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Quantifying the trade-off between water and electricity for tomato production in arid environments

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ABSTRACT

Production of vegetables for fresh consumption in arid regions is usually done in greenhouses fitted with evaporative cooling, which does strain the scarce water resource in those areas so much that [lack of] water frequently becomes the limiting factor. Greenhouses fit with sufficient mechanical cooling capacity (closed/semiclosed greenhouses) not only dispose of the need for evaporative cooling, but also allow for recovery of the water transpired by the crop as condense on the mechanical cooling and dehumidification system. The purpose of this paper is to investigate the trade-off between resources (water and electricity) within a closed greenhouse and evaluate its potential as the ultimate water saving production system. After a series of 8 closed-greenhouse trials in a desert environment, in Riyadh (KSA), benchmark numbers on water and energy use of such a system were established. Thanks to the recollection of more than 80% of the water supplied to the crop, production of 1 kg of fresh tomatoes was achieved at the expense of 4.2 L of water, which is 10 times lower that the lowest reported in evaporatively cooled greenhouses and 40 times lower than commercial practice in similar weather conditions. On the other hand, the required electricity use was about 8 kWh per kg of fresh produced tomatoes. From energy point of view it is shown that using desalinated water for evaporative cooling reduces the electricity consumption of fresh tomato production to about 1 kWh.kg⁻¹. From economic point of view a closed greenhouse might only result in lower variable costs when 10 liters of desalinated water costs more than 1.75 kWh of electricity.

1. Introduction

Arid and semi-arid regions largely depend on imports of fresh vegetables to meet the domestic needs as their local production is not enough (Fiaz et al., 2018). There are numerous reasons varying from vulnerability of transportation routes and fragile international relations (Elmi, 2017) to the environmental impact of food transportation (Bonča et al., 2017) indicating that import-based food security is far from ideal for any country. Gulf Cooperation Countries (GCC) are a representative example; currently importing 80–90% of consumed food is not an issue due to their high buying power but the importance of increasing local production is appreciated and efforts to that direction are made, alas without the desired success (Ben Hassen and El Bilali, 2019). One of the limiting factors for local agricultural production in these regions is water

scarcity (Ben Hassen and El Bilali, 2019). The Kingdom of Saudi Arabia is no exception; tomato is the most commonly grown vegetable, filling about 40% of the greenhouse area of the country. Yet in 2018 the quantity of imported tomatoes was 1.9 times the locally produced amount (Morci et al., 2020), meaning that only 34% of the consumed tomatoes is produced locally.

Currently, vegetable production in arid and semi-arid regions mainly takes place in evaporatively cooled greenhouses. However this is only achieved at the expense of large amounts of water. Cooling water accounts for more than 50% of the total water use in such systems (Fuchs et al., 2006). An evaporative cooling system in Mexico (area of Huejulta) consumes 68 and 93 L of water per kg of tomato to limit greenhouse air temperature below 30 and 27 °C respectively (van Kooten et al., 2006). In Arizona (USA) 1 kg of fresh tomatoes is produced at the expense of

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77 L of water of which more than 80% (62 L) is used for evaporative cooling (Kubota et al., 2006; Sabeh et al., 2011, 2007). Commercial growers in Saudi Arabia report that about 170 L of water are used for the production of 1 kg tomatoes grown in plastic tunnels, cooled with pad and fan systems (communication of Estidamah with local commercial growers), a combination of high cooling demand and low production.

Water use could be the main criterion to evaluate production systems for arid areas. The volume of water necessary to produce 1 kg of fresh product is defined as Product Water Use (PWU) (Hoekstra and Hung, 2005). Theoretically (in a perfectly closed loop when no water escapes to the environment) the PWU of a vegetable crop should be the reciprocal of its harvest index. In case of long-season, indetermined round tomatoes, fruits represent about 80% of the total fresh plant weight (de Koning, 1994; Heuvelink, 2018); this is translated to a theoretical minimum PWU of 1.25 L of water for each kg of fresh tomatoes. However, as greenhouses are generally not closed and in arid countries use additional water for evaporative cooling, the PWU realised in commercial greenhouses is much higher. In Dutch greenhouses with and without re-use of drain water, 1 kg of fresh tomatoes is produced in expense of 15 and 22 L of water respectively, namely the amount of water used by the fertigation system (van Kooten et al., 2008). The larger amount by far of the difference between theoretical and practically achieved PWU is explained by crop transpiration which consumes about 90% of the water taken up by the crop (Stanghellini, 2014). In arid and semi-arid regions where evaporative cooling is commonly applied, the water use for cooling is added to the irrigation in order to compute the total water use.

Obviously, PWU can be largely reduced by targeting the aforementioned major components of water consumption, namely crop transpiration and water use in evaporative cooling. Katsoulas et al. (2015) computed the water saving achieved thanks to reduced ventilation and recapturing of transpired water vapor as a function of installed cooling capacity in semi-closed greenhouses; they reported that up to about 2 and 4 times lower PWU can be achieved for the production of tomatoes in The Netherlands and in the Mediterranean (Greece and Algeria) respectively when cooling with capacity of 700 W.m⁻² was applied compared to natural ventilation as the one cooling process. The closed greenhouse concept allows for recapture of crop transpiration through a dehumidification system and/or a mechanical cooling system. This is the ultimate water saving greenhouse design as it prevents water leakage outside the greenhouse system. Research trials in closed greenhouses in The Netherlands (Wageningen UR) reported that 40-50% of the water supplied to the crop was recovered as condensation of transpired vapor from the greenhouse air (De Gelder et al., 2012); Opdam, Schoonderbeek, Heller, & De Gelder, 2005). Similar amounts of recovered water were also reported by commercial closed greenhouses in The Netherlands (Themato BV) resulting to a final PWU of about $4 \,\mathrm{Lkg}^{-1}$ (van Kooten et al., 2008).

Additional advantages of the closed greenhouse compared to ventilated greenhouses include: (a) the low presence of pests and diseases due to the little connection with the outside environments which can then reduce the use of pesticides by up to 80% (Opdam et al., 2005) and (b) the possibility of maintaining elevated $\rm CO_2$ concentrations resulting in higher crop growth and production. However, a mechanical cooling and dehumidification system is much more energy demanding in comparison to an evaporative cooling system.

In arid or semi-arid regions water is scarce but there is potentially an abundance of sustainable energy due to the large amount of sun shine. Moreover, electricity demand for cooling largely lines up with electricity produced by solar panels. Therefore the closed greenhouse concept seems a good match. To the knowledge of the authors there is not yet scientific literature providing quantitative understanding of the water and energy flows involved in closed greenhouses in arid regions, nor of the trade-off involved. The current study aims to close this gap by quantifying and evaluating the operation and resource use of a closed greenhouse in an urban desert area, in Saudi Arabia. Information from

multiple research trials are collected and presented in order to quantify the PWU that can be achieved in practice in a mechanically cooled greenhouse and the amount of electricity required for cooling. The mass balance of water is computed in order to estimate accurately the PWU and quantify every flow. Finally, the energy use required to support the achieved water savings is presented and the closed greenhouse is compared with evaporatively cooled greenhouses in terms of water use, energy use and productivity.

2. Materials and methods

The data presented in the current study were collected during four tomato experiments, from now on indicated as A, B, C and D, of various nature at the National Research and Development Center for Sustainable Agriculture (Estidamah) in Riyadh (24.7° N, 46.7° E), Saudi Arabia. All experiments were carried out in two identical greenhouse compartments, with only one factor (treatment) different (CO $_2$ concentration, use of artificial illumination, crop protection) during each experiment. The present study does not focus on the different treatments but only on the water and energy balances and the resource use per compartment, so the collected data set includes data from 8 different tomato cultivations grown for periods varying from 6 to 12.5 months (Table 1).

2.1. Greenhouses and climate control equipment

The greenhouse is a Venlo type glasshouse, gutter height of 6.5 m and span width of 4 m covered with tempered diffuse glass. Each compartment is $25\,\text{m}\,\text{x}\,16\,\text{m}$ of which $336\,\text{m}^2$ is growing area, equipped with heating (rail and grow pipes), high pressure fogging system (0.4 L. $\text{m}^{-2}\,h^{-1}$), shading screen (50% shading percentage), enrichment with liquid CO_2 and mechanical cooling. The air conditioning consists of 10 air treatment units (Thermokey) per compartment, with a total capacity of around $700\,\text{W.m}^{-2}$, placed close to the greenhouse cover and a dehumidification system (condensation on cold surface with capacity $4000\,\text{m}^3\,h^{-1}$ with a maximum condensation discharge rate of $16\,\text{L}\,h^{-1}$) that distributes the treated air through five ducts placed under the growing gutters. This therefore provides a dehumidification capacity of 48 g per m^2 growing area per hour. The condensate from all coolers and dehumidification is collected and reused in the greenhouse system as fresh water for irrigation.

The cooling capacity was sufficient for the greenhouses to operate fully closed, that is no air exchange with the outside environment (except for some inevitable leakage), nevertheless, in three of the four trials night-time ventilation was applied for 1–2 h for crop management purposes.

In all experiments the crop was round tomato harvested as loose. The tomatoes were transplanted about 30 days after sowing and they were grown on stone wool in hanging gutters, fitted with recollection of drain. The plant density was 2.5 stems per $\rm m^2$, and additional stems were kept in order to end up with a stem density of 4–5 stems per $\rm m^2$. In each trial the fresh yield per crop row was weighted and recorded at each harvest (usually twice per week) and the average of all crop rows excluding the side rows was used as greenhouse yield. Although the cultivars varied somehow among experiments, it was always the same [combination of]

Table 1Overview of the cultivation periods of the greenhouse trials that took place between 2016 and 2020. Each line of the table refers to one of the four trials. In each trial the start date, first harvest date and end date were identical between the 2 used greenhouse compartments.

Trial	Start Date	First Harvest	End Date
Α	6-Dec-16	6-Feb-17	12-Jun-17
В	5-Jul-17	30-Aug-17	25-Mar-18
C	8-Jul-19	8-Sep-19	19-Jul-20
D	8-Jan-20	15-Mar-20	24-Dec-20

cultivar(s) in each one of the two compartments.

2.2. Climate and fertigation settings

The climate and fertigation control as well as the data collection were arranged through a greenhouse process control computer (Ridder MultiMa). In each greenhouse there were 3 ventilated measuring boxes to record the temperature and humidity values and one measuring box to record $\rm CO_2$ concentration. All measuring boxes were placed in the central crop row and they were maintained at the height of the top of the crop. The average of all 3 measurements was used for climate control purposes.

The temperature 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 80% and 95%. 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 was used only at the beginning of the growing season to increase humidity; later on it was hardly required as the transpiration of the crop was sufficient to prevent too low humidity values in the greenhouse. The shading screen was used during the first two months of each trial, whenever global radiation exceeded $800~\rm W.m^{-2}.$

The irrigation water including liquid fertilizers was supplied through drip irrigation. 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 optimized during all trials to ensure that it would not hamper the plant growth and production. Specifically, the irrigation was controlled automatically based on external sun radiation in order to match crop's needs, starting with smaller amounts (about 0.5 cc per Joule for young crops) and increasing gradually to follow the growth of the crop (reaching about 4 cc per Joule for a fully grown crop) while maintaining a drain percentage of 25–30%.

The source of irrigation water and the water used in the fogging system was the municipal supply and it was first treated with a reverse osmosis (RO) unit. The water collected by the cooling/dehumidification units as well as the drain from the greenhouses was reused, the latter

after UV disinfection as shown schematically in Fig. 1.

2.3. Calculation of water flows

The detailed recording of water supply (irrigation, fogging) and water recovery (drain, condensation) allows the computation of water use and also water mass balance, to get insight into the water use of the crop in general as well as individual crop processes. Specifically the amount of water taken up by the crop can be computed and it is also possible to estimate how much of this water was transpired and how much was invested in fresh weight growth. This information enlightens the achieved PWU and how it is affected by the used technological equipment.

2.3.1. Water use

The water use (WU) of each compartment was calculated as the water input to the system minus the amount of water that was collected and reused (Eq. 1). Specifically, the water input consisted of the water supplied for irrigation (W_i) and the water used by the fogging system (W_f), which were individually measured. The reused water consisted of the drain water (W_d), which was measured, and the condensed water collected by the mechanical cooling and the dehumidification system, which were measured together (W_c).

$$WU = W_i + W_f - W_d - W_c \tag{1}$$

The condensation on greenhouse cover is not included in the computations as, given the high outside air temperature (usually warmer than inside), the temperature of the cover hardly ever would fall below dewpoint temperature, so the amount of condense on the cover would be anyhow small and was never enough to run-off. Therefore, any condensed water is re-evaporated and either condensed again on the dehumidification or cooling system where it would be measured or it escapes via leakage or ventilation, adding to the water use.

2.3.2. Water leakage

The WU as computed in Eq. 1 consists of the water stored in the crop as fresh weight growth and the water vapor escaped from the

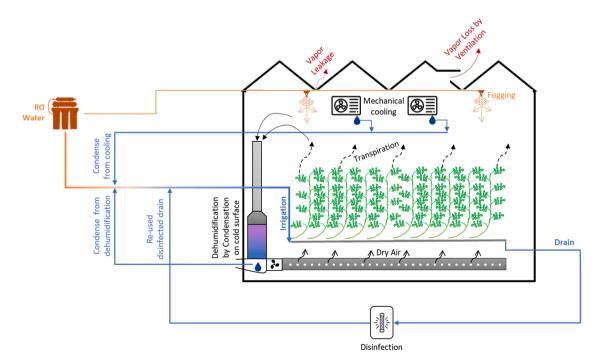


Fig. 1. Schematic representation of the main water flows in the greenhouse. Water input to the system (shown as orange) consists of the RO water used for irrigation and fogging. Water recovery (shown as blue) consists of the collected drain water and the condense collected on the mechanical cooling and dehumidification units; the recovered water is then used for irrigation. Water losses (indicated as red) consist of the vapor loss via (leakage) ventilation.

greenhouse through leakage and/or ventilation. Greenhouse leakage (air exchange in absence of intentional ventilation) was estimated based on the decay method, described by Baptista, Bailey, Randall, and Meneses (Baptista et al., 1999) and by using $\rm CO_2$ as tracer gas. According to this method, the tracer gas ($\rm CO_2$ in our case) is injected until a certain concentration is reached and then the decay of its concentration is monitored until the latter reaches about 80% of its initial value. The leakage ventilation can be determined by fitting a linear regression to the time interval that the natural logarithm of the difference of the concentration of the tracer gas inside and outside the greenhouse decreases linearly with time (Eq. 2). The regression coefficient equals the air exchange rate.

$$\ln(CO_{2, in} - CO_{2, out}) = L/H \bullet t + a \tag{2}$$

Where $CO_{2, in}$ and $CO_{2, out}$ is the concentration of CO_{2} inside the greenhouse and outside respectively, L is the greenhouse leakage in m³ / (m² hr), H is the height of the greenhouse (6.75 m), t is the time in hours and a is a regression constant. Air leakage changes may be affected by wind speed; therefore, to account for variable weather conditions, the described method was repeated for several days, obviously in the absence of a crop in the greenhouse. During a period of 10 days in May 2018 the greenhouse was kept closed and the CO_{2} concentration was raised to 1200 ppm. Then the rate of concentration drop was calculated until the concentration reached 800 ppm. The same trial was repeated for 10 days in April 2021 to assess the possible effect of greenhouse aging on leakage ventilation. As a difference (increased leakage) was indeed observed, for the trials performed between 2018 and 2021 the leakage was estimated through interpolation.

To calculate leakage at any moment, leakage ventilation was assumed to increase linearly with wind speed as described by Baptista et al. (Baptista et al., 1999) and calculated to increase with a rate of $0.095 \, \mathrm{m}^3 \, / (\mathrm{m}^2 \, \mathrm{hr})$ for every $1 \, \mathrm{m.s}^{-1}$ increase in wind speed.

2.3.3. Water loss through ventilation

For the time period when the windows were opened, the vapor loss through ventilation was computed via the air exchange rate and the difference of the absolute humidity between greenhouse air and outside air. For the computation of air exchange rate, the ventilation model described by De Zwart (1996) was used. According to this model, the air exchange rate consists of 2 components, namely the wind driven (ϕ_{wind}) and temperature difference driven (ϕ_{temp}) air exchange. These components of air exchange were computed separately. Also separate computations were performed for the leeward and windward side of vents and finally all components were combined into one using a vector-like summation (Eq. 3).

$$\varphi_{vent} = \sqrt{\varphi_{wind}^2 + (\varphi_{temp,W} + \varphi_{temp,L})^2} m^3 s^{-1} window^{-1}$$
(3)

The components of air exchange are calculated based on the window opening angle on the windward (θ_W) and leeward side (θ_L) , the dimensions of the window (length (l), width (w)), the slope of greenhouse roof (s), the temperature difference between greenhouse air and outside environment (ΔT) and the wind speed (u) as follows:

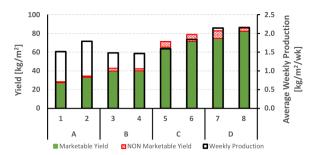


Fig. 2. Total yield (marketable (green bars) and non-marketable (red bars) shown separately) and average weekly total production (black open bars) achieved per trial and greenhouse.

Where C_f is a constant related to the energy discharge caused by friction (value of 0.6 used), g is the gravitational acceleration (ms $^{-2}$) and β is the thermal expansion coefficient (3.3 10^{-3} K $^{-1}$). Eq. 4 computes the sum of leeward (first part) and windward (second part) wind driven air exchange. Obviously by applying the window opening angle on the windward (θ_W) and leeward side (θ_L) on Eq. 5 the temperature driven air exchange on the windward ($\phi_{temp,W}$) and leeward ($\phi_{temp,L}$) side respectively can be calculated.

2.4. Energy use

Estimation of energy use for cooling and dehumidification is crucial as this is the resource with the highest consumption in exchange for the achieved water saving. The amount of heat removed from the greenhouse is computed based on the temperatures of the supplied and return water to/from the cooling and dehumidification system and the flow of water going through the system. These data are recorded in the process control computer. Although the cooling and dehumidification are two independent systems that can be also operated independently, in the present paper they are mostly discussed together as under the conditions used they are mainly operating complementary to each other; in other words the dehumidification system also acts as a cooling system (unless the dehumidified air is reheated which was not the case for the vast majority of the analyzed period) and the cooling system also obviously acts as a dehumidification system. Finally, the computed heat removal from both systems was transformed to electricity consumption by using an estimated coefficient of performance (COP) value. This COP considers the electricity use of the chillers, the fans of the heat exchanger and the water circulation pumps. On top of that, an additional electricity use of some 20 W.m⁻² is added to account for the electricity use of the air conditioning units in the greenhouse; this value is obtained from measurements performed in the greenhouse. The computation of COP is based on the Carnot efficiency using as inputs the temperature at the warm side of the chiller (Twarm) and the cooled water temperature (Tcool) (Eq. 6). The latter (T_{cool}) is measured and recorded in the process control computer while the former (Twarm) is estimated by assuming that the warm side of the chiller is some 10 °C above outside air temperature. This temperature difference results in computed COP values well in agreement with reference values provided by chiller manufacturers. As

$$\varphi_{wind} = \left(2.29\ 10^{-2} \cdot \left(1 - exp\left(-\frac{\theta_L}{21.1}\right)\right) + 1.2 \cdot 10^{-3} \cdot \theta_W \cdot exp\left(\frac{\theta_W}{211}\right)\right) \cdot l \cdot w \cdot u \left[m^3 s^{-1} window^{-1}\right]$$

$$\tag{4}$$

$$\varphi_{temp} = C_f \cdot \frac{l}{3} (|g \cdot \beta \cdot \Delta T|)^{0.5} \cdot (w \cdot (\sin \theta - \sin(s - \theta)))^{1.5} \left[m^3 s^{-1} window^{-1} \right]$$
 (5)

soon as real systems cannot operate at the ideal Carnot cycle and they operate at some fraction of it, an efficiency term (e) is also included in the COP computation. For the computation of COP the efficiency of the cooling system (e) was assumed equal to 0.4 (Meggers et al., 2012).

$$COPcooling = e \quad \bullet \quad \frac{T_{cool}}{T_{cool}} \tag{6}$$

Since the outside temperature fluctuates over the day, also the COP does. The COP is calculated on 5 min basis to capture the natural temperature variation.

3. Results

3.1. Crop yield

The achieved crop yield varied among the different trials between 28 and 86 kg/m² (Fig. 2). The larger part of this difference was caused by the different length of the trials (Table 1) therefore the average productivity of each crop in kg of fresh product per week is also presented. The different treatments applied as well as factors such as presence of diseases affected to some extent the crop productivity with the average production per week varying between 1.5 and 2.2 kg.m $^{-2}$ per week. The season in the year also influenced the weekly yield as a result of different amount of solar radiation (Fig. 3). The highest yield and highest average productivity were achieved in trial D.

3.2. Water use

3.2.1. Water input and water recovery

The absolute amount of water input to the greenhouses varied between the different trials (sum of the bars at the left part of Fig. 4). In all trials the contribution of fogging to the total water use was negligible (1% or less). Therefore, the water input to the greenhouses was equal to the irrigation water. The difference among the four trials can be mainly explained by the different duration of the trails as well as the season of the year each trial was done. The duration of trials A and B was less than C and D and not done during the whole summer season which is the most water demanding due to the higher amount of solar radiation (Fig. 3). If the total water input is expressed in relation to the amount of radiation, then it was similar in the first three trials and it was higher in the fourth trial due to higher maintained leaf area index resulting in higher crop transpiration. Specifically, during trials A, B and C irrigation was about 270 mL per MJ of sun radiation of which about 200 mL were taken up by the crop. In trial D the irrigation was about 370 mL per MJ but the drain percentage was comparable to the previous trials meaning that the crop uptake was also higher, reaching 270 mL per MJ.

The vast majority (85% on average) of the water input to the greenhouse was recovered and re-used, resulting in a final water use which represents on average only 15% of the water applied by the irrigation system (blue bars in Fig. 4). Water recollected as drain (bars with diagonal stripes) was about 25% of the irrigation supply year round. The latter was dependent on radiation, as described above, and varied from about 4 L m $^{-2}$ d $^{-1}$ in the winter to 11 L m $^{-2}$ d $^{-1}$ in summer.

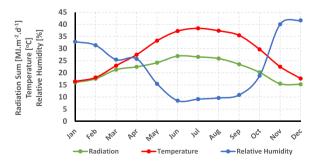
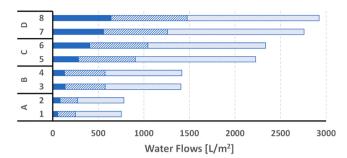


Fig. 3. Average outside weather conditions in Riyadh. Specifically, the average daily radiation sum (green), the average temperature (red) and the average relative humidity (blue) per month of the year are presented. Data were calculated based on measurements obtained from the weather station of the greenhouse during the 4 years that the described trials took place (2017–2020).



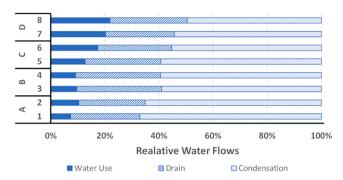


Fig. 4. Absolute (top) and relative (bottom) amounts of water in each water flow. The final water use (blue bars) is only a small percentage of the total water input to the system (sum of the bars) as the biggest part of it is recovered and re-used. Recovered water consists of 2 components, namely drain (bars with diagonal stripes) and condensation on cooling and dehumidification system (dotted bars).

The water recovered via condensation (bars with vertical stripes) was on average 60% of the initial water supply (Fig. 4). Cooling and dehumidification is needed year round and water recovery varied from about $3\,L\,m^{-2}\,d^{-1}$ in the winter to $7\,L\,m^{-2}\,d^{-1}$ in summer. Since the crop transpires constantly, the dehumidification system was almost continuously in operation. According to its specifications it should recapture some $1.15\,L\,m^{-2}\,d^{-1}$ water at full power; the rest of the vapor was collected by the cooling system.

3.2.2. Water loss through leakage and ventilation

Water use, the water that is not recollected (solid blue bars at the bottom in Fig. 4), is the water stored in the fresh biomass and the vapor lost via ventilation and leakage. The amount of final water use as a percentage of the total water input in the system was higher in trials C and D than in trials A and B. The major reason for this difference is that starting from trials C and D the vents were opened each night for $1{\text -}2\,h$ in order to prevent harmful volatiles (ethylene or other gases) to accumulate. In addition, leakage also increased (Fig. 5). The estimated air exchange under low wind conditions (less than 1 m.s $^{-1}$) was found to be about 0.24 m 3 /(m 2 hr) in 2018 and 1.7 m 3 /(m 2 hr) in 2021 (Fig. 5) or in other words the aging of the greenhouse resulted in about 7 times more air (and vapor) losses via leakage in 2021 compared to 2018. Such rapid aging can be explained by the extreme weather conditions (direct radiation and heat (Fig. 3)) to which the rubber sealing of the windows was exposed.

3.2.3. Product water use

Combining the water use (Fig. 4) and productivity (Fig. 2) data the PWU for each trial was calculated. The PWU varied between the different trials from 2 to $7.4\,L\,kg^{-1}$ (Fig. 6) with an average of $4.2\,L\,kg^{-1}$. As explained above (Section 1) the theoretical minimum PWU is the reverse of the harvest index of the crop and for the case of long-season, indetermined round tomatoes it is about $1.25\,L.kg.m^{-1}$; therefore the theoretically minimum required total water use per

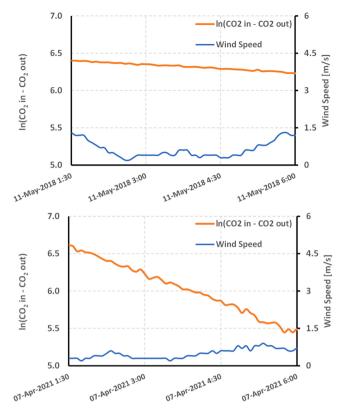


Fig. 5. Representative measurements of CO_2 concentration drop performed in 2018 (top) and 2021 (bottom) for the estimation of leakage ventilation of greenhouses. The presented data were collected under similar weather conditions, that is: night and wind speed (blue lines) below 1.5 m.s⁻¹. In 2021 the natural logarithm of the CO_2 concentration difference between inside and outside was decreasing about 7 times faster than in 2018, indicating an increase of leakage ventilation as an effect of greenhouse aging.

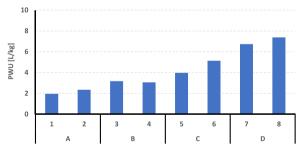


Fig. 6. Calculated PWU for each greenhouse compartment and trial.

greenhouse trial can be computed by multiplying the achieved yield with 1.25. In all trials the achieved PWU exceeded the theoretical minimum. However, for trial A that lasted only about 6 months the harvest index was probably lower than 80%, so that in trial A the achieved PWU is very close to what could theoretically have been attained. The achieved PWU increases with increasing air exchange (Fig. 7). This air exchange results in vapor loss to the outside environment which explains well why the achieved PWU is higher than the theoretical minimum. It can be concluded that for the analyzed greenhouse systems, under the weather conditions of Riyadh, PWU increases by more than 1 L.kg $^{-1}$ for each additional 10,000 m 3 .m $^{-2}$ of air exchange (Fig. 7). This is not strange considering that 14.2 gr of water vapor are lost each time that 1 m 3 of greenhouse air at 27 °C and 80% relative humidity is replaced by 1 m 3 of outside air at 37 °C and 10% relative humidity.

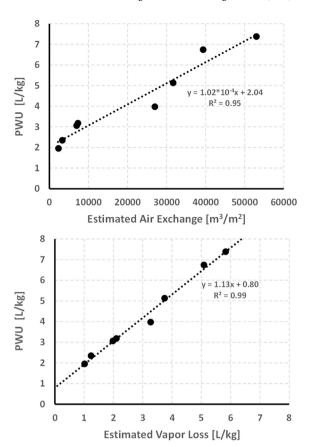


Fig. 7. Realised product water use against estimated air exchange (top) and vapor loss (bottom) expressed per kg of produced total yield via ventilation and leakage ventilation.

3.2.4. Crop transpiration

Estimating crop transpiration as the amount of vapor collected as condense and the vapor escaped the greenhouse through ventilation and leakage ventilation results in $600-2000\,L$ water per m^2 , depending on the trial. This amount equals on average 67% of the water supplied to the crop via irrigation and 91% of the water taken up by the crop or in other words, the difference between irrigation and drain. Only the remaining 9% was used in the biomass. The used system of recollecting crop transpiration managed to recover through condensation 82% on average of the transpired water vapor in all trials. It is clear that recapturing crop transpiration allows tremendous reduction of water use. In a ventilated greenhouse the transpired water would have been released to the environment, increasing the water use multiple times.

3.3. Electricity use

The aforementioned water savings can only be achieved at the expense of energy in the form of electricity required to operate the cooling and dehumidification system. The cooling energy use varied throughout the year from 25 MJ m $^{-2}$ d $^{-1}$ in summer to 5 MJ m $^{-2}$ d $^{-1}$ in winter. Given the fact that dehumidification is required year round, the energy consumption of the dehumidification system was fluctuating less between different months of the year, namely between 1.2 and 2 MJ m $^{-2}$ d $^{-1}$. Based on the computed COP, the installed cooling and dehumidification equipment consumes from 0.4 to 3 kWh m $^{-2}$ d $^{-1}$ depending on the month of the year (Fig. 8). In the performed trials the estimated total electricity use for cooling and dehumidification purposes varied between 230 (trial A) and 725 (trial D) kWh m $^{-2}$. The differences between the trials were obviously predominantly caused by the different length and season of the trials. Thanks to the condensation on the cooling and

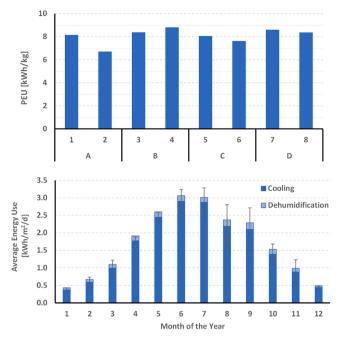


Fig. 8. Electricity consumption per kg produced tomato (top) and average daily electricity consumption per month (bottom). The daily average electricity use is shown separately for cooling (solid bars) and dehumidification (striped bars) purposes. The energy use data (bottom) are averaged for all the analysed trials and compartments. Vertical black error bars indicate the standard deviation of the monthly electricity use for cooling.

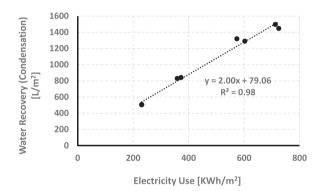


Fig. 9. Water recovery via condensation on the cooling and dehumidification system versus the electricity consumption of the aforementioned systems.

dehumidification systems about 500–1500 L m⁻² water were recovered and reused. On average for every kWh of electricity spent, about 2 L of water were recovered (Fig. 9).

If the electricity use is expressed in relation to the production of each trial and cultivar, the Product Electricity Use (PEU) is calculated in the same way as the PWU. The production of each kg of fresh tomatoes was achieved in expense of in average 8 kWh of electricity (Fig. 8).

4. Discussion

After completing a number of different research trials in closed greenhouses in arid conditions over a period of four years, benchmark numbers describing the productivity and more importantly the water and electricity use of such a production system under the specified weather conditions are established. The detailed recording of the major water flows enabled the accurate estimation of water use, crop transpiration and possibilities for water recollection. The achieved PWU of $2\text{--}7.4\,\text{L}\,\text{kg}^{-1}$ is to the knowledge of the authors the lowest ever reported

in an arid environment and the average of 4.2 L kg⁻¹ is some 40 times lower than the reported PWU that commercial growers in the area achieve. This number is also similar to the PWU achieved in closed greenhouses in northern latitudes; although cooling energy requirements differ of course a lot (De Gelder et al., 2012; Opdam et al., 2005). The observed range in the achieved PWU was explained by the different ventilation and leakage ventilation of the different trials rather than different varieties or treatments. The latter was also ensured by the well-controlled factors affecting crop growth such as greenhouse climate, fertigation, substrate and crop handling which were all optimized and repeatable among the different trials. The very small improvement of PWU that could have been attained by allowing the removed leaves to dry in the greenhouse was not deemed worth the increased potential for infection of the removed parts. The realized PWU was still above the theoretical minimum as no greenhouse can be completely air tight and vapor losses to the outside cannot be avoided. Even without any ventilation (trial A) vapor leakage cannot be completely avoided. However the achieved PWU was 10 times lower than the lowest reported in an evaporatively cooled greenhouse in similar climate conditions (Tsafaras et al., 2021) due to (i) no water used for cooling, (ii) recollection and re-use of crop transpiration and (iii) higher yield due to elevated CO2 concentration.

According to the presented data, 91% of the irrigation water consumed by the crop was used for crop transpiration. The latter is in agreement with published research (Stanghellini, 2014), confirming the accuracy of the measurements and computations of the water balances. Recollecting condensation on cooling and dehumidification system allowed the recovery and re-use of more than 80% of transpired water with higher values achieved at the trials without any ventilation. The achieved PWU was directly related to the amount of air exchange via ventilation and leakage with higher PWU values realized with increased air exchange; this finding is well in agreement with the simulation results reported by Katsoulas et al. (2015).

On the other hand, mechanical cooling and dehumidification of the closed greenhouse come with an increased electricity use. The latter was estimated during the described trials to be on average about 600 kWh m^{-2} y^{-1} . In the described trials 1 kg of fresh tomatoes was produced at the expense of 8 kWh on average. The latter is translated to costs of about 1.6 SAR in Saudi Arabia, against a grower price of tomatoes of 3 SAR per kg. Although a detailed economic evaluation of the [semi] closed greenhouse is outside the scope of the current study it is safe to conclude that it is hardly applicable on a commercial scale. The presented results focus on tomato crop but they can be potentially applied to some extent in other greenhouse vegetables as well. In that case the cooling requirements and therefore the relative electricity use would not differ a lot, given the fact that similar greenhouse climate would be required. Additionally, the PWU would also remain similar as it is mainly dependent on the harvest index of the crop and the vapor leakages of the greenhouse. However the computed PEU might differ as it largely depends on the yield.

One can argue that, potentially, the high electricity demand could be fulfilled from renewable resources. The latter is also well in line with country's goals. Saudi Arabia planned an investment of about \$ 109 billion for the installation of some 54 GW of renewable power capacity by 2032 with almost 76% of these capacity generated by solar power, taking advantage of the plentiful solar radiation available in the country (Pazheri, 2014). However, given that both greenhouses (that is: vegetable production) and photovoltaics (PV) make use of the sun radiation they cannot be combined in the same area. Under the weather conditions of Riyadh area, 1 m² of PV panel can produce about 280 kWh per year (Pazheri, 2014). Therefore, more than 2 m² of PV panel and the associated additional land surface are required to supply the electricity requirements for cooling and dehumidifying 1 m² of the described greenhouse.

The high electricity use of the closed greenhouse minimizes its commercial applicability unless water saving becomes extremely valuable. Even then there might be other alternatives such as using desalinized sea water in an evaporative cooling system. Desalinisation of sea water using reverse osmosis (RO) consumes some 5 kWh per $\rm m^3$ incoming water but the actual electricity use to produce 1 $\rm m^3$ desalinised water is at least double as the recovery rate for seawater in RO cannot exceed 50% (Altaee et al., 2014; Liu et al., 2011). Therefore, a grower who uses 170 L for the production of 1 kg tomatoes in a pad and fan greenhouse would spend about 1.7 kWh for seawater desalinisation. In other words, with the same amount of electricity one can produce 4.7 times more fresh tomatoes in an evaporatively cooled greenhouse with sea water desalinisation than in a closed greenhouse.

Moreover, there is definitely a lot of room for improvement of the PWU of evaporatively cooled greenhouse. For instance, Tsafaras et al. (Tsafaras et al., 2021) reported PWU of around 45 $\rm L.kg^{-1}$ in greenhouses with improved pad and fan cooling system in Saudi Arabia. Such an amount of water can be obtained from desalinized sea water at the expense of 0.45 kWh, to which another 0.5 kWh per kg of produced tomato should be added as the estimated electricity consumption of the fans (not published data from previous greenhouse trials in Estidamah). That is, a well-designed pad and fan system could produce 8.4 times more tomatoes with a given amount of electricity than the closed greenhouse. Of course a larger greenhouse area would be required to account for the lower productivity of a pad and fan greenhouse, compared to a closed greenhouse. Nevertheless, land is not scarce in Saudi Arabia as well as in other arid or semi-arid areas. Therefore efforts in improving the efficient use of water in evaporatively cooled greenhouses can result in more valuable and commercially applicable results than the closed greenhouse concept.

One should not forget, however, that such a competitive advantage of evaporatively cooled greenhouse hold only for dry climates. The current study took place in Riyadh area, in Saudi Arabia, where the climate is arid and therefore the results are only valid for similar arid climates. Evaporative cooling has lower cooling capacity and becomes less water efficient with increasing humidity of the outside environment due to the increase in wet bulb temperature; therefore, it can be hardly operated in a very warm and humid area (e.g. coastal areas at low latitudes). On the contrary, the performance of the described closed greenhouse is hardly affected by external humidity (and water losses through leakage and ventilation would be reduced resulting in higher water savings). Therefore the PWU and PEU calculated here would apply to closed greenhouses in any similarly warm but then humid region.

In conclusion, the closed greenhouse was proven to achieve tremendous water saving but this is achieved at the expense of so high electricity use that makes it commercially applicable only in case water is much more valuable than electricity. Water savings in commercial practice, in places whose climate allows for evaporative cooling, can be more easily achieved by improving the efficient use of cooling water rather than with closed greenhouses.

5. Conclusion

After a series of trials in closed greenhouses in arid climate (central of Saudi Arabia) the production of 1 kg fresh tomatoes was achieved with the average use of $4.2 \, \text{L}$ of water, ranging from $2 \, \text{L}$ to $7.4 \, \text{L}$ kg $^{-1}$. This is 10 times lower than the water used in a very efficient evaporatively cooled greenhouse and 40 times lower than commercial practice for average Saudi tomato growers. This was achieved by installing sufficient cooling capacity to minimize ventilation, so that the majority of crop transpiration could be recollected. Also the drainage from the soilless cultivation system was collected and reused. The effect of air exchange on product water use was also quantified, explaining why the amount of water used per unit of produced yield was higher than the theoretical minimum value. This low use of water comes at the cost of large amounts of electricity for cooling. From energy point of view, producing fresh vegetables in a closed greenhouse requires 8 times more electricity than for a pad and fan greenhouse using desalinated sea water. In the dry

arid climate of central Saudi Arabia, only when 10 liters of desalinated water costs more than 1.75 kWh of electricity, the variable costs of a closed greenhouse might drop below the variable costs of a pad and fan greenhouse. In conclusion, the trade-off between water and electricity use is presented and it is the cost of these resources that will predominantly define whether a closed greenhouse would be preferred over an evaporatively cooled greenhouse or not. Finally, the costs of water and or electricity can change over time while the presented trade-off not, therefore the presented approach can be used to indicate the most suitable greenhouse design for a specific area and moment in time.

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.

Data availability

Data will be made available on request.

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