresponding author.

E-mail address: ilias.tsafaras@wur.nl (I. Tsafaras).

<https://doi.org/10.1016/j.agwat.2021.106807>

Received 9 June 2020; Received in revised form 16 January 2021; Accepted 8 February 2021

Available online 1 March 2021

0378-3774/© 2021 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

amounts of water. Fuchs et al. (2006) demonstrated that the amount of water consumed in such systems easily exceeds the water use for irrigation, whenever ambient relative humidity is lower than about 50%. Hence, the cooling process is the major component of water use in greenhouses in Saudi Arabia, as well as in other arid or semi-arid regions. Sabeh et al. (2011) reported 4 times higher water consumption for (evaporative) cooling (62 L) than for irrigation (15 L) per kg of produced tomatoes during their experiment. Given the fact that water is a scarce and valuable resource in the arid and semi-arid regions, the importance of water efficient production systems is crucial. It is impossible to overstate the importance of efficient water use in Saudi Arabia, a country covered by 95% by desert, with an average of 114 mm rainfall per year. Yearly withdrawals add up to an astounding 1056% of its total renewable water resources (Napoli et al., 2018), with (fossil) groundwater accounting for the rest. The worrying rate of depletion of groundwater resources, 88% caused by agriculture, was indicated by FAO (2017), which observed that the water used in agriculture in 2017 was 3 times more than in 1980 (FAO, 2008).

Several factors ensure that greenhouses have a higher water use efficiency than open field production (Stanghellini, 2013). Scientific research and technological developments during the last years have resulted in new growing techniques and new greenhouse designs that reduce water use (Katsoulas et al., 2015). A closed irrigation loop allows drain re-use, and it can reduce the use of irrigation water and fertilizers by 20–30% compared to an open irrigation system (Stanghellini et al., 2003). As water use for evaporative cooling is the major component of water use in greenhouses in dry regions, research should also focus on reducing water use for cooling.

Carefully maintained pad walls that are not clogged and variable speed fans are reported to reduce the water use for cooling in pad and fan systems (Al-Helal et al., 2004, 2007; Kittas et al., 2003; Sabeh et al., 2011, 2007; Sethi and Sharma, 2007). However, to the knowledge of the authors, there is no published scientific research showing a detailed comparison of the effect of different greenhouse designs on water use for evaporative cooling by pad and fan systems in arid regions.

The current paper evaluates the options for reducing water use of pad and fan cooling systems, by improving the design of the greenhouse and the cooling system. In particular, we focus on means to increase the efficiency of the cooling system by extracting air from the greenhouse at the highest possible temperature, and on how both the ratio of cover-to-ground area and the cooling efficiency of the pad wall affect cooling water use. This is done through simulation studies, supported by information obtained from greenhouse trials at the National Research and Development Center for Sustainable Agriculture (Estidamah), in Riyadh, Saudi Arabia. The Estidamah research center, a cooperation of the Saudi Government, the company SABIC, King Saud University and Wageningen University and Research, is in operation since late 2016 with the primary goal to carry out research on water saving techniques and greenhouse design adapted to the Saudi climate conditions.

2. Materials and methods

The data collected during an experiment in 2 different greenhouse compartments in Estidamah were used to validate a greenhouse climate simulation model including pad and fan cooling. Thereafter we ran a scenario study to predict the effect of three design elements on use of cooling water. The elements that were considered are: (a) the exhaust air temperature as a direct result of the positioning of the exhaust fans, (b) the greenhouse cover to ground ratio and (c) the cooling efficiency of the pad wall.

2.1. Greenhouse experiment

2.1.1. Greenhouses and climate control equipment

The experiment was carried out in two different greenhouse compartments in Estidamah research center in Riyadh (24.7°N, 46.7°E). The

first greenhouse compartment (similar to the typical design of the region, from now on named Lower-Technology and indicated as L) is a single plastic tunnel (40 m × 8 m of which 288 m² is growing area in 5 crop rows, gutter height 3 m and total height 5.4 m), covered with polyethylene film and equipped with a pad and fan system consisting of a cellulose pad wall (8 m × 2 m × 15 cm) and 3 fans with capacity of 15,000 m³ h⁻¹ each, adding up to a total air exchange capacity equal to 140.6 m³ m⁻² h⁻¹ (equivalent to a maximum of 33 volume exchanges per hour). The fans are “on-off” controlled and they can be operated independently from each other. Two of the three fans are placed 2 m above the ground and the third 1.6 m higher than the other two (Fig. 1A).

The second greenhouse compartment (Medium-Technology and indicated as M) is a Venlo type greenhouse, (40 m × 12 m of which 432 m² is growing area in 8 crop rows, gutter height 6.5 m, ridge height 7.3 m and span width 4 m) covered with standard horticultural tempered glass. The greenhouse compartment is part of a bigger greenhouse complex and is equipped with rail pipe heating system, high pressure fogging system (0.4 L m⁻² h⁻¹), shading screen (50% shading percentage) and a pad and fan system consisting of a plastic pad wall (12 m × 3 m × 15 cm) and 6 frequency-controlled fans with capacity of 15,000 m³ h⁻¹ each. The total air exchange capacity reaches 187.5 m³ m⁻² h⁻¹, equivalent to 27 volume exchanges per hour. All the fans are placed 5 m above the ground. The ground is covered with white reflective plastic foil (Fig. 1C and D).

The fans in both greenhouses were extracting air, that was drawn in through the pad wall at the other end of the greenhouse. This “depression” operation is much more common (and usually more efficient) than the opposite version.

The transmissivity of both greenhouses was determined by comparing values of 2 calibrated PAR sensors, one placed at a not shaded place outside the greenhouse and the other moved with constant speed (0.5 m s⁻¹) along the crop lines at the height of the crop wire. Each sensor was logged every 2 s. The average transmissivity of the L greenhouse was 48%, whereas transmissivity of the M greenhouse was 62%. The higher transmissivity of the M greenhouse in comparison to the L is mainly the result of both different covering material and less construction elements per unit ground area. Additionally, the cover of the M greenhouse was frequently cleaned with a roof washer machine to remove the accumulated dust; this operation could not be applied on the cover of the L greenhouse, which did enhance the difference in transmissivity between the two greenhouses.

2.1.2. The crop

The crop was a round tomato (*Solanum Lycopersicon L.*) variety (“Tone Guitar” from Seminis), for loose harvest. The plants were sown on 27th January 2019, transplanted in the greenhouse on 24th February and the first harvest took place on 5th May. The experiment was finalized on 23rd December 2019. In both greenhouses the plants were grown on a hydroponic system (using stone wool as substrate) that allowed drain collection (Fig. 1B and D). All plants were grown on a high wire system with a stem density of 5 stems per m². The marketable weight of each harvest (twice a week) was recorded for the each greenhouse, excluding the side rows.

2.1.3. Climate and fertigation control

The climate and fertigation control as well as the data collection were arranged through a greenhouse process control computer (HortiMaX MultiMa). In each greenhouse there were 3 ventilated measuring boxes to record the temperature and humidity values, all placed in one middle crop row. The first measuring box (Sensor 1) was placed 5 m away from the pad wall; the second measuring box (Sensor 2) was placed in the middle of the crop row; and the third one (Sensor 3) about 5 m away from the exhaust fans (Fig. 2). All three measuring boxes were maintained at the height of the top of the crop. The average of the three measuring boxes was used by the climate computer for control purposes



Fig. 1. View of the greenhouses where the described experiment took place. The L plastic tunnel from outside (A) and inside (B) and M glass Venlo greenhouse (C and D) where the exhaust fans are placed high above the crop (C).

and also in this study as (mean) greenhouse air temperature.

The temperature in both greenhouses was maintained between 25 and 28 °C during the day and between 18 and 20 °C during the night. The relative humidity was fluctuating between 65% and 85% during the day depending on the operation of the pad and fan system and the status of the crop. The cooling setpoint was set at 26 °C during the day and 19 °C during the night period with small variations for crop steering purposes. Fogging in the M greenhouse was used only at the beginning of the growing season to increase humidity. During the night, the relative humidity was maintained around 75–80%. The shading screen in the M greenhouse was only used during the first two months of the trial, whenever global radiation exceeded 800 W m⁻².

The irrigation water including liquid fertilizers was supplied through drip irrigation in both greenhouses. The pH and EC of the irrigation and drain, as well as the concentration of each individual macro and micro nutrient were monitored on a regular basis to ensure that the crop would not face any deficiency. The irrigation supply was based on external sun radiation, starting with smaller amounts (about 0.5 cc per m² per Joule) and increasing gradually to follow the growth of the crop (reaching about 3 cc per Joule for a fully grown crop).

The irrigation water for all greenhouses and the water used in the fogging system was treated with a reverse osmosis unit. The collected

drain from the greenhouses was disinfected (UV disinfection unit) and reused.

2.1.4. Calculation of water consumption and water use efficiency

The water use (WU) of the greenhouses was calculated as the water input to the system minus the amount of recovered and re-used water:

$$WU = W_i + W_{pw} + W_f - W_d \quad [L \text{ m}^{-2} \text{ time}^{-1}] \quad (1)$$

where the water supplied for irrigation (W_i), the water supplied to (and evaporated by) the pad walls (W_{pw}) for cooling purposes and the water used by the fogging system (W_f) (where applicable) are the input water flows. The recovered and reused water consisted of the collected drain water (W_d). All aforementioned water flows are measured with flowmeters connected to the process control computer and all data are recorded digitally with an accuracy of 1 L.

2.2. Simulation study

The dynamic greenhouse climate simulation model KASPRO (De Zwart, 1996) was used to compute the water use for the pad and fan cooling system.

KASPRO simulates the greenhouse climate as well as the energy and

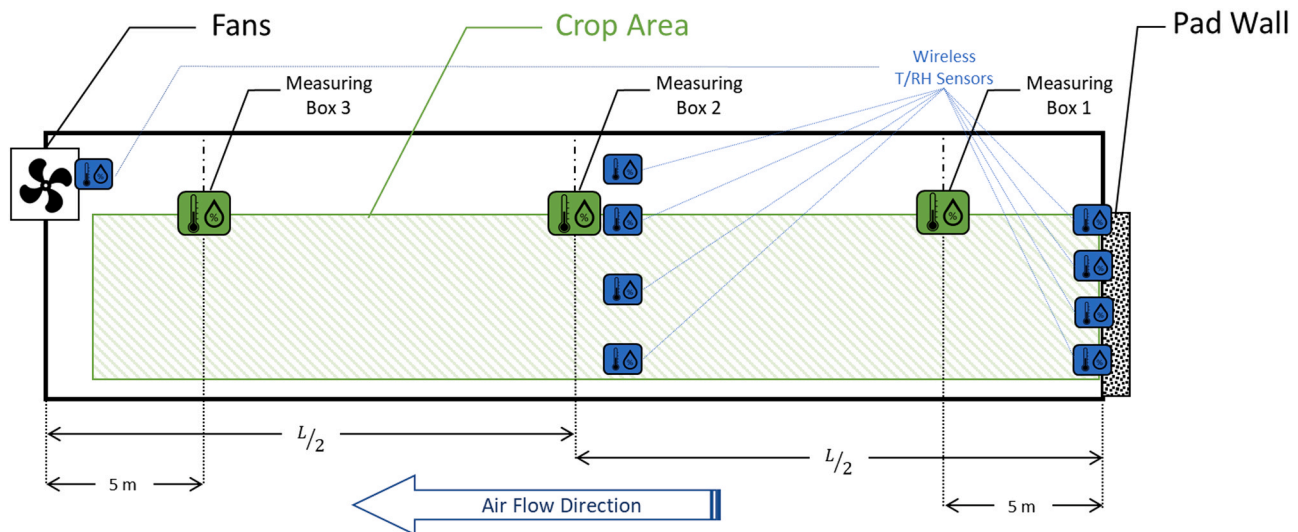


Fig. 2. Graphical representation of the permanent (measuring boxes shown in green) and temporary additional (wireless, shown in blue) sensors placement in a cross section of a greenhouse. The green patterned rectangle represents the crop area. The exact dimensions of greenhouse length (L), height and fan position are different for the 2 analyzed greenhouses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mass fluxes, based on the computation of all relevant heat and mass balances. The heat balances include both the convective and radiative processes. The mass balances include both exchange processes of gases (air, water vapor, etc.) and phase changes such as canopy transpiration (Stanghellini, 1987), condensation on cold surfaces and evaporation. KASPRO can simulate a full-scale greenhouse based on the construction elements, greenhouse equipment such as heating, cooling, screening, lighting and misting, different covering materials and their properties (transmissivity, reflectivity, emissivity), crop type (climate requirements and characteristics e.g. leaf area and transpiration), set points for inside climate and the outside weather conditions of a given location. A replica of commercially available climate controllers is used to control greenhouse climate. The output of the model includes climate variables, and energy and mass fluxes.

First, the model was validated with the measured climate and water use data for both greenhouses, for the period of the experiment. Then, the model was used in desk studies to compute the effect on water use of: (a). the temperature of the air extracted by the fans; (b). the cover surface to ground ratio of the greenhouse and (c). the (cooling) efficiency of the pad wall.

2.2.1. The pad and fan module of the simulation model

By simulating the greenhouse climate with the aid of the local weather conditions, the crop and the applied climate strategy, the model can calculate the water evaporation from the pad wall for a given time, based on the energy balance:

$$WU_{PW} \cdot \Delta H_{VAP} \cdot \rho_W = \Delta T_{PW} \cdot C_V \cdot \rho_{AIR} \cdot \varphi \quad (2)$$

where: WU_{PW} ($L m^{-2}$) is the amount of water evaporated from the pad wall per greenhouse area; ΔH_{VAP} ($kJ kg^{-1}$) is the latent heat of vaporization of water; ρ_W ($kg L^{-1}$) is the water density; C_V is the specific heat of air ($kJ kg^{-1} K$); ρ_{AIR} ($kg m^{-3}$) is the air density and φ ($m^3 m^{-2}$) is the air flow through the pad wall per unit ground area. ΔT_{PW} (K) is the air temperature drop at the two sides of the pad wall, calculated as the difference between the temperature (dry bulb) of the air outside (T_{OUT}) and of the air leaving the pad wall inside the greenhouse (T_{PW}):

$$\Delta T_{PW} = T_{OUT} - T_{PW} \quad (3)$$

The temperature of the air leaving the pad wall (T_{PW}) is calculated based on the cooling efficiency (η) of the pad wall and the outside weather conditions, namely temperature (T_{OUT}) and humidity:

$$\eta = \frac{T_{OUT} - T_{PW}}{T_{OUT} - T_{OUT,WB}} \quad (4)$$

where $T_{OUT,WB}$ is the wet bulb temperature of the outside air (ASAE, 1995; Kittas et al., 2003). The cooling efficiency of the pad wall is an input for the model.

Finally, the net cooling effect of the pad wall (P_{COOL} [$W m^{-2}$]) is the amount of sensible heat removed from the greenhouse air. This is proportional to the temperature difference (ΔT_{PF} (K)) of the outlet air (leaving the greenhouse through the fans, T_F) from the inlet air (going in through the pad wall, T_{PW}) (Eq. 6):

$$P_{COOL} = \Delta T_{PF} \cdot \rho_{AIR} \cdot C_V \cdot \varphi \quad (5)$$

$$\Delta T_{PF} = T_F - T_{PW} \quad (6)$$

The calculation of the outlet air temperature (T_F) is crucial as it affects the cooling effect and thus the water use of the system. Given the fact that in greenhouses equipped with pad and fan systems, temperature differences are usually observed over the horizontal and vertical direction (Kittas et al., 2003; Nikita-Martzopoulou et al., 2008), T_F might differ from the average greenhouse air temperature (T_{IN}). The model used in the present study, KASPRO, is a “stirred tank” model which does not account for spatial temperature differences. Therefore a correction factor (Outlet Temperature Above Mean / OTAM (K)) was included in the model and added to the mean greenhouse air temperature (T_{IN}) to account for these spatial temperature differences (Eq. 7). This correction factor is a user input. In the present study, the value of OTAM is estimated from in-situ measurements (see Section 2.2.2 below) and it is assumed constant.

$$T_F = T_{IN} + OTAM \quad (7)$$

2.2.2. Determination of the input parameters for the model validation

As the cooling efficiency of the pad wall and the OTAM are required inputs for the model, they were estimated, through additional measurements, carried out with the use of wireless sensors (Wireless Value BV). During one week in July 2019, air temperature was monitored at different heights and locations of the greenhouse (Fig. 2). Specifically, four sensors were placed a few centimeters in front of the pad wall. The average of these four measurements was used as the T_{PW} . Four sensors were placed in the middle of the greenhouse (at the same location where the second measuring box was placed) and spread over the vertical

direction so that the lowest was about 30 cm above the gutter, the next one in the middle of the height of the canopy, the third one at the top of the canopy (next to the greenhouse measuring box) and the highest one 50 cm and 1 m above the top of the crop in the L and M greenhouse respectively. The highest sensor measured the temperature at the area above the crop so it was placed higher in the M greenhouse where this area is much larger than in the L. Finally, one sensor was placed in front of each exhaust fan for the determination of the exhaust air temperature (T_F). The average value of in total three sensors in the L greenhouse and six sensors in the M greenhouse was considered as T_F .

The value of OTAM was calculated (based on Eq. (6)) as the difference of T_F from greenhouse air temperature (T_{IN}). The latter was the average measured value of the three measuring boxes hanging along one middle crop row at the top of the crop.

The pad wall cooling efficiency was calculated based on Eq. (4) where T_{PW} was obtained from the additional measurements described above and T_{OUT} from the weather station of the greenhouse.

As both the OTAM and the pad wall cooling efficiency are constant parameters in the model, the average of the values obtained during the analyzed period was finally used as input for the simulations.

2.2.3. Scenario studies

After model validation, the simulation study aimed to quantify the effect of three factors related to the greenhouse design and operation, namely the OTAM, the greenhouse cover to ground area and the cooling efficiency of the pad wall, on the water use by the pad and fan system. Therefore, three groups of scenario simulations were conducted. In each group of simulations only the studied factor varied between the simulations and all the other model parameters were not changed.

As shown in Eqs. (5)–(7), the value of OTAM directly affects the cooling effect of a certain amount of extracted air. It can be easily concluded that higher values of OTAM require less air exchange to obtain a desired cooling effect. Therefore, the amount of incoming air and the water use by the pad wall is reduced. The exact effect of OTAM on water use by the pad and fan system was shown by calculating 25 scenarios of the same cropping season, whereby the value of OTAM was increased from 0 to 12 K with a step of 0.5 K and maintained constant per scenario. All the other inputs (greenhouse and equipment characteristics, climate control setting, crop) were the same in all scenarios. The described scenarios were performed for both the L and M greenhouse.

In both the measured and simulated data, the cooling requirements and the water use are expressed per m^2 of greenhouse area. Taking into account that a greenhouse in the studied weather conditions is heated up via both radiative (solar radiation) and convective heat transfer between its cover and the (usually warmer) outside environment, the ratio of cover to ground area also affects the amount of energy that has to be extracted per m^2 and therefore the water use. In practice, this means that we expect the cooling requirements (per unit ground area) of a single tunnel or single span greenhouse to exceed the cooling requirements of a multi tunnel or multi span greenhouse. Ten simulations for each type of studied greenhouse type (L and M) were performed where the parameter cover to ground area in the model was adapted to correspond to greenhouses with 1 (single) to 10 (multi) tunnels or spans.

Finally, the cooling efficiency of the pad wall affects the water use of the cooling system. For both greenhouses simulations with cooling efficiencies varying from 0.3 to 1 with a step of 0.05 were performed to quantify the effect of pad wall's cooling efficiency on water use.

3. Results

3.1. Greenhouse climate

Despite the harsh weather conditions in Saudi Arabia, in both greenhouses the evaporative cooling systems managed to maintain greenhouse air temperature and humidity in the desired range. A pad

wall can theoretically (efficiency 100% according to Eq. (4)) cool the air up to the wet bulb temperature. Under the dry weather in Riyadh area (Fig. 3A) the wet bulb temperature was on average 8 K (winter) to 20 K (summer) lower than the dry bulb temperature, explaining why the pad and fan systems were well capable to maintain the greenhouse air temperature in the desired range, up to 14 K lower than outside on average (Fig. 3B).

Air temperature and humidity were for the most time similar in both greenhouses. During the early summer period the temperature in the M greenhouse was maintained 0.7–1 K higher than in L (Fig. 3B), for crop steering purposes, in view of the higher light intensity, thanks to the higher transmissivity of the M greenhouse. Additionally, the heating system in the M greenhouse ensured higher night-time temperatures during the short cold periods at the beginning and the end of the growing period. Finally, during the same periods, natural ventilation was sometimes used instead of evaporative cooling in the M greenhouse, resulting in slightly lower humidity in comparison to the L greenhouse which was always cooled with the pad and fan system.

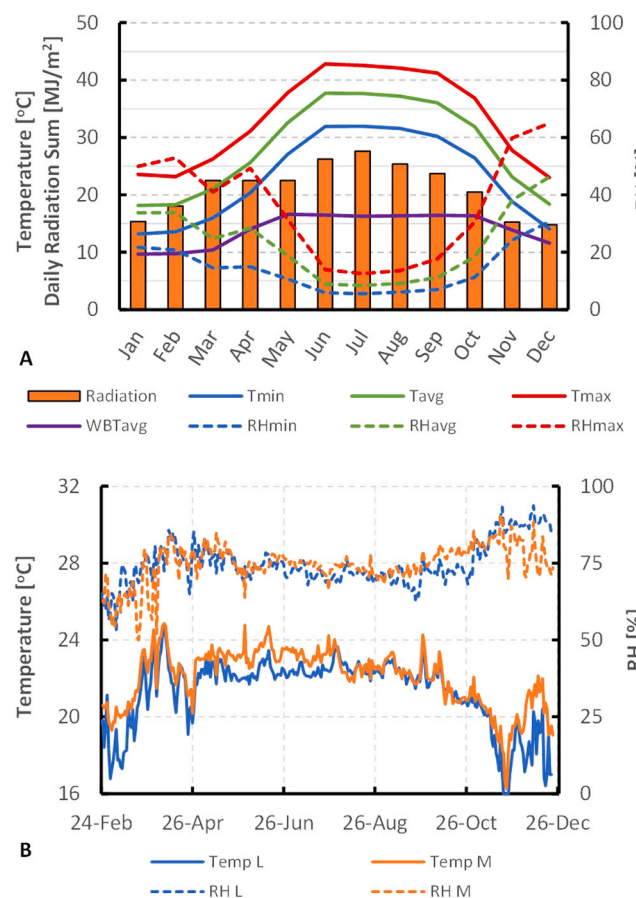


Fig. 3. Measured outside weather conditions during 2019 (A) and realized greenhouse climate during the period of the trial (B). Specifically, the average daily radiation sum per month (orange bars), average, minimum and maximum monthly temperatures (green, blue and red continuous lines respectively) and average, minimum and maximum monthly relative humidity (green, blue and red dashed lines respectively) are presented in A. Additionally, the (average monthly) wet bulb temperature (purple line) is presented to indicated the cooling potential of an evaporative cooling system. Greenhouse climate, specifically daily average greenhouse temperatures (continuous lines) and relative humidity (dashed lines), are presented in B. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Production

After a harvesting period of 33 weeks, fresh marketable weight of production reached 61.5 kg m^{-2} and 70.4 kg m^{-2} in the L and the M greenhouse respectively. Taking into account that the climate and the fertigation strategy were similar in both greenhouses, the difference in production can be well explained by the different amount of light reaching the crop due to the different light transmissivity of the two greenhouses.

3.3. Water use

The measured water use during the cultivation period (24th February 2019 – 23rd December 2019) is presented in Fig. 4A. Total water use in the L greenhouse was 6443 L m^{-2} whereas it was 4435 L m^{-2} in the M greenhouse. The vast majority of this water, 85% and 72% for the L and M greenhouse respectively, was devoted to the evaporative cooling and the rest to irrigation. The contribution of the fogging system to the water use of the M greenhouse ($<1 \text{ L m}^{-2}$) was minimal (therefore it is hardly visible in Fig. 4). The water used for irrigation (after drain re-use) in the M greenhouse (1246 L m^{-2}) was about 27% more than the corresponding amount of water used in the L greenhouse (980 L m^{-2}), as a result of both higher production and higher transpiration, both initiated by the higher amount of light in the M greenhouse. However, the water use in the pad wall was 42% lower in the M greenhouse (3190 L m^{-2}) than in the L (5463 L m^{-2}) resulting in more than 30% lower total water use in the M greenhouse. As we will see, there are three reasons for that difference with the main one being the placement of the fans which are located higher in the M greenhouse and due to the vertical air temperature profile they can extract warmer air (Fig. 5) increasing the cooling capacity of the system. Additionally, the cooling efficiency of the pad wall was found to be higher in the M than in the L greenhouse (Fig. 6), resulting in lower water use. Finally, the cover to greenhouse ground area ratio is higher in the single span L greenhouse (about 2) than in the multi span M greenhouse (about 1.7), resulting in more heat transfer from the hot outside environment to the greenhouse.

On a daily basis, the contribution of the evaporative cooling in the total water consumption varied through the year based on the weather conditions. In particular, the daily water use for irrigation varied from 2 L m^{-2} in the darker period to $5\text{--}6 \text{ L m}^{-2}$ in the summer. The water used for evaporative cooling varied from no use in winter up to 35 L m^{-2} and 20 L m^{-2} in the L and M greenhouse respectively during the summer, representing on average about 90% and 80% respectively of the daily total water use during the latter period.

The Product Water Use (PWU) (reciprocal of Water Use Efficiency) (Fig. 4B), was calculated as the amount of water required for the production of 1 kg of fresh, marketable tomato. Over the whole growing cycle, there was 40% less water spent per kilogram tomato produced in the M greenhouse than in the L, as a result of both lower water use and

higher production per unit greenhouse area. The water used for cooling per kg produced tomato was about half in the M than in the L greenhouse (45 L kg^{-1} and 89 L kg^{-1} respectively) whereas the water used for irrigation was higher in the M than in the L greenhouse (17.7 L kg^{-1} and 15.9 L kg^{-1} respectively) mainly as a result of higher transpiration rate.

3.4. Parametrization and validation of the model

In both greenhouses the air temperature increased from the pad wall towards the exhaust fan side and with the height of the greenhouse. The exhaust air temperature was found 3.3 K and 9.5 K warmer than the inlet air temperature in the L and M greenhouse respectively. In the middle of the greenhouse the air temperature at the top of the crop was on average about 1 K and 2 K warmer than at the bottom of the crop in the L and M greenhouse respectively. The temperature increased 1 K more with height in the next 50 cm in the L greenhouse and more than 4 K in the next 1 m in the M greenhouse. The average values of OTAM obtained from the measurements and used in the simulation study were 1 K and 5 K for the L and M greenhouse respectively (Fig. 5, Table 1, Table 2).

Using the measured values of T_{PW} , T_{out} (as measured from the weather station) and Eq. (4), the pad wall efficiencies were calculated (Fig. 6). The estimated pad wall cooling efficiency varied through the day depending on factors such as the air speed through the pad wall and the outside air temperature but for the modeling part of the study a constant value was used. The average values of the pad wall cooling efficiency over the whole week, 0.8 and 0.85 for the L and the M greenhouse respectively, were used as (constant) input to the model, for the whole simulated period. These values are in agreement with the measured efficiencies reported by Franco et al. (2014) for similar air velocities.

The model predicted with fair accuracy both the greenhouse climate and the water consumed by the cooling system in both greenhouses (L and M). The simulated greenhouse climate and water consumption showed a close match with the measured data (Fig. 7), proving the validity of the described model for simulations of evaporative cooled greenhouses in arid weather conditions.

3.5. Scenario studies

The first scenario study examined the effect of the outlet air temperature in water consumption (Fig. 8) showing that the water use in the pad and fan system is drastically reduced by increasing outlet air temperature. As it is also shown in Eq. (5), for the same amount of air extracted from the greenhouse, the removed sensible heat is proportional to the temperature difference between incoming and extracted air. Therefore, if for example the average greenhouse air temperature is 5 K higher than the temperature of the incoming air from the pad wall, then extracting air 5 K warmer than the average greenhouse air results

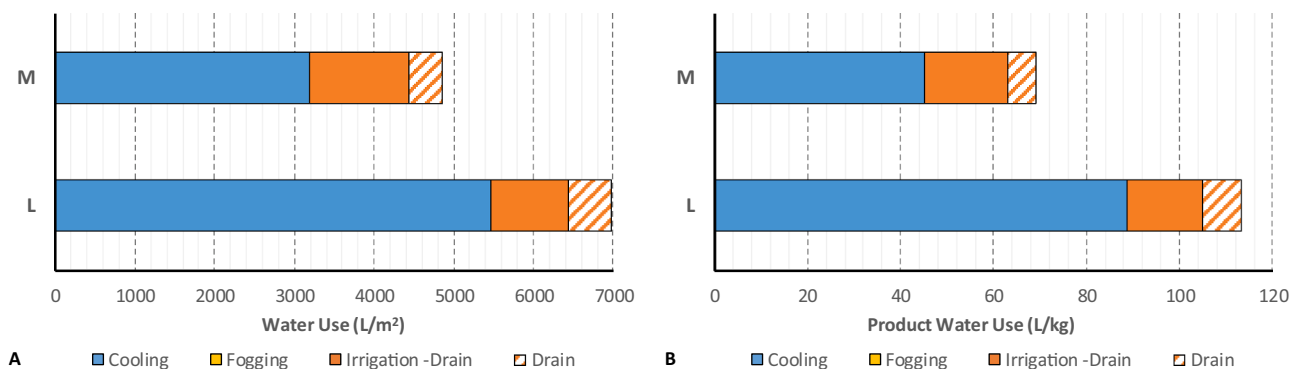


Fig. 4. Water use and recovery by each sub-process at each greenhouse system (L plastic tunnel and M Venlo glasshouse) during the experiment (24th February 2019 – 23rd December 2019) expressed as water amount per greenhouse area (A) and as water amount per fresh weight production (B).

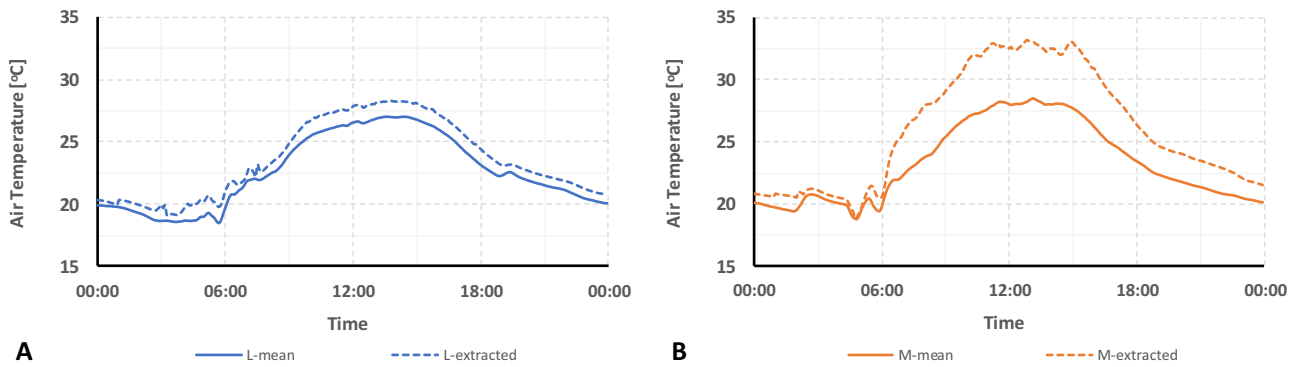


Fig. 5. Measured mean (continuous lines) and extracted from the fans (dashed lines) air temperature in the L (A) and the M (B) greenhouse. The shown data represent an average day after computing the average value of the measured period (20th – 26th July 2019) for each time of the day (cyclemean).

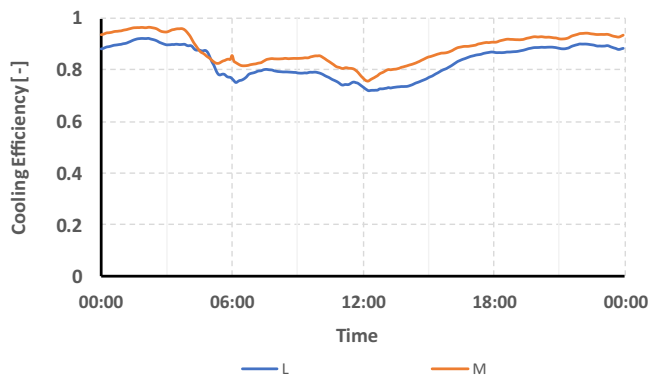


Fig. 6. Pad Wall efficiency values determined through measurements during a representative day for the L (blue line) and M (orange line) greenhouse. The shown data represent an average day after computing the average value of the measured period (20th – 26th July 2019) for each time of the day (cyclemean). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Average air temperature (°C) recorded at different locations in the L greenhouse.

| | Average (T _{IN}) | Exhaust fans (T _F) | MB 3 | MB 2 | MB 1 | Pad wall |
|-----------------------------|----------------------------|--------------------------------|------|------|------|----------|
| 50 cm above top of the crop | | | | 23.7 | | |
| Top of the crop | 22.5 | 23.6 | 23.6 | 22.6 | 21.4 | 20.3 |
| Bottom of the crop | | | | 21.5 | | 20.3 |

Table 2
Average air temperature (°C) recorded at different locations in the M greenhouse.

| | Average (T _{IN}) | Exhaust fans (T _F) | MB 3 | MB 2 | MB1 | Pad wall |
|---------------------------|----------------------------|--------------------------------|------|------|------|----------|
| 1 m above top of the crop | | 28.8 | | 27.8 | | |
| Top of the crop | 23.7 | | 24.9 | 23.6 | 22.7 | 19.3 |
| Bottom of the crop | | | | 21.5 | | 19.3 |

in twice the net cooling effect than extracting air at the average greenhouse air temperature. The latter would mean that half the amount of outside air has to pass through the pad wall and be brought in the greenhouse to dissipate the same amount of heat and so half the amount of water is evaporated. The design of the M greenhouse takes advantage

of the spatial air temperature distribution and by being higher and having the exhaust fans placed high, the extracted air is warmer than the average greenhouse air (Fig. 5, Table 2). Therefore, the total amount of air that needs to be extracted from the greenhouse is less in comparison to the L greenhouse where the extracted air is at about the average greenhouse air temperature (Table 1). As for a given pad wall efficiency the water use is proportional to the amount of air exchange (Eq. 2), the design of the M greenhouse reduces the amount of air extracted from the greenhouse and consequently results in less water use by the pad and fan system. According to the simulation results, the water use for cooling purposes in the L greenhouse (OTAM equals 1 K) would have been almost 25% less if the extracted air was 5 K warmer than the average greenhouse air temperature, as in the M greenhouse.

The larger the cover to ground area ratio is, the larger the heat exchange with the outside environment, resulting in increased cooling requirements and consequently more water use (Fig. 9). The simulation results showed that the water use for cooling purposes in the L greenhouse would have been about 7% less if the cover to ground ratio was smaller and equal to the corresponding value of the M greenhouse.

Finally, the cooling efficiency of the pad wall seriously affects the water use (Fig. 10) as it can also be concluded from the model description. According to Eq. (5) the cooling effect of the pad and fan system for a given amount of air is proportional to the temperature difference between the exhaust and inlet air (ΔT_{PF}). If the inlet temperature increases (as it happens in case of lower saturation efficiency of the pad wall) and assuming that the exhaust temperature is not changing, in order to achieve the same cooling effect, the amount of air passing through the pad wall increases. However, the additional air only contributes to the greenhouse cooling as soon as it is colder than the exhaust air temperature. The amount of water evaporated to cool the additional air from the outside temperature to the exhaust air temperature increases the total water consumption in case of a pad wall with lower saturation efficiency. According to the simulation results, a minimum cooling efficiency of 0.6 is required to achieve the desired greenhouse temperature under the studied arid weather conditions, therefore results at lower efficiencies are not shown. Water use reduced with increased efficiency and it was calculated that a pad wall with efficiency higher than 0.9 would use about half of the water used by a pad wall with efficiency equal to 0.6. According to the simulation results, the water use by the pad wall of the L greenhouse (efficiency equal to 0.8) would have been about 12% less if that pad wall would have had the same efficiency as the one in the M greenhouse (0.85).

4. Discussion

The pad and fan system is the most popular cooling system for greenhouses in Saudi Arabia as well as in other areas characterized by hot and dry weather (Al-Helal et al., 2004; Sabeh et al., 2011). Under the weather conditions of Riyadh, the evaporative cooling in the L and M

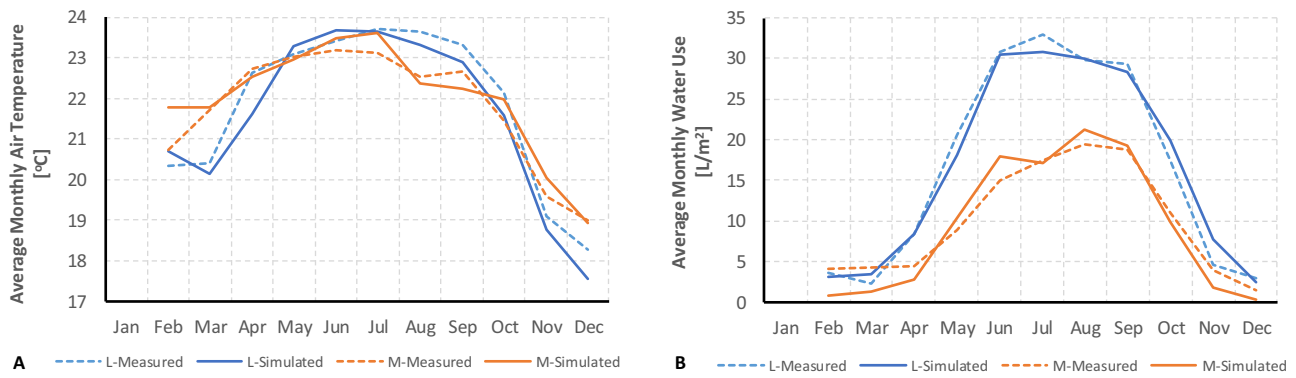


Fig. 7. Simulated (continuous lines) and measured (dashed line) monthly average of the daily temperature (A) and water consumption by the pad and fan system (B) in the L (blue lines) and M (orange lines) greenhouse during the cultivation period from end of February until end of December 2019. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

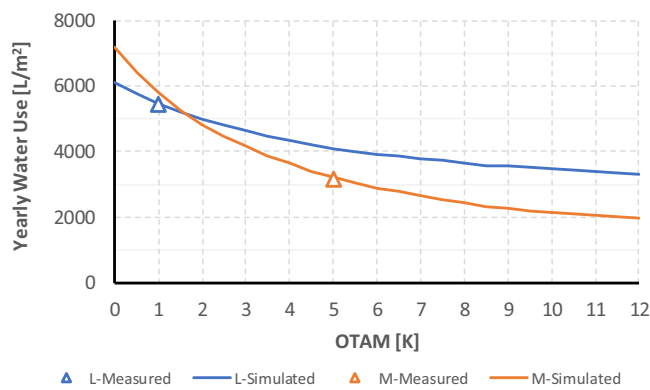


Fig. 8. Simulated (lines) and measured (triangles) water use for various outlet air temperatures (OTAM) in the L (blue) and M (greenhouse). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

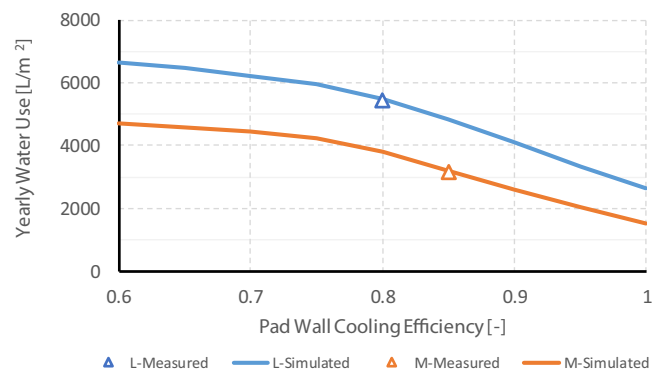


Fig. 10. Simulated (lines) and measured (triangles) water use for various pad wall cooling efficiency values in the L (blue) and M (greenhouse). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

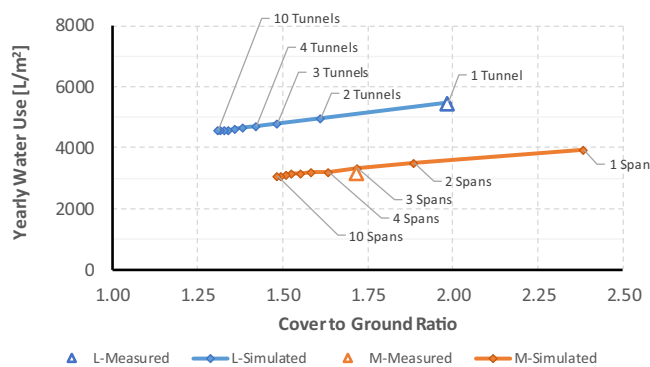


Fig. 9. Simulated (lines with diamond shape markers) and measured (triangles) water use for various values of cover to ground ratio corresponding to various number of tunnels (blue) or spans (orange). The number of tunnels/spans varies from 1 (single tunnel or span greenhouse with the highest cover to ground ratio) to a maximum of 10 tunnels or spans (multi tunnel or multi span with the lowest cover to ground ratio). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

greenhouses was proven well capable to maintain the greenhouse air temperature and humidity within the target range, even when the latter was 20 K less than the outside air temperature. Under these conditions, 1 kg of tomato was produced at the expense of 105 L and 63 L water in the L and M greenhouse respectively. The achieved PWU was

comparable to the corresponding value (77 kg L^{-1}) reported by Sabeh et al. (2011) under similar climate conditions in Arizona (USA) and significantly lower than what good commercial growers can achieve in Saudi Arabia (170 L kg^{-1} , personal communication). However, it is still far above values reported in the literature from places in the world with less warm weather (Stanghellini et al., 2003), indicating that vegetable production under desert conditions can be very water demanding, mainly due to the high needs for evaporative cooling.

The Venlo (M) greenhouse was proven to be more water efficient than the traditional tunnel (L), achieving a water saving of 40% per unit of produced product. We have shown that three design elements explain this improvement.

KASPRO was validated and proven to predict with fair accuracy the climate and water use in evaporative cooled greenhouses in arid conditions. Using a time varying value of the input parameter OTAM could increase even more the accuracy of the computed climate and water use, especially the fluctuations between day and night but given the fact that cooling is mainly active during the daytime the variations within a day (24 h) are of minor importance. The latter was well proven by the agreement between simulated and measured data. Based on the simulation results (Fig. 8), the placement of the fans, that allowed the extraction of air about 5 K above the average greenhouse air temperature, resulted in water savings of 55% and 45% compared to the scenarios that in the same greenhouse (M) the extracted air temperature would be equal to the average greenhouse air temperature or 1 K higher respectively, as in the L greenhouse. This was achieved by reducing the amount of air extracted from the greenhouse. Similar water saving can be of course achieved by increasing the height of tunnel greenhouse as

soon as this allows the placement of the fans higher and the extraction of warmer air. The temperature difference of the exhaust air was responsible for more than half of the water saving in cooling water achieved in the M in comparison to the L greenhouse. As soon as this difference was maintained, it was calculated that the M greenhouse consumes in all studied scenarios less water for cooling than the L greenhouse, even if the cover to ground ratio was increased (Fig. 9) or even if the cooling efficiency of the pad wall was lower (Fig. 10). On the other hand, without the advantage of extracting warmer air, the more transparent M greenhouse would consume more cooling water than the L greenhouse despite the higher cooling efficiency of the pad wall and the lower cover to ground ratio (Fig. 8). Summarizing, this indicates a great potential for water saving, taking into account that in most commercial greenhouses, the fans are located lower than the top of the canopy. A more detailed analysis of the spatial air temperature and humidity distribution might help to optimize the position of the exhaust fans and minimize the water use for cooling purposes, through a greenhouse design allowing for placement of the fans well above the crop in order to extract air from the warmest spot of the greenhouse while still maintaining optimal growing conditions near the crop. It has to be noted that although it was proven that increasing the described temperature gradients results in lower cooling water use, an as homogeneous as possible temperature at crop level is desired for uniform crop growth and production. Ideally the temperature gradients should develop on the vertical direction and above the top of the crop so that the growth and production is not hampered.

Furthermore, it was shown that the (slightly) higher cooling efficiency of the pad wall contributed for about 16% additional decrease in cooling water use in the M greenhouse (comparing scenarios for the M greenhouse with cooling efficiencies of 0.8 and 0.85, Fig. 10). The effect of pad wall cooling efficiency on the amount of evaporated water is reported in scientific literature (Abdel-wahab, 1994; Kubota et al., 2006). According to the simulation results (Fig. 10) increasing the pad wall cooling efficiency from 0.8 to 0.85 reduces the water use for cooling by about 12–16% when on the contrary reducing it from 0.8 to 0.75 increases the water use by 8–10%. The aforementioned results represent a rather conservative estimation of the effect of the increasing pad wall efficiency on water saving as the exhaust air temperature is considered not changed. Increasing the pad wall cooling efficiency reduces the required amount of extracted air to achieve a specific cooling effect and consequently reduces water consumption, as explained in the case of OTAM. In reality, if the fans are frequency-controlled, reducing the pad wall's saturation efficiency will increase the fan speed in order to meet the increased requirement of air exchange resulting in lower horizontal temperature differences and thus lower exhaust air temperature (Kubota et al., 2006). As explained in this paper, the latter will increase water use even more. In the described experiment, the higher pad wall efficiency in the M compared to the L greenhouse was achieved thanks to three factors: (i) lower air velocities through the pad walls are reported to increase saturation efficiency (Al-Helal, 2007; Franco et al., 2014; Kubota et al., 2006). The speed of the air drawn in through the pad walls was not measured but given the dimensions of the pad walls and the capacities of the fans, it was about 0.8 m s^{-1} in the L greenhouse when all three fans were in operation and it could reach a maximum of about 0.7 m s^{-1} in the M greenhouse when the fans were operated at their maximum capacity. However, the frequency controlled fans of the M greenhouse were not operated at their maximum speed so the actual wind speed through the pad wall was even lower. The bigger pad wall surface per ground area at the M than in the L greenhouse (the pad wall in the M greenhouse is 1 m higher than in the L when the length of both greenhouses is the same) ensured that more air volume per greenhouse ground area could enter the greenhouse at lower wind speeds and definitely contributed to the achieved higher cooling efficiency. Abdel-Wahab (1994) already 25 years ago, during their research in Saudi Arabia, indicated the controllable ventilation rate as a solution that reduces water use in a pad and fan system and increases the energy

and water use efficiency of the system. (ii) Plastic pad walls like the one used in the M greenhouse are reported to achieve higher saturation efficiencies than cellulose pad walls (Franco et al., 2014). (iii) Plastic pad walls like the one used in the M greenhouse can be easily cleaned with high pressure water, preventing clogging that reduces the saturation efficiency (Al-Helal et al., 2004).

5. Conclusion

Evaporative cooling is by far the largest water use in the greenhouses where it is applied. In the present research it is proven that there is a great potential in water saving by modifying the design of greenhouses with evaporative cooling in arid areas. We have experimentally shown that greenhouse design can significantly reduce product water use of tomato in desert conditions. We have used such experimental data to validate a simulation model whereby we have shown that a. the extracted air temperature, which is directly related to the placement of the exhaust fans, has a major effect on water demand for cooling; b. the pad wall saturation efficiency has also a major effect on water use and c. that greenhouse complexes with lower cover to ground ratio result in less cooling requirements per unit ground area than small units with higher cover to ground ratio.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank The National Research and Development Center for Sustainable Agriculture (Estidamah), Riyadh, Saudi Arabia for supporting this work financially. The presented research would have never been completed without the motivation and the hard work of the Operation Team at ESTIDAMAH research center, who perfectly executed the research plan and ensured the smooth function of the greenhouse and of the control equipment.

References

- Abdel-wahab, S.K., 1994. Energy and water management in evaporative cooling systems in Saudi Arabia. *Resour. Conserv. Recycl.* 12, 135–146.
- Al-Helal, I., Al-Abadi, N., Al-Ibrahim, A., 2004. A study of evaporative cooling pad performance for a photovoltaic powered greenhouse. In: Proceedings of the International Symposium on Greenhouses, Environmental Controls and In-House Mechanization for Crop Production in the Tropics 710, pp. 153–164.
- Al-Helal, I.M., 2007. Effects of ventilation rate on the environment of a fan-pad evaporatively cooled, shaded greenhouse in extreme arid climates. *Appl. Eng. Agric.* 23, 221–230. <https://doi.org/10.13031/2013.22605>.
- ASAE, 1995. Standard Engineering Practice Data, 42nd ed. ASAE Standards.
- De Zwart, H.F., 1996. Analyzing Energy-saving Options in Greenhouse Cultivation using a Simulation Model. Wageningen University.
- FAO, 2008. Irrig. Middle East Reg. Fig. – AQUASTAT Surv., 2008.
- FAO, 2017. AQUASTAT Main online Database. URL (<http://www.fao.org/nr/water/aquastat/data>).
- Franco, A., Valera, D.L., Peña, A., 2014. Energy efficiency in greenhouse evaporative cooling techniques: cooling boxes versus cellulose pads. *Energies* 7, 1427–1447.
- Fuchs, M., Dayan, E., Presnov, E., 2006. Evaporative cooling of a ventilated greenhouse rose crop. *Agric. Meteorol.* 138, 203–215.
- Katsoulas, N., Sapounas, A., De Zwart, F., Dieleman, J.A., Stanghellini, C., 2015. Reducing ventilation requirements in semi-closed greenhouses increases water use efficiency. *Agric. Water Manag.* 156, 90–99.
- Kittas, C., Bartzanas, T., Jaffrin, A., 2003. Temperature gradients in a partially shaded large greenhouse equipped with evaporative cooling pads. *Biosyst. Eng.* 85, 87–94.
- Krishna Bahadur, K.C., Dias, G.M., Veeramani, A., Swanton, C.J., Fraser, D., Steinke, D., Lee, E., Wittman, H., Farber, J.M., Dunfield, K., 2018. When too much isn't enough: does current food production meet global nutritional needs? *PLoS One* 13.
- Kubota, C., Sabeh, N.C., Giacomelli, G.A., 2006. Water use for pad and fan evaporative cooling of a greenhouse in a semi-arid climate. In: Proceedings of the International Symposium on Greenhouse Cooling 719, pp. 409–416.

- Napoli, C., Wise, B., Wogan, D., Yaseen, L., 2018. Policy options for reducing water for agriculture in Saudi Arabia. In: Biswas, A.K., Tortajada, C., Rohner, P. (Eds.), *Assessing Global Water Megatrends*. Springer, pp. 211–230.
- Nikita-Martzopoulou, C.H., Bartzanas, T., Kittas, C., Sapounas, A.A., 2008. Fan and pad evaporative cooling system for greenhouses: evaluation of a numerical and analytical model. In: *Proceedings of the International Workshop on Greenhouse Environmental Control and Crop Production in Semi-Arid Regions 797*. pp. 131–137.
- Nikolaou, G., Neocleous, D., Katsoulas, N., Kittas, C., 2019. Effects of cooling systems on greenhouse microclimate and cucumber growth under mediterranean climatic conditions. *Agronomy* 9, 300.
- Sabeh, N.C., Giacomelli, G.A., Kubota, C., 2007. Water use by greenhouse evaporative cooling systems in a semi-arid climate. In: *Proceedings of the ASAE Annual Meeting*. American Society of Agricultural and Biological Engineers, p. 1.
- Sabeh, N.C., Giacomelli, G.A., Kubota, C., 2011. Water use in a greenhouse in a semi-arid climate. *Trans. ASABE* 54, 1069–1077.
- Sethi, V.P., Sharma, S.K., 2007. Survey of cooling technologies for worldwide agricultural greenhouse applications. *Sol. Energy* 81, 1447–1459.
- Stanghellini, C., 1987. *Transpiration of Greenhouse Crops: an Aid to Climate Management*.
- Stanghellini, C., 2013. Horticultural Production in Greenhouses: Efficient use of Water. *Int. Symp. Grow. Media Soil. Cultiv.* 1034, pp. 25–32.
- Stanghellini, C., Kempkes, F.L.K., Knies, P., 2003. Enhancing environmental quality in agricultural systems. In: *Proceedings of the International Symposium on Managing Greenhouse Crops Saline Environment*, 609, pp. 277–283.