https://doi.org/10.71252/2177-34912025720004
ISSN: 2177-3491
revista Ceres

Irrigation water productivity in grape tomato under different matric potential ranges

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Editors:
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Submitted: March 24th, 2024.
Accepted: December 21st, 2024.

ABSTRACT

The knowledge of critical limits of water potential in the substrate (Ψ) allows performing irrigations that do not exceed the capacity of water storage and do not harm crop yield. In this study, substrate water retention curve was determined by inverse modeling and originated two ranges of Ψ used for irrigation scheduling: range 1, upper critical (UPΨ) = -6 kPa and lower critical (LCΨ) = -40 kPa; and range 2, UPΨ = -14 kPa and LCΨ = -40 KPa. These limits were applied in the irrigation scheduling of grape tomato in a fixed form and by changing Ψ according to the crop development stage (DS). The water productivity (WP) was determined as a function of variations in the values and form of application of Ψ. The experiment was carried out in a greenhouse. Plants were cultivated in pots filled with substrate, fertigated by an automated drip irrigation system. Tomato evapotranspiration was determined using a weighing lysimeter. Soil water content was monitored by GS1 and TDR100 sensors. Yield was not significantly affected by the different ranges of Ψ applied. WP was statistically higher in plants subjected to range 2 throughout the crop cycle and in at least one of the DS.

Keywords: *Solanum lycopersicum* L.; drip irrigation; irrigation management; water potentials in the substrate.

INTRODUCTION

The soil is a reservoir with limits on soil water availability for plant. Therefore, proper management of irrigation via soil water sensing (SWS) depends on prior knowledge of critical limits of potential (Ψ) or soil water content (θ). The upper critical (UC) limit (reference to turn off irrigation) is considered to be the field capacity, corresponding to matric potentials between 6 kPa and 33 kPa[1] and the lower critical (LC) limit (reference to turn on irrigation) is considered somewhere between 35 kPa and 75 kPa[2-4]. Generally, a single range between UC and LC are recommended for the entire tomato production cycle.[4,5]

The choice of UC and LC values affects the availability of soil water to plants with consequences on the depth and frequency of irrigation. However, these ranges can be applied in different ways at different stages of the crop cycle, when aim is to maximize water productivity. This is especially important when considering UC and LC used as thresholds for automatically triggering an irrigation system. Additionally, knowledge of soil and plants' water potential can be used to develop, calibrate and test crop growth models and water budget models.[6]

Irrigation management via SWS based on UC and LC depends on prior knowledge of the Soil Water Retention Curve (SWRC). Conventionally, SWRC is determined by static equilibrium methods. An alternative to static equilibrium methods for SWRC determination is inverse modeling (IM) of data from transient water flow experiments. IM consists of using a numerical model based on the discretization of Richards' equation capable of simulating spatial-temporal variations of θ or Ψ under transient conditions. Through the relation between θ or Ψ data measured experimentally and modeled, the set of parameters of the Van Genuchten's equation is generated from an objective function that approximates the simulated values to the observed values. The parameters obtained will generate the SWRC. Some authors[7,8] have applied inverse modeling to obtain SWRC using Hydrus – 1D software.[9]

In this context, the objective of this study was to evaluate the irrigation water productivity of grape tomato cultivated in substrate and subjected to irrigation management via SWS considering different UC and LC thresholds of matric potential applied according to the crop development stage.

MATERIALS AND METHODS

Experimental characterization

The experiment was carried out in a greenhouse, at the Federal Institute of Education, Science and Technology Baiano - Campus Governador Mangabeira (12º36'30.53" South latitude and 39º01'51.71" West longitude).

The greenhouse used is an arched roof type (oriented in the east/west direction), with length of 27 m, width of 6 m and ceiling height of 3 m. The structure of the greenhouse consisted of anti-aphid screen on the sides and a 150-nm-thick anti-UV plastic film on the top. In total, 245 polyethylene pots, with individual volumetric capacity of 8 L, were placed inside the greenhouse. The planting spacing was 1 m between rows and 0.5 m between plants. The polyethylene pots were filled with commercial substrate Carolina soil class XVI, composed of limestone, sphagnum peat, coconut fiber and rice husk. It also presents dry matter density of 160 kg m^{-3}, pH of 6.5 and electrical conductivity 0.7 mS/cm.

The pots were distributed in 7 cultivation rows, using the two rows closest to the sides of the greenhouse as borders. The treatments were completely randomized within planting lines and subjected to one of the two potential ranges (-6 to -40 kPa or -14 to -40 kPa) throughout the crop cycle and those subjected to combinations of these ranges according to the crop cycle had 21 and 6 replicates, respectively, Therefore, the experiment consisted of 8 treatments, according to Table 1, thus totaling 78 experimental plots.

Table 1: Variations in the application of the ranges of matric potential of water in the substrate by phenological stages of grape tomato

Matric potential range |Ym| (kPa)	Phenological stage of application
|Ym| 6 to 40 kPa	Entire cycle
|Ym| 14 to 40 kPa	Entire cycle
|Ym| 14 to 40 kPa	Stage I (Vegetative growth)
|Ym| 14 to 40 kPa	Stage II (Flowering)
|Ym| 14 to 40 kPa	Stage III (Fruiting)
|Ym| 14 to 40 kPa	Stages I and II
|Ym| 14 to 40 kPa	Stages I and III
|Ym| 14 to 40 kPa	Stages II and III

Irrigation was applied by a drip system, with management via SWS, keeping the lower critical limit (moment of starting the motor pump) fixed at -40 kPa as determined by Zheng et al.[5], Coolong et al.[10], and Wang et al.[4] With the aim of varying the soil-water availability to plants the upper critical limit (moment of turning off the motor pump) there were two: -6 kPa and -14 kPa. Additionally, the effect of using the value of -14 kPa in only one stage of crop development (I; II; or III) and in two stages of crop development (I and II; I and III; II and III) was evaluated.

Nutrition, fertilization and cultural practices

The plants were fertigated with nutrients (macro and micronutrients) using synthetic fertilizers. The nutrients supplied during the "development" vegetative phase and "fruiting" are: N (111.95 and 164.10), P (61.99 and 93), K (156.11 and 371.27), Ca (80.06 and 108), Mg (23.54 and 33.30), S (47.96 and 64.67), B (0.221 and 0.3247), Cu (0.0325 and 0.045), Fe (2.00 and 2.00), Mn (1.18 and 1.75), Mo (0.0612 and 0.0612) and Zn (0.262 and 0.262), the amount of the nutrients presented above refer to g/1000 L water.

The seedlings of tomato plants were obtained by sexual propagation, through sowing in trays with 126-mL cells filled with substrate. The transplanting of the seedlings to the experimental plots was performed 25 days after germination, according to Abaurre[11] (2010), who recommends that the seedlings be transplanted when they have four to six true leaves (usually between 20 and 30 days after germination), without etiolation, are well developed and in optimal sanitary conditions.

At 10 days after transplanting (DAT), tomato seedlings were vertically supported by stakes and, as the plants grew, they were tied to the support using plastic twine, following the technical recommendations indicated by Abaurre[11] (2010).

In addition, the electrical conductivity of the substrate (EC_{sub}) was monitored throughout the crop cycle. For this, porous-cup extractors were installed in the growing pots at 0.1 m depth, and readings were performed every 3 days. The electrical conductivity of the substrate solution extracted varied between 1.9 and 2.9 dS m^{-1}, throughout the tomato crop cycle. The nutrient solution used for fertigating the plants ranged between 0.90 and 1.80 dS m^{-1}, in order to maintain the electrical conductivity range of the substrate solution between 1.8 (electrical conductivity of the nutrient solution using water of 0.25 dS m^{-1} and the nutrient ions of the nutrient solution adopted/recommended for tomato cultivation) and 4.9 dS m^{-1}. The maximum electrical conductivity of the substrate solution of 4.9 dS m^{-1} was adopted based on the study conducted by Andriolo et al.[12], who observed a non-significant effect on the yield of tomato when it was cultivated below this electrical conductivity level in substrate.

Substrate water sensors and weighing lysimeters

The soil water sensors were calibrated, generating curves and equations that correlate values of substrate volumetric water content (θ) with those of electrical signal (mV V^{-1}) for the use of GS1 sensors (Decagon Devices, Inc., Hopkins CT, Pullman, USA) (Equation 1) and dielectric constant (Ka) for the use of TDR (Campbell Scientific, INC., Logan, Utah, USA) (Equation 2).

$$\theta = 0.617 \times Electrical\ signal - 0.6064\ (R^2=0,9422) \quad (1)$$

$$\theta = 0.0115 \times Dielectric\ constant + 0.1224\ (R^2=0,9849) \quad (2)$$

The TDR used was the TDR-100 model, connected to a set of multiplexers and a CR800 Campbell Scientific datalogger to obtain and store the values of substrate volumetric water content, at time intervals of 30 min.

The GS1 sensors were used in the automation of irrigation management, monitoring two growing pots to control irrigation management with the Ψ range from -6 to -40 kPa and two more growing pots for the Ψ range from -14 to -40 kPa. In turn, TDR sensors were used for additional monitoring of θ variation in two weighing lysimeters (one lysimeter for the range from -6 to -40 kPa, and another for the range from -14 to -40 kPa) and in two pots of each irrigation management condition used in the experiment, totaling 18 pots monitored by TDR.

The weighing lysimeters were installed in the center of the greenhouse, one lysimeter to determine the evapotranspiration of a plant cultivated under the potential range between -6 and -40 kPa, and another for a plant cultivated under the range between -14 and -40 kPa. Each lysimeter consisted of an 8 L polyethylene pot filled with substrate and a weighing platform with capacity of 60 kg and weighing accuracy of 0.006 kg.

The weighing lysimeters were used to quantify the evapotranspiration of the crop between two irrigation events. For this, the hourly mass variation was automatically recorded on the weighing platforms. Thus, it became possible to determine the volume of water consumed, for the conditions of cultivation under both the potential range between -6 and -40 kPa and the potential range between -14 and -40 kPa, according to Equation 3.

$$Volume_{water} = Mass_t - Mass_{t+1} \quad (3)$$

Where, $Volume_{water}$ = volume of water consumed by the crop at a specific time (L); $Mass_t$ = mass (kg) of the weighing lysimeter immediately after the end of an irrigation; $Mass_{t+1}$ = mass (kg) of the weighing lysimeter immediately before starting an irrigation.

The weighing platforms were calibrated by applying and removing known masses, thus obtaining fitting equations that correlate mass (kg) with electrical signal (mV V^{-1}) (Equations 4 and 5).

$$Mass = 46.707 \times Electrical\ signal - 14.002 \quad (R^2 = 0.9998) \quad (4)$$

$$Mass = 88.895 \times Electrical\ signal - 13.357 \quad (R^2 = 1.0000) \quad (5)$$

Where, Mass = weighing lysimeter mass (kg); Electrical signal = Electrical signal emitted by the load cell (mV V^{-1}).

Obtaining substrate hydraulic properties (SHP) by inverse modeling

SHP were determined through an inverse modeling experiment, using HYDRUS - 1D software, version 4.16.0110.[9] For this, two GS1 substrate moisture sensors (Decagon) were installed at depths of 0.05 and 0.12 m in each of the two weighing lysimeters.

The weighing lysimeters were saturated with the drain closed. The lysimeter substrate was allowed to dry, so water outflow occurred only through the evaporation process. Variations in the water content in the substrate and the mass variation that occurred on the weighing platform (water loss by evaporation) were measured and stored in a Campbell Scientific CR800 datalogger at 15-minute intervals, for a period of 52 days.

The data obtained from the variation of water content in the substrate and evaporation were entered in HYDRUS - 1D software, to solve Equation 6 of Richards[13], which estimates the flow of water in the substrate.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] \quad (6)$$

Where, h = water pressure in the substrate (m H_2O); θ = water content in the substrate ($m^3.m^{-3}$); t = time (h); z = vertical coordinate (m); K(θ) = represents the substrate hydraulic conductivity function (m h^{-1}).

SWRC (Equation 7) and the substrate water conductivity curve (SWCC) (Equation 8) were described using the Mualem-van Genuchten model.[14, 15]

$$\begin{cases} \theta(h) = \theta_s & h \geq 0 \\ \theta(h) = \theta_r + (\theta_s - \theta_r)\left[\frac{1}{1+|\alpha h|^n}\right]^{(1-\frac{1}{n})} & h < 0 \end{cases} \quad (7)$$

$$K(\theta) = K_S S_e{}^{\lambda}\left[1 - \left(1 - S_{e^{\frac{n}{n-1}}}\right)^{1-\frac{1}{n}}\right]^2 \quad (8)$$

$$S_e = \frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} \quad (9)$$

Where, θ_r = residual water content ($m^3 m^{-3}$); θ_s = saturated water content ($m^3 m^{-3}$); h = matric potential (m); K (θ) = unsaturated hydraulic conductivity of the substrate (m h^{-1}); K_s = saturated hydraulic conductivity of the substrate (m h^{-1}); S_e = effective saturation; α, n and λ = empirical parameters.

In HYDRUS - 1D software, the hydraulic parameters of the substrate (θ_r, θ_s, α, n, λ and Ks) were determined by minimization between observed and simulated θ in space and time. For this, the total differences obtained between the observed and simulated values of θ were used, which can be expressed from an objective function (Φ) (Equation 10).

$$\Phi(\theta, \beta) = \sum_{j=1}^{m}\sum_{i=1}^{nj}\left[\theta_{TDR,j}(z_i, t_i) - \theta_{EST,j}(z_i, t_i, \beta)\right]^2 \quad (10)$$

Where, Φ = objective function; θ_{TDR} = water content in the substrate; θ_{EST} = soil water content estimated using hydraulic parameters of the soil optimized in β (Θ_r, Θ_s, α, n, λ and Ks); t_i = time of reading; z_i = position of the moisture sensor; j = number of readings performed at the same point; m = number of different sites of moisture measurements; n = number of measurements performed.

It can be noted in Equation 8 that the right side of the equation refers to the residual between the sums of the values of water content observed with the GS1 sensor at the time ti for j measurements at zi and the corresponding values of water content estimated using the substrate parameters optimized in β. The objective function (Φ) was minimized using the nonlinear Levenberg-Marquardt method.

With the hydraulic properties of the substrate, the pairs of values (θ x Ψ) that represented the critical limits for irrigation management were determined (Figure 1).

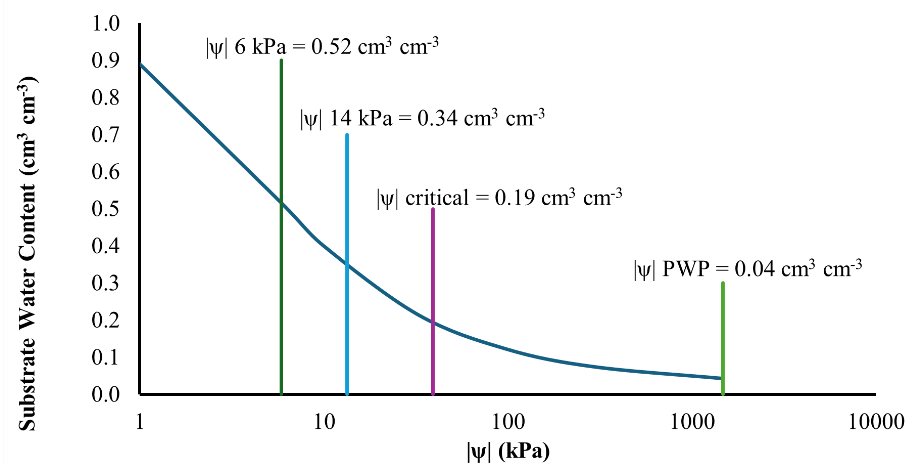

Figure 1: Substrate water retention curve.

Irrigation management and substrate moisture monitoring

Irrigation management was carried out in an automated manner, using an Arduino board, GS1 sensors, solenoid valves and a motor pump set.

The decision-making to start and end an irrigation event was based on the lower and upper limits of substrate moisture (Table 1). Two values of matric potential were used as upper limit: -6 kPa (0.52 cm^3 cm^{-3}) and -14 kPa (0.34 cm^3 cm^{-3}). The lower limit was equal to -40 kPa (0.19 $cm^3 cm^{-3}$), fixed for both conditions of irrigation depth replacement adopted, a value derived from the studies of Wang et al.[4], Zheng et al.[5] and Coolong et al.[10] Thus, it became possible to determine the irrigation time required to raise the substrate moisture from the lower limit to the upper limit, according to Equation 11.

$$T_{\text{irrigation}} = \frac{(\theta_{UL} - \theta_{LL}) \times \text{Volume}_{Pot} \times \frac{1}{Ef}}{Q_E} \qquad (11)$$

Where, $T_{irrigation}$ = irrigation time required to raise the substrate moisture from the lower limit to the upper limit (h); θ_{UL} = volumetric water content of the substrate at the upper limit (cm^3 cm^{-3}); θ_{LL} = volumetric water content of the substrate at the lower limit (cm^3 cm^{-3}); Volume_{Pot} = volume of the growing pot (L); Ef = water application efficiency of the irrigation system (decimal) equal to 90%; Q_E = emitter flow rate (L h^{-1}).

The loss of water by deep percolation after completion of irrigation events was not identified after 10 days after transplantation (DAT).

Meteorological monitoring

A weather station, composed of pyranometer, thermometer and hygrometer to measure solar radiation, temperature and relative air humidity, respectively, was set up inside the greenhouse (Figure 2A and 2B). The average temperature in the period was 23.8 °C. The minimum and maximum daily temperatures in the period ranged from 15.99 to 22.89 °C and from 25.83 to 41.50 °C, respectively. The average relative air humidity in the period was 79.19%, with the daily minimum and maximum values ranging from 32.63 to 74.76% and from 90.40 to 96.20%.

Analysis of tomato growth and yield

For the conditions of replacement of the irrigation depth required to return the substrate moisture to the potentials of -6 and -14 kPa, destructive analyses of three plants (for each irrigation management condition) were performed at 25-day intervals, determining the following variables: stem diameter (SD), plant height (PH), leaf fresh mass (LFM), stem fresh mass (SFM), number of leaves (NL), leaf dry mass (LDM), stem dry mass (SDM) and leaf area (LA).

SD and PH were determined using a digital caliper and a measuring tape, respectively, whereas the variables LFM, SFM, LDM and SDM were determined using a precision scale (± 0.01 g) and NL was determined by counting.

For determining the LA of tomato plants, fitting equations were initially obtained through the correlation between the actual values of leaf area (obtained by scanning the leaves and using ImageJ software) and leaf length (L) and/or leaf width (W). The correlation between actual values and (L x W) was adopted to obtain the fitting equations because it showed the highest R^2 values. The fitting equations were obtained using two plants (for each collection and/or destructive analysis), for the collections carried out at 25 (Equation 12) and 49 days after transplantation (DAT) (Equation 13). These fitting equations were used to estimate the leaf area of the other plants collected for destructive analysis.

$$LA = 0.2117 \times L \times W + 18.440 \ (R^2 = 0.9135) \quad (12)$$

$$LA = 0.3120 \times L \times W - 21.677 \ (R^2 = 0.9306) \quad (13)$$

Where, LA = leaf area of a single leaf (cm^2); L = leaf length (cm); W = maximum leaf width (cm).

Ripe tomatoes were harvested weekly in all plants and for both irrigation management conditions investigated, in the period between 56 and 111 DAT. In the laboratory, the diameter, length, number and mass of the fruits were determined.

Irrigation water productivity

The irrigation water productivity ($Prod_{water}$) for the different irrigation management conditions was quantified based on the relation between production and water consumption of the crop after transplantation, according to Equation 14.

$$Prod_{water} = \frac{FrFM}{Total\ volume_{water}} \quad (14)$$

Where, $Prod_{water}$ = irrigation water productivity (Kg m^{-3}); FrFM = fruit fresh mass (Kg); Total $volume_{water}$ = total volume of water applied via irrigation after transplanting (m^3).

Statistical analysis

The variables related to the growth and yield of tomato crop and irrigation water productivity were subjected to analysis of variance and F test at 5% probability level. Subsequently, the means were compared using the Tukey test at 5% probability level.

RESULTS

The information regarding the substrate hydraulic properties (SHP) obtained through inverse modeling is presented in Table 2. The statistical indicators R^2 = 0.978, MAE = 0.042 m^3 m^{-3} and RMSE = 0.051 m^3 m^{-3} revealed good convergence of the modeling in the optimization of SHP.

Figure 2 illustrates the variations of water storage in the substrate calculated from the values of volumetric water content obtained via TDR in development stage I. The average value of the matric potentials for the lower limit

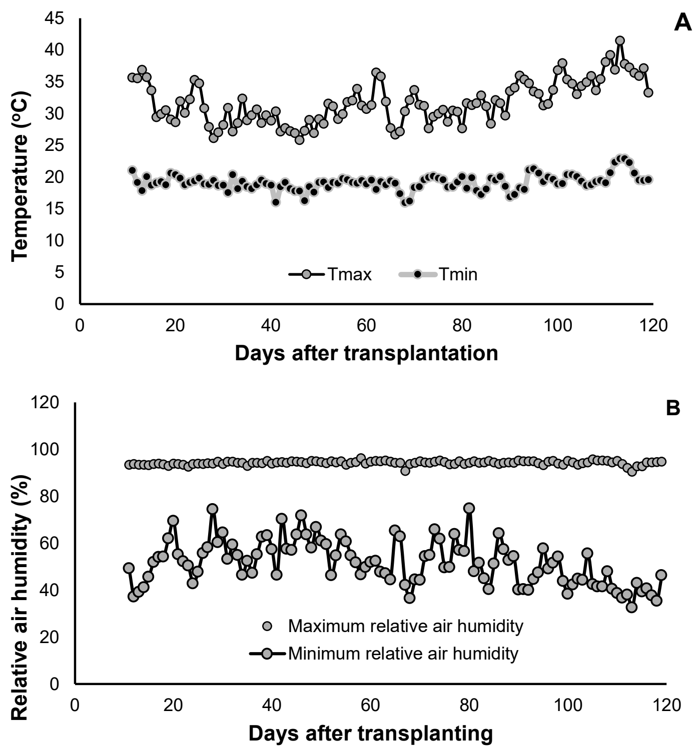

Figure 2: Maximum temperature (Tmax); (Tmin) do ar (A) e umidade máxima e mínima do ar (B), dias após o transplantio, no interior da casa de vegetação.

in the period of 8 days for the conditions of replacement of the irrigation depth required to return substrate moisture to matric potentials of -6 and -14 kPa were -39.80 ± 2.52 kPa and -41.96 ± 2.69 kPa; and the mean values of the matric potentials for the upper limit were -4.68 ± 0.55 kPa and -9.04 ± 0.62 kPa. The average limits observed of the volume of water stored in the pots were: 0.81 ± 0.06 liters and 1.9 ± 0.06 liters for the potential range from -6 to -40 kPa and 0.89 ± 0.04 liters and 1.52 ± 0.05 liters for the potential range from -14 to -40 kPa. Figure 3 shows the distinctions in terms of irrigation frequency and volume of water applied as a function of the potential ranges. To maintain the soil in the range -14 to -40 kPa, an average of 1.5 liters/plant was applied every 48 hours, while to maintain the soil in the range -6 to -40 kPa, 0.6 liters/plant was applied every 36 hours.

The accumulated volumes of water applied in range 1 were 5.38, 30.50 and 35.63 L plant^{-1}, for the vegetative, flowering and fruiting phenological stages, respectively, with a total volume of 71.50 L plant^{-1}. In range 2, the accumulated volumes of water applied were 4.20, 22.74 and 32.55 L plant^{-1} for the vegetative, flowering and fruiting phenological stages, respectively, with a total volume of 59.49 L plant^{-1}. Therefore, the volume of water applied to plants subjected to the range from -14 to -40 kPa was approximately 16.79% lower, when compared to the total accumulated volume applied to plants subjected to the range from -6 to -40 kPa.

When comparing the condition of application of the range of matric potential of water in the substrate from -14 to -40 kPa in only one of the crop development stages with the condition of replacement of the irrigation depth required to return the matric potential of water in the substrate from -6 to -40 kPa in the entire crop cycle, reductions of 1.65, 10.84 and 4.30% in water consumption were found for stages I, II and III, respectively. When the condition of replacement of the irrigation depth that returned the matric potential of water in the substrate to the range from -14 to -40 kPa was applied in stages I and II, I and III, and II and III, the saving of accumulated water applied was 12.49, 5.95 and 15.14%, respectively.

The frequency and/or interval between irrigations obtained as an effect of the application of the different potential ranges, for the vegetative, flowering and fruiting stages, was on average 48, 24 and 24 h for the condition of replacement of the irrigation depth required to return the matric potential of water in the substrate to -6 kPa and 36, 18 and 15 h for the condition of replacement of the irrigation depth required to return the matric potential of water in the substrate to -14 kPa, respectively.

For the conditions of replacement of the irrigation depth required to return the matric potentials of water in the substrate to -6 and -14 kPa, there was no significant effect at 5% probability level for the variables SD, NL and SDM, at 25, 49, 75 and 103 DAT. Other variables also showed no significant effect, such as: PH at 25, 75 and 103 DAT; LFM

Table 2: Substrate hydraulic properties obtained by inverse modeling

θ_S (m^3 m^{-3})	θ_R (m^3 m^{-3})	α (m^{-1})	n (–)	λ (–)	K_S (m day^{-1})
0.893	0.024	0.037	1.604	0.5	0.093

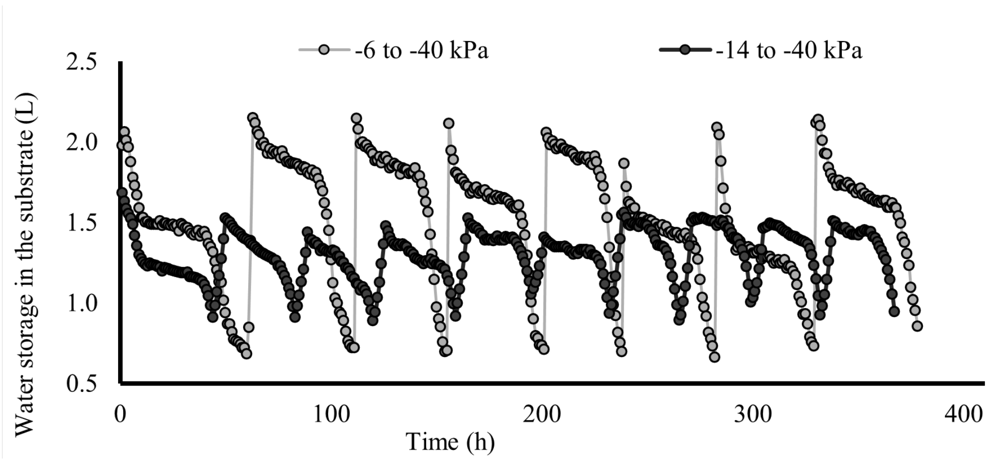

Figure 3: Variations in water storage in the growing substrate of grape tomato subjected to -6 kPa and -14 kPa.

at 25 and 103 DAT; SFM at 25, 75 and 103 DAT; LDM at 49 and 103 DAT; and LA at 25, 75 and 103 DAT. The variables PH at 49 DAT, LFM at 49 and 75 DAT, SFM at 49 DAT, LDM at 75 DAT and LA at 49 DAT were significantly affected at 5% probability level.

For the variables that differed statistically, the condition of replacement of the irrigation depth required to return the matric potential of water in the substrate to -14 kPa caused reductions of approximately: 9.77% for PH at 49 DAT; 30.10 and 27.46% for LFM at 49 and 75 DAT, respectively; 30.74% for SFM at 49 DAT; 43.19% for LDM at 75 DAT; and 25% for LA at 49 DAT, when compared to the condition of replacement of the irrigation depth required to return the matric potential of water in the substrate to -6 kPa (Table 3).

When analyzing the effect of the conditions of replacement of the irrigation depth required to return the matric potentials of water in the substrate to -6 and -14 kPa on the variables production (Prod), number of fruits (NFr) and irrigation water productivity ($Prod_{water}$), it was observed that $Prod_{water}$ was significantly affected at 5% probability level by the F test. A non-significant effect was found for the conditions of replacement of the irrigation depth required to return to substrate moisture to the matric potential of -14 kPa, when applied only in stage I, II or III and/or when applied in stages I and II, I and III, and II and III, for the variables Prod, NFr and $Prod_{water}$ (Table 4).

When tomato is subjected to regulated water deficit by varying LC in the tomato development stages, distinctions between the phases are generally observed.[16-18] Our study shows that applying less water does not necessarily imply deficient irrigation.

For the condition of replacement of the irrigation depth required to return the matric potential of water in the substrate to -14 kPa throughout the crop cycle, $Prod_{water}$ was 17.70% higher, when compared to the condition of replacement of the irrigation depth required to return the matric potential of water in the substrate to -6 kPa (Table 4). We reduced the amount of water applied to the crop by changing only the UC limit, keeping the LC limit fixed at -40 kPa, as recommended by Wang et al.[4], Zheng et al.[5] and Coolong et al.[10] It is demonstrated that $Prod_{water}$ can be increased without necessarily having a soil water deficit, but by decreasing the amount of water available in the soil from the LC limit optimum for plants.

DISCUSSION

The difference in relation to the total volume of water applied in plants subjected to the two potential ranges (-6 to -40 kPa and -14 to -40 kPa) may be due to the fact that there is a linear relation between evaporation speed and soil moisture, until the moment when linearity is non-existent and the evaporation speed is very slow.[19] This physical phenomenon of soil water loss by evaporation[19] may explain this difference in relation to the total volume of water applied, since irrigation management was automated, with the critical limit of water in the substrate fixed for both irrigation management conditions and varying only the upper limit of water in the substrate. Thus, the matric potential of water in the substrate referring to the upper limit of water in the substrate can be reduced and promote lower water losses by evaporation.

Table 3: Mean values of stem diameter (SD), plant height (PH), leaf fresh mass (LFM), stem fresh mass (SFM), number of leaves (NL), leaf dry mass (LDM), stem dry mass (SDM) and leaf area (LA) of tomato plants subjected to different ranges of soil water potential (Ψ)

|Ψm| (kPa)	Mean values							
	SD (mm)	PH (cm)	LFM (g)	SFM (g)	NL	LDM (g)	SDM (g)	LA (m^2)
				First harvest - 25 DAT				
6 to 40	5.7a	79.7a	110.6a	55.9a	12.7a			0.3a
14 to 40	7.0a	85.0a	99.1a	57.8a	12.3a			0.2a
				Second harvest - 49 DAT				
6 to 40	9.9a	177.3a	497.7a	249.1a	22.3a	56.4a	34.7a	0.9a
14 to 40	8.0a	160.0b	347.9b	172.5b	22.3a	41.9a	26.4a	0.7b
				Third harvest - 75 DAT				
6 to 40	12.1a	269.0a	383.6a	295.1a	33.0a	49.9a	52.5a	0.6a
14 to 40	11.0a	279.0a	278.3b	258.3a	28.0a	28.4b	35.8a	0.5a
				Fourth harvest - 103 DAT				
6 to 40	14.0a	383.7a	145.0a	440.9a	29.0a	22.5a	76.8a	0.2a
14 to 40	12.8a	395.7a	174.7a	454.2a	28.7a	27.0a	79.7a	0.3a

Table 4: Mean values of production (Prod), number of fruits (NFr) and irrigation water productivity (Prodwater) in tomato cultivation considering different ranges of matric potential of water in the substrate applied in different stages of the crop cycle

Matric potential |Ψm|	Cultivation stages	Mean values		
		Prod (g)	NFr	$Prod_{water}$ (kg m^{-3})
6 to 40 kPa	Entire cycle	2253.76a	210.62a	31.52b
14 to 40 kPa	Entire cycle	2207.28a	182.40a	37.10a
14 to 40 kPa	Stage I	2346.43a	222.50a	33.67a
14 to 40 kPa	Stage II	1952.28a	174.83a	30.63a
14 to 40 kPa	Stage III	2414.37a	199.83a	35.29a
14 to 40 kPa	Stage I and II	2079.08a	176.83a	33.23a
14 to 40 kPa	Stage I and III	2384.88a	188.17a	35.47a
14 to 40 kPa	Stage II and III	2094.66a	195.20a	34.53a

When range 2 was applied in only one of the crop development stages and/or in stages I and II, I and III, and II and III, the highest percentages of water saving occurred when this range was applied in stage II.

Associated with the phenomenon of water loss by evaporation, a possible explanation may be the higher leaf area index of the plant covering the growing pot during the phenological stage of flowering, since in the vegetative stage the plants (seedlings) had a low leaf area index and in the fruiting stage the leaf area index near the growing pot was low due to the pruning of leaves (removal of leaves below the tomato bunch(es) harvested).

In a study with tomato crop cultivated in soil and in a protected environment, Wang et al.[20] found that the highest intensity of water loss by evaporation occurred in the seedling stage, which corresponds to the phenological stage of lowest leaf area index.

The higher irrigation frequency for the condition of replacement of the irrigation depth required to return to the substrate moisture to the matric potential of -14 kPa is probably due to the shorter water storage range associated with the system on/off scheduling (Figure 2). According Wang et al.[4] too much soil water content under higher soil matric potential would reduce the soil store ability, which affected the water use efficiency.

The non-significant effects for the Prod and NFr variables under the conditions of matric potentials of water in the substrate ranging from -6 to -40 kPa and from -14 to -40 kPa are probably due to the fact that tomato crop under both irrigation management conditions was subjected to the same lower critical value. In studies carried out by Wang et al.[4] (cultivating *Solanum lycopersicum* Mill., cv. Shijihongguan) and Zheng et al.[5] (cultivating *Lycopersicon esculentum* L-402), matric potentials of water in the soil greater than -50.00 and -40.00 kPa, respectively, also did not lead to decrease in the yield of tomato crop cultivated in soil.

As demonstrated, by maintaining the LC limit at – 40 kPa and varying the UC limit, it is possible to obtain a lower volume of irrigation applied at critical stages without affecting the grape tomato production variables. It is important to verify that the reduction in the volume of water applied did not imply the need to reduce soil moisture to levels below the LC limit established for the crop. These results are particularly important for irrigation automation because when the adopted UC limit approaches soil saturation, the risk of percolation and leaching increases, especially due to the inaccuracies of sensor readings, the uncertainties inherent in the calibration process, and the errors involved in determining soil hydraulic properties.

In a study conducted by Coolong et al.[10] in 2009, evaluating the “Mountain Fresh” tomato subjected to soil water tensions ranging between -30 and -10, -30 and -25, -45 and -45, and -45 and -40 kPa, it was observed that crop yield was not significantly affected under any of these irrigation management conditions.

These non-significant results in the present study suggest that the range of matric potential of water in the substrate from -14 to -40 kPa promotes reduction in water application, when compared to the matric potential range from -6 to -40 kPa, without causing significant differences in crop yield. In addition, it shows that when the upper limit does not return to the maximum water storage capacity of the substrate (-6 kPa), $Prod_{water}$ is statistically higher (Table 4).

Therefore, it is recommended to experiment with other ranges for tomato cultivation, since the alteration and/or reduction in the upper limit of water in the substrate adopted for irrigation management can promote reductions in water application.

CONCLUSIONS

As a way to preliminarily support the automatic irrigation management via SWS, avoiding waste of water, nutrients and energy, the limits of potential between -14 and -40 kPa are recommended as references for the moment of turning the system on and off, although other values should be studied and compared to them by future studies.

The application of the range of matric potential between -14 and -40 kPa in one or two different phenological stages of tomato crop will not cause significant reductions in water productivity or crop yield.

Determining the hydraulic properties of the substrate via inverse modeling allowed the determination of lower matric potentials close to the permanent wilting point (-1500 kPa), thus expanding the range of matric potentials of interest for irrigation management (matric potential referring to field capacity, critical to the crop of interest and permanent wilting point).

Irrigation management carried out from the knowledge of substrate moisture referring to the matric potentials of water in the substrate at field capacity, at the critical point to the crop and at the permanent wilting point and by automation system via SWS allows the moisture in the substrate to be maintained within the range between the upper limit adopted and the critical point to the crop, thus providing the ideal conditions of water in the substrate for the potential development of the crop.

ACKNOWLEDGEMENTS, FINANCIAL SUPPORT AND FULL DISCLOSURE

We thank CAPES program for postgraduate scholarship, the company ISLA for supplying seeds, FAPESB and CNPq. 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.

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