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Evapotranspiration and Crop Water Stress Index in Mexican Husk Tomatoes (*Physalis ixocarpa* Brot)

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1. Introduction

The scarcity of water availability observed in some dams in Mexico during the last years and the over-exploitation of groundwater have pushed to establish strategies for a rational and efficient use of water resources. The modernization and rehabilitation of irrigation systems stands out among these strategies, in order to improve their efficiency and profitability.

Irrigation scheduling is a decision process used to estimate the amount and timing for applying irrigations, in order to minimize deficiencies or excess in soil moisture, which could cause adverse effects in growth, yield and quality of crops; however, irrigation is usually applied without any technical advice for farmers, and rather solely on an empirical basis. Crop irrigation scheduling should consider diverse factors, such as water requirements and growth characteristics for each species and variety, atmospheric evaporation demand, and physico-chemical and biological conditions of the soil that determine its water retention capacity, since, in addition to the effective root depth, these determine the amount of water that can be used in the crop's evapotranspiration process.

Values for crop evapotranspiration and crop water requirement are identical (Allen et al., 1998); however, crop water requirement refers to the amount of water that needs to be supplied, while crop evapotranspiration refers to the amount of water that is lost through evapotranspiration (ET). Evapotranspiration includes two processes that occur simultaneously in the soil-plant-atmosphere system, and there is no easy way of separating these processes: loss of water from the soil through evaporation and from the plant through transpiration (Burman & Pochov, 1994).

In order to estimate evapotranspiration of a specific crop, it is necessary to take into account some crop characteristics and environmental conditions. Meteorological conditions determine the evaporative demand of the atmosphere, while the crop canopy and the soil

humidity determine the magnitude at which the demand will be satisfied. Crop evapotranspiration can be calculated according to the FAO methodology (Allen et al., 2006) in the basic form of $ET_c = K_c ET_o$, where K_c is the crop coefficient. Then, crop evapotranspiration can be estimated if reference evapotranspiration (ET_o) measurements or estimations are available. These terms represent the meteorological demand (ET_o), and the ability of these plants and the soil to satisfy this demand (Jensen & Wright, 1978).

ET_o is a climatic parameter expressing the atmospheric evaporation capability. According to FAO (Allen et al., 1998), reference evapotranspiration (ET_o) is defined as the maximum amount of water that a hypothetical reference crop loses; at a height of 0.12 m, a surface resistance of 70 s m^{-1} and an albedo of 0.23 m, which is similar to what happens on an extensive green grass surface of uniform height that actively grows and is well-irrigated.

Among the methods used to measure evapotranspiration on a cultivated surface, the use of a lysimeter stands out, which measures evaporation directly from the soil when it is bare, or evapotranspiration from the plants when there is a crop established. A lysimeter is a large container full of soil, generally installed in the field to represent natural environmental conditions, and where the water-soil-plant system conditions can be regulated at convenience and measured with more precision than in the natural soil profile (Hillel, 1980). This method contributes a direct measurement of the crop evapotranspiration and is frequently used to study climate effects and to evaluate estimation methods. When a weighing lysimeter is not available, the water balance method is commonly used in the field, which allows calculating the actual crop evapotranspiration (ET_c), which allows to estimate the soil moisture loss in the soil-plant-atmosphere system, of special importance for irrigation scheduling purposes (Lubana et al., 2001).

Various approaches and methods have been used for irrigation scheduling: direct and indirect measuring of soil humidity, measuring the energetic state of water in the soil, estimating the atmospheric demand and, in experimental conditions, determining plants' water potential (Buchner et al., 1994) or infrared thermometry (Giuliani et al., 2001). However, diverse experimental methods have been used to obtain the ET_o from meteorological information and the ET_c from crop coefficients (Kc), which have generated different types of curves (Doorenbos & Pruitt, 1977; Jensen, 1981; Burman & Pochov, 1994; Allen et al., 1998; Dodds et al., 2005). In this study, the hypothesis is that with the soil's matric potential values in conditions of maximum water availability, it is possible to estimate the crop evapotranspiration and then the crop coefficients for husk tomato (*Physalis ixocarpa* Brot).

Idso et al. (1981) developed the Crop Water Stress Index (*CWSI),* an empirical method used to quantify the humidity tension in crops under arid conditions, which first depends on the determination of two baselines: with or without water stress. The baselines are specific for the crop and are influenced by the climate (Bucks et al., 1985). Jackson et al. (1981) modified the *CWSI* method by including more variables: vapor pressure deficit (*VPD*), net radiation (R_n) and aerodynamic resistance (r_a), in order to obtain a better theoretical prediction of the effects of climate on the crop temperature. This approximation is better than the empirical method, especially in humid climates (Keener & Kircher, 1983).

The *CWSI* method has had great practical use for irrigation scheduling for crops in arid and semi-arid environments (Calado et al., 1990; Itier et al., 1993; Anconelli et al., 1994; Jones, 1999; Orta et al., 2003; Yuan et al., 2004; Şimşek et al., 2005; Erdem et al., 2005). This is due primarily to the fact that the sensors required are easy to handle. In irrigated agriculture, the economic and ecological water cost is high when uncertainty in water availability is

considered, something that can increase with climate change; therefore, the cost of the sensors used to quantify needed data, related to climate variables and water stress, can justify the investment associated with the method (Feldhake et al., 1997).

Water evaporated by a plant surface has the function of stabilizing the leaves' temperature in response to the atmospheric evapotranspiration. Based on this fact, Jackson et al. (1981) present the theory behind the energy balance which partitions net radiation from the sun into two components: sensible heat that heats the air and latent heat that is used for transpiration. When a crop goes through water stress, stomata close and transpiration decreases, and therefore, leaf temperature increases. When there is no water stress a plant transpires completely, and the leaf temperature fluctuates from 1 to 4° C less than the air temperature; in this case, the *CWSI* is zero. When transpiration decreases, the leaf temperature increases and can reach 4 to 6 °C more than the air temperature. In case of high water deficit, transpiration from the leaves is drastically reduced with simultaneous increase in leaf temperature; when the plant is dead or is not transpiring for a long time, the *CSWI* is one (Jackson et al., 1982).

The objectives of the study were: i) Determine the inferior and superior baselines of the *CWSI* method in husk tomato crop for irrigation scheduling; ii) Understand the effect of the irrigation depth and plastic mulching in different crop phenological stages in response to the water stress index; iii) Determine the tomato husk crop evapotranspiration from the soil matric potential and the loss of soil moisture measured by the lysimeter; iv) Propose an alternative way for Kc calculation using the foliar area index.

2. Theory of the crop water stress Index (*CWSI*) and evapotranspiration

The Crop Water Stress Index (CWSI) is a measure of the relative transpiration rate occurring from a plant at the time of measurement, using data from plant temperature (T_c) and vapor pressure deficit which is a measurement from the air dryness. The CWSI, as proposed by Idso (1981) and Jackson et al. (1981), is defined by the following relationship:

$$CWSI = \frac{\left[\left(T_c - T_a\right)_m - \left(T_c - T_a\right)_{li}\right]}{\left[\left(T_c - T_a\right)_{ls} - \left(T_c - T_a\right)_{li}\right]} \tag{1}$$

where T_c is the crop temperature and T_a is the air temperature. The "m" subscript denotes the difference between the two measured temperatures, *li* (inferior limit) denotes the non-water stress baseline expressed as the difference between the two temperatures when evapotranspiration is not restricted by water availability, and *ls* (superior limit) denotes the hypothetical non-transpiring upper baseline expressed as the difference between the two temperatures when evapotranspiration is zero.

The crop water stress index is estimated by determining the relative distance between the lower baseline representing non-stress conditions (well-irrigated condition) and the upper baseline representing no-transpiration (totally stressed condition). It is assumed for the *CSWI* to vary between 0 and 1. Since it is not normally feasible to measure crop temperature without stress and a crop with stress simultaneously, the values for the inferior and superior limit of a canopy of interest can be calculated through an energy balance analysis on the surface. This energetic balance can be expressed as:

$$R_n = G + H + \lambda E \tag{2}$$

where R_n is the net radiation (Wm^{-2}), G is the heat flow on the soil surface (Wm^{-2}), H is sensible heat flow in the air (Wm^{-2}), and λE is the latent heat flow (Wm^{-2}). The terms H and λE in equation (2) are a function of temperature gradients and vapor pressure, respectively, and can be expressed as:

$$H = \frac{\rho_a C_p (T_c - T_a)}{r_a} \tag{3}$$

and

$$\lambda E = \frac{\rho_a C_p (e_s - e_a)}{\gamma (r_a + r_c)} \tag{4}$$

where ρ_a is the water density (kg m^{-3}), C_p is the specific heat in the air (J kg^{-1} °C), e_s is the saturation water vapor pressure at a temperature of T_c (kPa), e_a is the actual air water vapor pressure (e_a), γ is the psicrometric constant (kPa°C^{-1}), r_a is the aerodynamic resistance (sm^{-1}), and r_c is the canopy resistance to the water vapor flow (s m^{-1}).

Equation (2) can be simplified by assuming that $G = 0.1\ R_n$ (Feldhake et al., 1996), and therefore, by defining I_c as coefficient of radiation interception equal to 0.9, so that equation (2) becomes:

$$I_c R_n = H + \lambda E \tag{5}$$

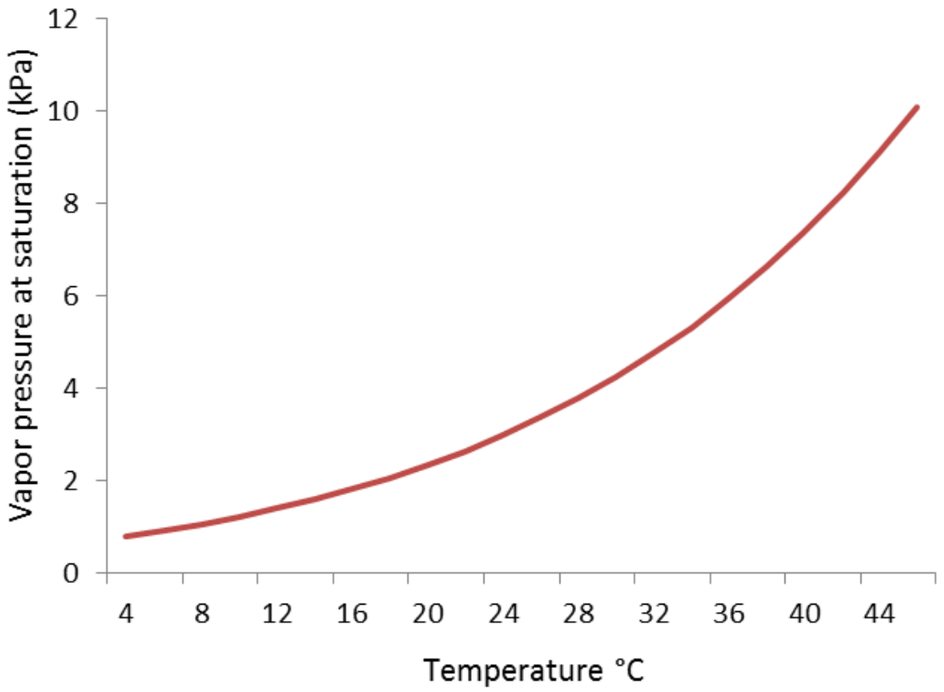


Fig. 1. Relationship between temperature and vapor pressure at saturation

When a volume of air is retained over an evaporating surface of water, equilibrium is reached between the water molecules that are incorporated into the air and those returning to the water source. At that moment, it is considered that the air is saturated, for it cannot hold any additional molecules of water. The corresponding pressure is called water vapor pressure at saturation (e_s). The amount of water molecules that can be stored in the air depends on the temperature (T). The higher the air temperature is, the higher the capacity to store water vapor and the higher the vapor pressure at saturation (Fig. 1). The curve slope changes exponentially with temperature. At low temperatures, the slope is small and varies slightly with the increase in temperature. At high temperatures, the slope is greater and slight changes in temperature produce great changes in the slope. The saturation vapor pressure curve slope (Δ) is an important parameter related with the water evaporation and is used in the calculation of reference evapotranspiration (ET_o) using weather data.
The value of Δ (kPa°C^{-1}) can be defined as:

$$\Delta = \frac{\left(e_s - e_a\right)}{\left(T_c - T_a\right)} \tag{6}$$

Jackson *et al*. (1988) found that the slope (Δ) can be calculated with:

$$\Delta = \left[45.03 + 3.014T_c - T_a + 0.05345(T_c - T_a)^2 + 0.00224(T_c - T_a)^3\right]10^{-3} \tag{7}$$

Combining equations 3, 4, 5 and 6, the temperature difference between the crop and the air can be estimated with equation (8):

$$T_c - T_a = \left[\frac{r_a I_c R_n}{\rho_a C_p}\right]\left[\frac{\gamma\left(1+\frac{r_c}{r_a}\right)}{\Delta+\gamma\left(1+\frac{r_c}{r_a}\right)}\right] - \frac{e_s - e_a}{\Delta+\gamma\left(1+\frac{r_c}{r_a}\right)} \tag{8}$$

Calculating the superior limit $(T_c–T_a)_{ls}$ when evapotranspiration is zero, r_c tends to the infinite and equation (8) is reduced to:

$$T_c - T_a = \frac{r_a I_c R_n}{\rho_a C_p} \tag{9}$$

When evapotranspiration is not limited by water availability and is equal to the reference rate, r_c approaches 0 and equation (8) is expressed as:

$$T_c - T_a = \left[\frac{r_a I_c R_n}{\rho_a C_p}\right]\left[\frac{\gamma}{\Delta+\gamma}\right] - \frac{e_s - e_a}{\Delta+\gamma} \tag{10}$$

Since the r_c does not really get to be zero in the reference evapotranspiration, the psicrometric constant γ is substituted by γ^* in equation (10):

$$\gamma^* = \gamma\left(1+\frac{r_{cp}}{r_a}\right) \tag{11}$$

where r_{cp} (sm^{-1}) is the canopy resistance in reference evapotranspiration. The crop's resistance can be determined by the O'Toole & Real method (1986).
Aerodynamic resistance can be calculated with a semi-empirical equation, according to Thorn & Oliver (1977), which is:

$$r_a = \frac{4.72\left\{\ln\left[\frac{z-d}{z_0}\right]\right\}^2}{\left(1+0.54\mu\right)} \tag{12}$$

where z is the reference height (m), d the displacement height (m), z_0 the texture length (m), and μ the wind velocity ($m\ s^{-1}$). The terms z_0 and d can be calculated from the height of the plant (h), in crops with a full cover, these parameters are calculated with:

$$z_0 = 0.13h \tag{13}$$

and

$$d = 0.63h \tag{14}$$

Another way of developing the energy balance equation to predict the difference in temperature between the crop and the air (T_c - T_a), is by arranging the terms of the superficial energy balance (Jackson et al., 1981):

$$T_c - T_a = X_1 X_2 - X_3 \tag{15a}$$

$$X_1 = \frac{r_a\left(R_n - G\right)}{\left(\rho_a C_p\right)} \tag{15b}$$

$$X_2 = \frac{\left[\gamma\left(1+\frac{r_c}{r_a}\right)\right]}{\left[\Delta+\gamma\left(1+\frac{r_c}{r_a}\right)\right]} \tag{15c}$$

$$X_3 = \frac{\left(e_s - e_a\right)}{\left[\Delta+\gamma\left(1+\frac{r_c}{r_a}\right)\right]} \tag{15d}$$

where all the terms are previously defined. Thus, equation (15b) is equal to equation (9) and they can be used to obtain the *CWSI* superior limit (dT_{ls}), where crop resistance (r_c) approaches the infinite. Equations (15c) and (15d) are used in the case of a non-water stressed crop (inferior limit), where r_c is assumed to be equal to zero.
The *CWSI* can also be expressed in terms of evapotranspiration, based on Jackson et al. (1981):

$$CWSI = 1 - \frac{ETc}{ET_0} \tag{16}$$

where ET_c is the actual crop evapotranspiration and ET_o is the reference evapotranspiration. Substituting its values, there is:

$$CWSI = \frac{\gamma\left(1+\frac{r_c}{r_a}\right)-\gamma\left(1+\frac{r_{cp}}{r_a}\right)}{\Delta+\gamma\left(1+\frac{r_c}{r_a}\right)} \tag{17}$$

Where the r_c/r_a relation is expressed as:

$$\frac{r_c}{r_a} = \frac{\frac{r_a R}{\rho C_p}-(T_c-T_a)(\Delta+\gamma)-(e_s-e_a)}{\left[\gamma\left((T_c-T_a)-\frac{r_a R_n}{\rho C_p}\right)\right]} \tag{18}$$

r_{cp} is the canopy resistance at potential transpiration, r_c is the canopy's actual resistance, r_a is the aerodynamic resistance to the transport of sensible heat in the air; the other parameters and variables have already been defined.

The relation between actual (ET_c) and reference (ET_o) evapotranspiration approaches more the theoretical values proposed by Jackson (1982), because it does not depend as much on the conditions of wind velocity as in the classical form, according to Idso et al. (1981). When replacing the *VPD* estimations from minimum temperature (Idso, 1982) with air temperature measurements in direct radiation on irrigated plots, not only does the correlation with the actual evapotranspiration increase, but in addition, it partially corrects the influence of the superficial soil temperature in small values for the leaf area index (*LAI*). Therefore, the estimation precision for evapotranspiration through the *CWSI* is given by the relation between actual evapotranspiration (ET_c) and the leaf's water potential (ET_o) at dawn (Itier et al., 1993).

3. Methodology applied for the water stress index and evapotranspiration in crops

3.1 Crop Water Stress Index (*CWSI*) determination

Canopy surface temperature was measured with infrared thermometer and later used to estimate the crop water stress index (*CWSI*) for husk tomato (*Physalis ixocarpa* Brot.) produced under drip irrigation, to study the effect of irrigation depth and plastic mulching. A completely randomized experimental design with three repetitions was used. The effects of five irrigation depths were studied; irrigation depth reposition of 40, 60, 80, 100 and 120 % of reference evapotranspiration (ET_0), estimated with the Penman-Monteith. The *CWSI* was calculated from temperature measurements for the crop and the air, and relative humidity measured with an infrared ray gun. Then, the vapor pressure deficit (*VPD*) was estimated. The equation that defines the *CWSI* inferior limit expresses the relation between the *VDP* and the difference in crop and air temperature (T_c-T_a).

Measured or actual evapotranspiration (E) divided by reference evapotranspiration (E_p), defined in equation (16) when working out ETc/ET_0 is:

$$\frac{ETc}{ET_0} = 1 - CWSI$$

Due to the differences in measurements of T_c-T_a vs *VPD*, the crop does not require irrigation until the *CWSI* reaches a threshold value, which can be from 0.1 to 0.2, depending on the crop. During this time, the crop is transpiring at a lower rate than the optimal and the crop yield begins to decline. The lower limit of a crop in a specific place can be determined two days after a maximum irrigation depth is applied on the crop.

Infrared thermometers or thermal seekers are used to measure the crop superficial temperature (Fig. 2). They measure the quantity of long wave radiation emitted by a surface as described by Stefan-Boltzman black body law in function of the temperature.

$$I = \varepsilon \sigma T^4 \tag{19}$$

where I is the radiation emitted by the surface (Wm^{-2}), σ is the Stefan-Boltzman constant (5.674×10^{-8} W m^{-2} K^{-4}), ε is the energy that a body emits at a given temperature, for a black body it is 1 and for others it is less than 1, T is the temperature on the surface (°K).

Fig. 2. Field measurement of parameters with infrared ray gun in husk tomato (*Physalis ixocarpa* Brot).

This CWSI method utilizes the temperature data for timing irrigation. A reduced form of expressing equation 1 is:

$$CWSI = \frac{(dT - dT_i)}{(dT_s - dT_i)} \tag{20}$$

where dT is the difference of measured air and crop temperatures; dT_s is the upper limit of the air temperatures minus the canopy temperature (crop without transpiration) and dT_i is

the lower limit of temperatures in the air minus the canopy temperature (fully-irrigated crop).

In order to determine the upper and lower limits in the *CWSI* equation, the method developed by Idso et al. (1981) is used, which considers changes in both limits due to variations in the air vapor pressure deficit (*VPD*). The *VDP* is the difference between the saturation pressure and the actual vapor pressure (eq. 21) and it is a good indicator of the actual evaporating capacity of the air.

$$DPV = e_s - e_a \tag{21}$$

where e_s is the water vapor pressure at saturation at a given air temperature and e_a is the current water vapor pressure (water vapor partial pressure in the atmosphere). When the air does not become saturated, the current vapor pressure will be lower than the vapor pressure at saturation.

The water vapor pressure at saturation (e_s), in kPa, is the maximum amount of water vapor that air can hold at a given temperature (T in °C) and it is calculated with equation (22):

$$e_s(T) = 0.611 \exp\left[\frac{17.27T}{T + 237.3}\right] \tag{22}$$

The actual water vapor pressure e_a can be obtained from equation (23) if the relative humidity (*HR*) and the crop temperature are measured with the infrared ray gun.

$$HR = \frac{e_a}{e_s} 100 \tag{23}$$

A *VPD* equal to zero indicates that the air holds the maximum water vapor possible (this corresponds to a relative humidity of 100%). The lower limit of the *CWSI* changes as a function of the water vapor pressure due to the *VPD*. The *CWSI* varies in the range between 0 and 1, when plants are subject to appropriate irrigation conditions and even to conditions of total water stress. Idso (1982) demonstrated that the lower limit of the *CWSI* is a linear function of the *VPD* for several crops. Once the parameters are estimated by the linear regression, the temperature difference between air and canopy can be calculated for a non-water-stressed crop (inferior limit) and a maximum stressed crop (superior limit), using the following two equations:

$$dT_i = a + b(DPV) \tag{24a}$$

$$dT_s = a + b\left[e_s(T_a) - e_s(T_a + a)\right] \tag{24b}$$

where *VPD* is expressed in kPa, $e_s(T_a)$ is the saturation vapor pressure at air temperature T_a (kPa), and $e_s\ (T_a + a)$ is the saturation vapor pressure at air temperature plus the value of the intercept for the crop. Thus, with the measurement of air humidity (relative humidity, wet bulb temperature, etc.), the air temperature and the leaf temperature, it is possible to determine the *CWSI*.

3.2 Crop evapotranspiration determination (ET_c)

In order to estimate the crop evapotranspiration, the equation must be expressed as:

$$ET_C = K_c K_s ET_o \tag{25}$$

where K_c is the crop coefficient obtained experimentally; K_s is the soil water availability coefficient, which was assumed to be equal to one in this study; ET_o is the reference evapotranspiration, estimated through the Penman-Monteith equation (Allen et al., 1998) with the average values of ambient variables measured between 6:00 and 19:00 h with an automatic weather station. The equation for calculating ET_o is given by the following relation:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \tag{26}$$

where: R_n is the net radiation flux density on the crop surface (MJ m^{-2} d^{-1}); G is the soil heat flux density (MJ m^{-2} d^{-1}); T is the average daily air temperature (°C); u_2 is the wind speed at 2 m high (m s^{-1}); e_s is the saturation vapor pressure (kPa); e_a is the actual vapor pressure (kPa); Δ is the slope of vapor pressure-temperature curve (kPa °C^{-1}) and γ is the psychometric constant (kPa °C^{-1}).

3.2.1 Experimental site and genetic material used

The study was carried out in Chapingo, Estado de México, located geographically at 19° 29′ N and 98° 53′ W, and an altitude of 2250 m. The climate in the location corresponds to a sub-humid temperate climate with summer rains, a dry season in the winter and thermal variation between 5° and 7° C (Arteaga et al., 2006). The annual average temperature is 15.5° C, with May being the warmest month and January the coldest. The annual average precipitation is 664 mm.

Mexican husk tomato was cultivated with a drip irrigation system during the period between March and June in 2007. The "CHF1-Chapingo" variety was used, a variety released commercially by the University of Chapingo, Mexico.

3.2.2 Seedling production and transplant

The seeds were sown on February 24, 2007, Julian day (J_d) = 55, in polystyrene trays with 200 cavities filled with a substrate consistent with a mixture of peat moss and vermiculite. The transplant was performed on March 30 (J_d = 89), and the last harvest was performed on June 30 (J_d = 181). The planting arrangement was 1.5 m between lines and 0.45 m between plants, with a density of 16122 plants ha^{-1}.

3.2.3 Physical and chemical characteristics of the soil

The soil texture was clay loam with an apparent density of 1.25 and 1.36 g cm^{-3} at 0.1 and 0.3 m of depth, respectively, a real density of 2.35 at 0.1 m and 2.39 g cm^{-3} at 0.3 m of depth; soil moisture at field capacity (FC) was 29.6 % and at a permanent withering point (PWP), it was 16.5 %. The soil retention curve was determined in the lab with the pressure cell and membrane, from soil samples taken with the Uhland probe, which were later dried in the stove at 105 ° C for 24 h, for later obtaining the porous space and the saturation soil moisture. Later, the moisture content (W) was determined by weight difference, in function of successive suction changes (ψ) during a sample drying process (Figure 1). The results indicate that the soil has medium to high capacity for water retention, with a void space or

volumetric saturation water content (θ s) that varies from 0.47 to 0.43 between 0.1 and 0.3 m of depth.

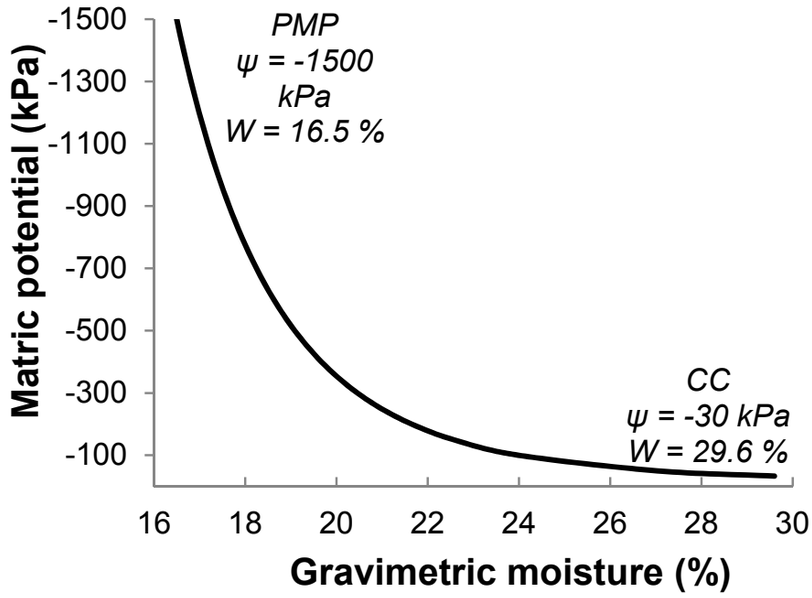


Fig. 3. Moisture retention curve in the experimental site.

The soil pH is practically neutral (6.99), moderately poor in organic material (1.48%), average in inorganic nitrogen (22.3 mg kg^{-1}), average in assimilable phosphorous (28.79 mg kg^{-1}), high in available potassium (646 mg kg^{-1}), moderately high in available calcium (2545 mg kg^{-1}), very high in available magnesium (1425 mg kg^{-1}), average in assimilable iron (8.51 mg kg^{-1}), moderately low in assimilable copper (0.79 mg kg^{-1}), average in assimilable zinc (1.44 mg kg^{-1}), moderately high in assimilable manganese (17.58 mg kg^{-1}), and very high in assimilable boron (2.63 mg kg^{-1}).

3.2.4 Treatments and experimental design

Five levels of irrigation depths were applied: 40, 60, 80, 100 and 120 % of the estimated ET_0, determined with the Penman-Monteith method (Allen et al., 1998) and two levels of silver-black plastic mulching, with and without. The treatments were distributed in a completely randomized design with three repetitions, where the depth-treatment area correspond to the area controlled by an irrigation valve, which was divided into two experimental units, one with mulching and the other without. The experimental unit for each treatment was 10 rows, 35 m long, separated at 1.5 m and 0.45 between plants.

The irrigation method was drip tape, with uniformity efficiency of 92%. The nominal characteristics are: inner diameter of 16 mm, 0.254 mm caliber, 1 L h^{-1} flow, space between transmitters of 0.3 m, and maximum pressure of 1200 kPa.

Characteristics of the plastic mulching were: 1.2 m width, for a 0.6 m bed, 2.28 mm caliber, partial perforation with a diameter of 0.063 m and 0.45 between spaces. The plastic laying was made with a mechanical mulching machine that contains devices for building the bed, fertilizing, and placing the tape and the plastic.

The watermark gypsum block sensors, with a range of measurement of 0-200 kPa, were installed at three depths (0.1, 0.3 and 0.4 m) in each treatment. A detailed description regarding the basic principles, characteristics, installation, and operating instructions can be found in Thompson et al. (2006).

3.2.5 Measuring humidity and estimating ET_c, ET_o and K_c

With the daily matric potential data measured with the watermark probes, which measure the content of water in the soil with a gravimetric or volumetric basis and the value, they are then transformed to matric potential using the soil moisture retention curve as shown on Fig. 1. The probes were installed at 0.1 and 0.3 m deep in the lysimetric container, and with the loss of measured soil moisture, a relation was obtained to estimate the ET_c as a function of matric potential. In order to estimate the crop's evapotranspiration, equation (25) was used, and the K_c was obtained experimentally; the K_s was assumed to be equal to one and the ET_0 was estimated through the Penman-Monteith equation (Eq. 26), with the average values of climatic variables measured between 6:00 and 19:00 h in an automatic station.

In order to estimate the crop evapotranspiration (ET_c), a weighing lysimeter was used, built with an undisturbed soil structure, and equipped with a mechanical-electronic system. The soil monolith had a prism-shaped, with a square base of 1.8 m per side and a depth of 1.5 m; the superior side of the monolith coincides with ground level, and the base has a draining system that allowed the exit of water. The lysimeter precision of the weighing system allowed detecting changes in weight that correspond to 0.15 mm of the water depth. The lysimeter soil water balance is indicated in Equation 27:

$$\pm\Delta S = P + R - (ET_c + I + E) \tag{27}$$

where ΔS is the change in the soil water content; P is precipitation; R is the irrigation contribution; ET_c the crop evapotranspiration; I is the deep infiltration or percolation; and E is the surface runoff.

Before establishing the experiment, the soil moisture loss was calibrated for the lysimeter with the matric potential of the first 0.3 m of depth, for which tensiometers were installed at 0.1 and 0.3 m deep. The incidence of rains was avoided and the calibration period lasted for 22 days. Based on the volumetric content at soil saturation (θ_s), which varies from 0.43 to 0.47, the irrigation depth was calculated for a specific depth (P_r) with equation 28:

$$L = (\theta_s - \theta_0) P_r \tag{28}$$

where θ_0 is the initial volumetric water content. Using the lysimeter area of 3.25 m², the water volume needed to saturate the top 30 cm of soil depth was calculated in 466 L.

The change in soil moisture in the lysimeter was determined daily through weight changes. The moisture loss was obtained through the weight difference between the previous hour or day and the current hour or day. The readings were registered every hour, from 8:00 to 18:00 h.

The crop evapotranspiration (ET_c) was obtained through linear models generated from experimental data from moisture loss in the weighing lysimeter (Y) and the matric potential (x). At a depth of 0.1 m: Y_1=-0.776x -1.028, R^2=0.96; at 0.3 m: Y_2=-1.362x -8.89, R^2=0.92 (Fig. 2a and 2b). Given that when the soil moisture content decreases, more energy is required to extract the water retained; these simple models are good estimators of the soil moisture loss as a function of the matric potential. They express that for each kPa of tension, there is a loss

of moisture in average of 0.78 mm in the layer 0.1 m deep; and at a depth of 0.3 m, the average loss of humidity is 1.36 mm for every kPa of tension. Finally, crop coefficients were estimated for each phenological stage, through equation (25).

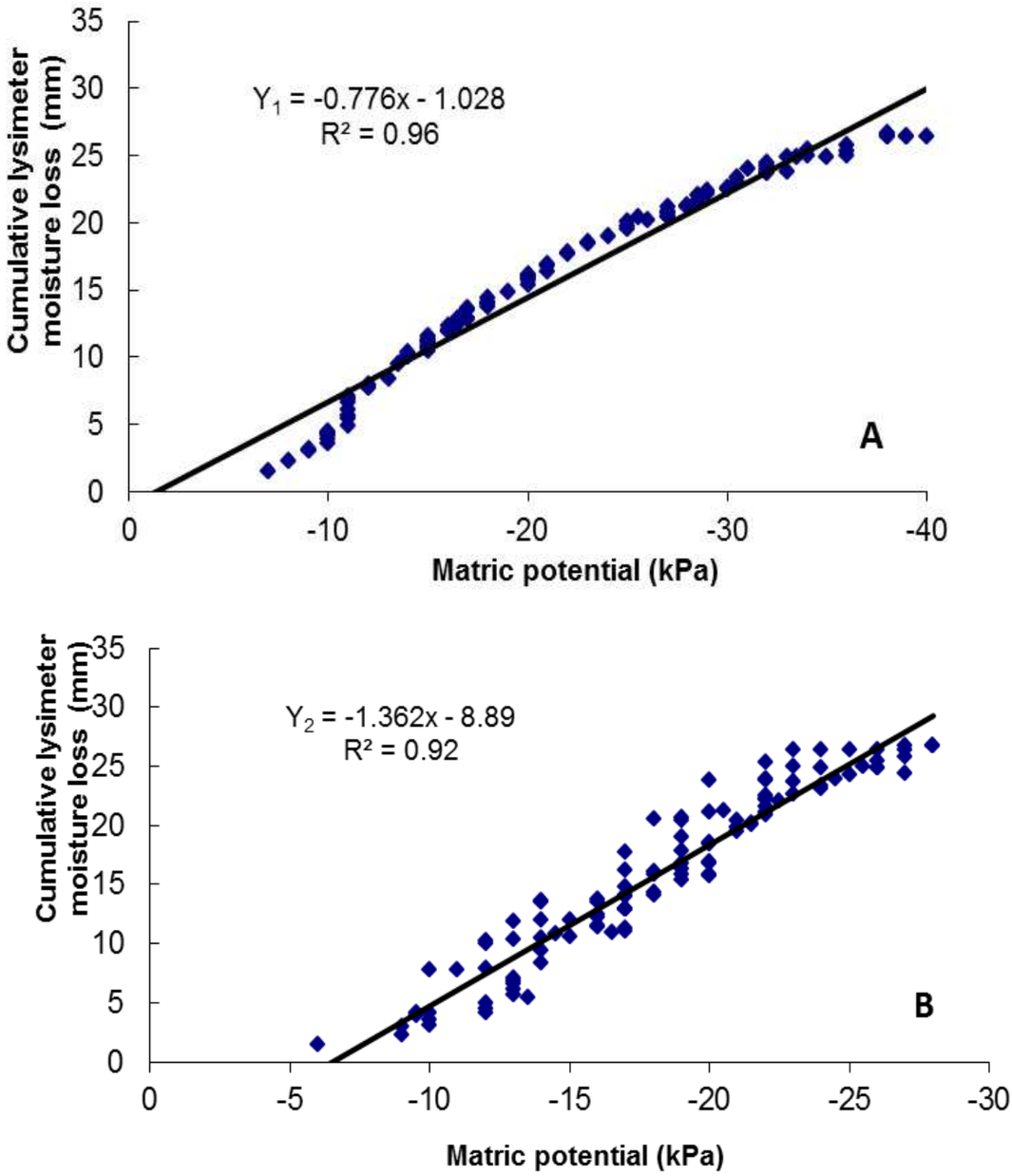


Fig. 4. Relationship between the matric potential at 0.1 m (A) and 0.3 m (B) depths and the lysimeter moisture loss in mm, obtained from experimental data during 22 continuous days. Each point of the observed values represents the water loss measured every 2 h between 8:00 and 18:00 h.

In order to relate the K_c and the leaf area index, the latter was determined in samples of 3 to 10 plants collected in the field and taken to the lab, starting on the date of transplant. Samples were taken on the following Julian days: 103, 117, 124, 138, 145, 159, 166 and 177. The leaf area was measured with a leaf area integrator, LICOR LI-3100 (LICOR, Inc. Lincoln, NE, USA).

4. Results and discussion

4.1 Upper and lower limits of the crop water stress index

Because the infrared ray gun requires sunny days to measure the water stress index, and as the method suggests that measurement must be done at the same time (from 12 to 15 pm) when the crop water demand is high. Data were taken for all treatments on Julian days: 123, 136, 145, 147, 152, 161, 162, 163, 164, 165, 166, 167 and 178. Measurements began on day 123 because it was the first day when crop water stress effects on the irrigation depth and the plastic mulching were observed.

Based on the method proposed by Idso et al. (1981), the parameters that define the lower and upper limits of the *CWSI* are presented in Figure 5. The equation that defines the lower *CWSI* baseline is: $T_c - T_a = 1.21 - 1.31VPD$ (r^2 =0.68, P<0.01, n=42), where T_c-T_a is in °C, and *VPD* in kPa. Idso (1982) reported the following relation for the lower limit in tomato crops: $T_c - T_a = 2.86 - 1.96\ VPD$. For corn, Irmak *et al.* (2000) found the following relation: $T_c - T_a = 1.39 - 0.86VPD$. It can be observed that all relations are different, which is in agreement with the results obtained by Bucks et al. (1985), who point out that the intercept and slope values vary depending on the climate, type of soil and crop being cultivated.

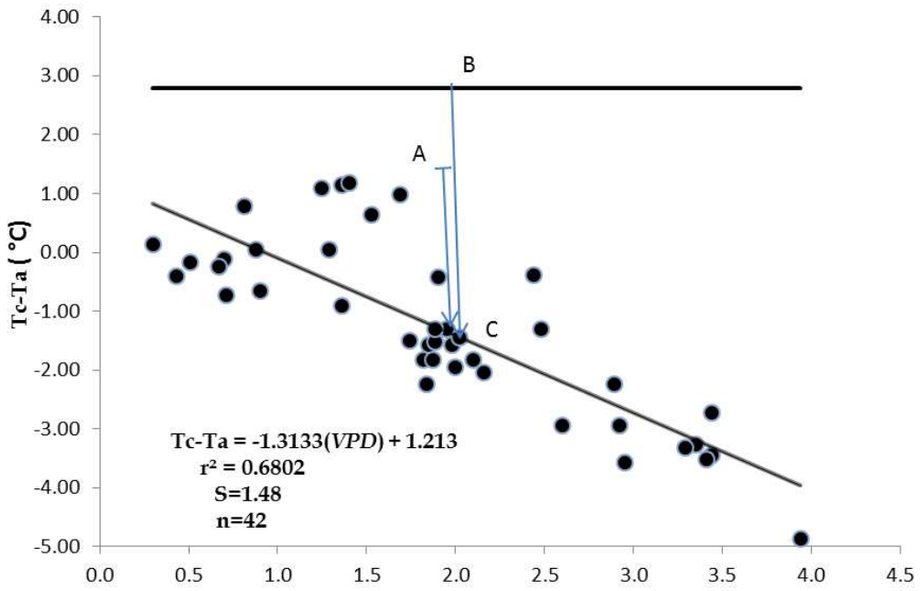


Fig. 5. The lower (A-C) and upper (B-C) baselines for husk tomato crop for determining the crop water stress index. S = Standard deviation.

The down-sloping line (Fig. 5) represents the baseline without water stress, that is, the difference between the air temperature and the crop temperature during periods with adequate water supply at different *VPD*; in this case, stomata were supposed to be open and temperature difference was a function of *VDP*, since an increase in VDP entails an increase in the drying power of the atmosphere and, therefore, in plant transpiration. The horizontal line (upper baseline, Fig. 5) is the difference between the air temperature and the crop temperature associated with periods of greater stress (with water limitations), when there is no transpiration. The average value was 2.8 °C with n = 25. For the corn crop, Irmak et al. (2000) determined an average value of 4.6 °C, a value greater than that found in this study, which means that husk tomato is more sensitive to possible water stress than the corn crop.
A *VPD* equal to zero indicates that the air contains the maximum amount of water vapor possible (relative humidity = 100%). The lower limit of the *CWSI* changes as a function of vapor pressure due to the *VPD*. The *CWSI* varies between 0 and 1 when plants are subject to appropriate irrigation conditions and up to conditions of total water stress. The lower limit in this research was developed in a range of *VPD* of 0.3 to 4.0 kPa. Gardner & Shock (1989) suggest that it is necessary for the range of *VPD* to vary from 1 to 6 kPa in order to define the baseline that can be used in other locations.
Calculation of *CWSI* can be done in a graphical approach starting from the following relation: *CWSI* = *AC/BC*, where point *A* is the difference between the temperatures of the leaf minus the air at the moment of measuring, point *B* is the difference in maximum temperature between the leaf and the air (superior limit), and point *C* the minimum difference (inferior limit) in the *VPD* conditions in which temperature measuring was carried out for the leaf and the air (*A*). Therefore, the *CWSI* is determined by the relative distance between the lower line (*A*-*C*) that represents the conditions without stress, and the u line (*B*-*C*) where there is no transpiration. For example, in Figure 5, it is considered that point *A* has a value of T_c-T_a equal to 1.4 °C that corresponds to a value of *VPD* equal to 2.0 kPa. Starting from the definition by Idso (1981), the distance between point *A* and the inferior limit (*C*) is 2.8 °C, and the distance between the superior and inferior limit in 2.0 kPa is 4.2 °C. Thus, the *CWSI* is equal to the ratio of both relative distances 2.8/4.2 = 0.66. This means that a difference in temperatures of 1.4 °C between the crop and the air indicate possible problems of crop water stress.
The CWSI, estimated from infrared thermometry, can be used for crop irrigation scheduling. Various researchers have obtained the parameters to set the inferior and superior baselines for other crops (Idso, 1982, Jones et al., 1997; Orta et al., 2003 & Erdem et al., 2005).

4.2 Effect of the irrigation sheet and plastic mulching on the water stress index

The variance analysis showed that there are highly significant differences ($P<0.01$) of the effect of irrigation depth on the *CWSI* during the different crop phenological stages, and not so for the effect of plastic mulching, since it is only significant for the maturation stage (M), on days 161 and 165; the effect of the interaction was not significant ($P>0.05$) in the different stages of the crop development. According to the analysis of mean comparison ($P<0.05$), mulching had a mean of 0.15 to 0.2 in the vegetative stage (V), while without mulching, there was a mean value of 0.21 to 0.26 (Table 1). During the reproductive (R) and maturation stages, the mean values vary between 0.14 and 0.28 with mulching and from 0.27 to 0.33 without mulching (Table 2).

Mulching	Crop Water Stress Index (CWSI)		
	V 123 (3-05-07)[y]	*R.145 (25-05-07)*	*M.178 (27-06-07)*
No mulching (0)	0.21 a	0.21 a	0.33 a[z]
With mulching (1)	0.20 a	0.15 a	0.28 a
Mean	0.21	0.18	0.30
DSH	0.085	0.064	0.084
CME	0.012	0.007	0.012
CV(%)	54.15	45.76	36.38

[z] Values with the same letter within a column are equal according to the Tukey test, with $P<0.05$; DSH: Honestly Significant Difference; CME: Mean Square Error; and CV: Variation Coefficient.
[y] Notation V 123 (3-05-07) indicates that V is the vegetative stage, 123 the Julian day, and (3-05-07) the date corresponding to day, month and year.

Table 1. Effect of plastic mulching on the water stress index during different phenological stages in the husk tomato crop.

Irrigation depth	Crop Water Stress Index (*CWSI*)		
	V 123 (3-05-07)[y]	*R 145 (25-05-07)*	*M 178 (27-06-07)*
40 (0)	*0.40 a*	*0.37 a*	0.53 a[z]
60 (1)	0.17 b	0.22 b	0.42 ab
80 (2)	0.38 a	0.12 b	0.32 bc
100 (3)	0.08 b	0.10 b	0.11 cd
120 (4)	0.0 b	0.10 b	0.15 d
MEDIA	0.21	0.18	0.30
DSH	0.19	0.14	0.19
CME	0.012	0.007	0.012
C.V. (%)	54.15	45.76	36.38

[z] Values with the same letter within a column are equal according to the Tukey test, with $P<0.05$; DSH: Honestly Significant Difference; CME: Mean Square Error; and CV: Variation Coefficient.
[y] Notation V 123 (3-05-07) indicates that V is the vegetative stage, 123 the Julian day, and (3-05-07) the date corresponding to day, month and year.

Table 2. Effect of the irrigation depth on the water stress index during different stages of development of the husk tomato crop.

Table 2 shows the relation between irrigation depth and *CWSI*. In general, it can be noted that the treatment of 40% irrigation depth gave the highest *CWSI* values in the different stages of crop development, and is statistically significant from the other levels. The lowest *CWSI* values were obtained with the irrigation depth of 100 and 120% of the ET_o treatments, being statistically equal to the 60 and 80% ET_0 treatments. This is because there was a normal water supply during the crop season. As water availability for the plant decreased, the CWSI value increased up to 0.7 in the treatment with severe irrigation restrictions (40%), without plastic mulching.
The functions that relate the water stress index with irrigation depth and plastic mulching were the following:
During the vegetative stage, with $r^2=0.74$, CME=0.025 and n=30:

$$CWSI_v = 0.73 - 0.135(a) - 0.418(b) + 0.061(b^2) + 0.037(ab) \quad (29)$$

during the reproductive stage, with r^2=0.66, CME=0.007 and n=30:

$$CWSI_r = 0.40 - 0.06(a) - 0.18(b) + 0.029(b^2) + 0.0003(ab) \quad (30)$$

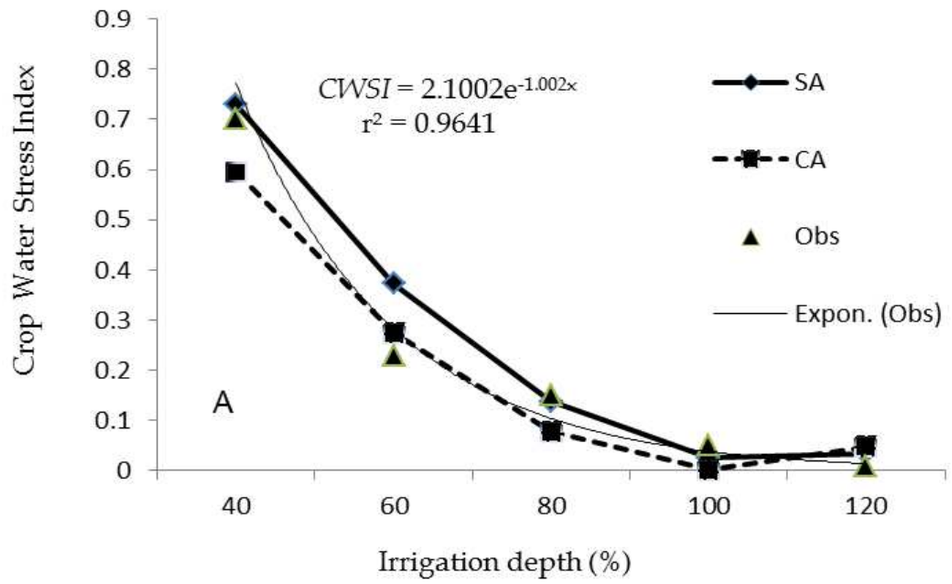
and, finally, for the maturation stage with r^2=0.62, CME=0.020 and n=30:

$$CWSI_m = 0.59 - 0.267(a) - 0.232(b) + 0.028(b^2) + 0.52(ab) \quad (31)$$

where *a* is the effect of the plastic mulching: *b* represents the Penman-Monteith irrigation depth treatment; and *ab* is the effect of the interaction of plastic with the irrigation depth. The determination coefficients (r^2) are acceptable and indicate that the models predict the *CWSI* in an acceptable manner, and that the mean square errors are relatively small.

In figures 6a, 6b and 6c, the relations between irrigation sheets and plastic mulching with the *CWSI*, for the vegetative, reproductive and maturation stages, respectively, are presented. Equations 29, 30 and 31 are drawn, substituting the value of 0 without mulching and 1 with mulching, and the 0, 1, 2, 3 and 4 values that correspond to the irrigation sheet reposition: 40, 60, 80, 100 and 120%, respectively. The exponential models were generated from the values observed with the *CWSI* averages obtained with and without plastic padding.

The relation between the water stress index and the irrigation sheet is negative and exponential; as the irrigation sheet increases, the *CWSI* decreases until it reaches 0 when 100 or 120% of the ET_0 is applied. The differences between having mulching or not, in different phenological stages, indicate that the *CWSI* value with mulching is less than without plastic mulching. This is due primarily to the reduction of evaporation from the soil in treatments with plastic. In this regard, Şimşek et al. (2005) observed that when the irrigation sheet decreases, the rate of transpiration by the crop also decreases, producing as a result the increase in the crop's temperature and the *CWSI*; this produces a decrease in the crop yield.



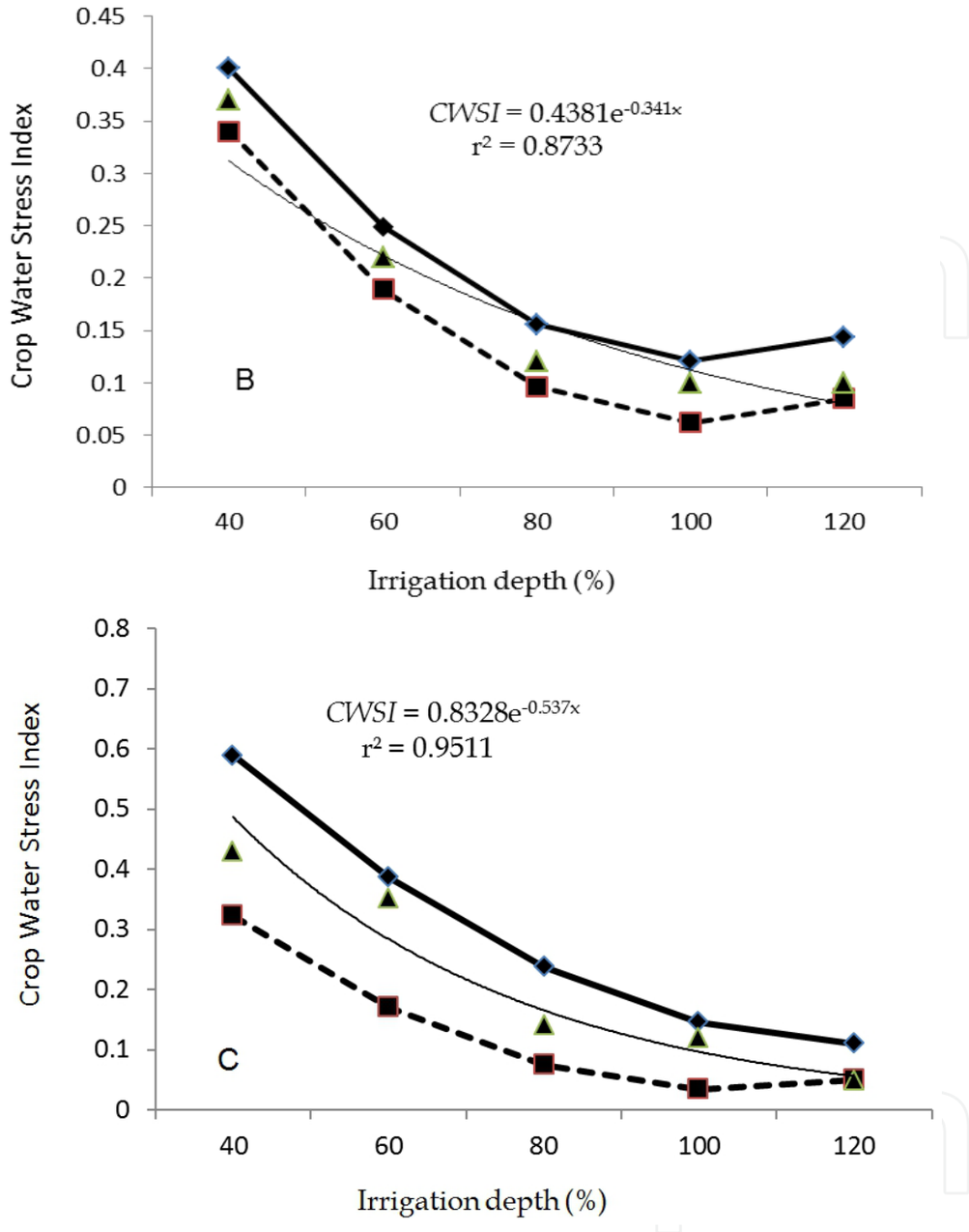


Fig. 6. Crop Water stress index estimation in husk tomato crop, during the following stages: A) vegetative, B) reproductive and C) maturation, without (SA) and with (CA) plastic mulching from the irrigation depth calculated as a fraction of the Penman-Monteith ET_o.

Prediction of the *CWSI* in the vegetative stage can be done through the exponential function: $y=2.1e^{-1.0x}$, with $r^2= 0.96$ determined from the average values associated to the irrigation depth effect on day 136; that is, taking into consideration the values obtained with and without plastic mulching. For the reproductive stage, an exponential function was obtained, $y=0.44e^{-0.34x}$, with $r^2= 0.87$, which was determined based on the average data observed on

day 145, and during the stage of maturation the function $y=0.82e^{-0.53x}$, with $r^2= 0.95$, was determined according to the mean values observed on day 165 (Fig. 6a, 6b and 6c). The *CWSI* threshold varies according to the plastic mulching treatment, with and without. In general, it can be noted that with the irrigation depth calculated higher than 60% of the ET_0, the crop's water stress can be avoided, both with and without plastic mulching.

4.3 Crop coefficients per phenological stage

In this case, the crop coefficients were determined for the treatment with a depth equivalent to ET_0 = 100% and without plastic mulching. The crop coefficients were obtained through the relation between the crop evapotranspiration and the reference evapotranspiration (Eq. 26). The ET_c values were calculated daily from matric potential data of the top 0.1 m layer during the vegetative-reproductive stage and 0.3 m layer in the reproductive-fructification and maturation-senescence stages, those depths are the most active where roots take most of the water. When substituting these values in the linear equations generated in the weighing lysimeter to estimate the ET_c, the crop coefficients were obtained by phenological stage (Table 3).

Stage	Days	ET_c (mm)	ET_0 (mm)	Kc
Vegetative-Reproductive	45	50.20	165.60	0.30
Reproductive-Fructification	35	121.50	111.96	1.10
Maduration-Senescence	20	71.36	82.92	0.86

Table 3. Crop coefficients for husk tomato under drip irrigation in different phenological stages, as a function of days after transplant without plastic mulching.

The K_c values estimated here are similar to those proposed by Allen et al. (1998) for tomato (*Lycopersicon esculentum* L.) crops without plastic mulching, except during the initial stage where a higher value, of 0.6, was found.

In the cumulative curves for ET_c and ET_0 (Fig. 7), it can be noted that the ET_o has a linear behavior during the crop growth, while the ET_c does not produce a linear behavior and generally presents lower values than the ET_0. Evapotranspiration rates depend on crop management and phenological stage. The crop evapotranspiration is different of the reference evapotranspiration (ET_0), due to the differences in soil cover, vegetation properties and aerodynamic resistance, with respect to that of grass (Allen et al., 1998). The effects of the crop characteristics are incorporated into the crop coefficient. During the initial stage of growth, the main component is due to soil evaporation, particularly on its sun-exposed area, and the soil moist surface that has influence on the value of superficial resistance, which is the sum of soil resistance and root resistance. Immediately after moistening the soil from an irrigation or rain event, the rate of transference from vapor to water from the soil is high.

The crop coefficient (K_c) includes the effects of evapotranspiration on the soil and crop surfaces and depends on the water availability in the soil around the root area and the less moist soil surface exposed. These values are obtained from crops that are adequately irrigated, without water stress. Other duration time parameters can also be used, such as days of development, thermic-solar units, or cumulative ET_o (DeTar, 2004; Bandyopadhyay et al., 2005; DeTar, 2009).

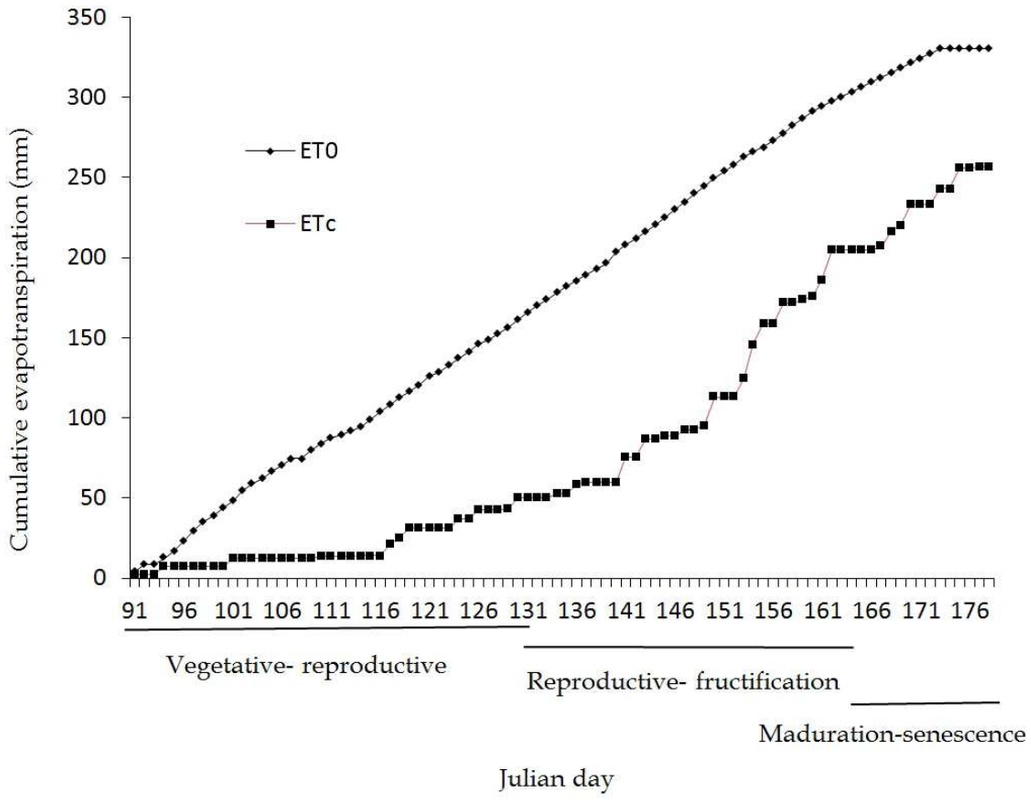


Fig. 7. Seasonal trend of cumulative ETc and ET_o evapotranspiration in the husk tomato crop under drip irrigation,without plastic mulching and.

The unique coefficient values (temporal average) of the tomato crop (K_c) without stress, adequate management and a height of 0.6 m, in sub-humid climate with minimum relative humidity (HR_{min} = 45 %), and wind speed of u = 2 ms^{-1} for its use in the Penman-Monteith equation ET_0. Allen et al. (1998) suggest Kc values for the initial, intermediate and final stages of 0.6, 1.15 and 0.7 to 0.90, respectively; they make clear that when the crop grows from 1.5 to 2 m high, a K_c of 1.2 can be used during the intermediate stage.

4.3.1 Kc for crop with plastic mulching

Plastic mulching with drip irrigation reduces significantly water evaporation from the soil surface. However, there is a general increase in the crop transpiration due to the transference of sensible and radiative heat from the plastic cover to the crop canopy. Although the transpiration rate with plastic can increase in an average of 10-30% during the crop season, compared to no plastic cover, the value of K_c in average decreases 10-35% due to the reduction of evaporation in the soil (Allen et al., 1998).

The crop coefficients for husk tomato, under drip irrigation and plastic mulching, are reduced in 35% for those with covering according to Allen et al., 1998. In consequence, K_c values for covering can be 0.2, 0.71 and 0.56 for the vegetative-reproductive, reproductive-maturation and maturation-senescence stages, respectively.

Crop coefficients and leaf area index are important values to achieve a better use of water resources. In figures 8 and 9, the relation found between K_c and the Leaf Area Index (*LAI*) is

presented, evaluated after transplant of the crop without (Eq. 32) and with plastic mulching (Eq. 33), considering well-irrigated conditions:

$$Kc = 0.6569\,LAI + 0.2404\,,\ R^2 = 0.96,\quad n = 8,\quad P < 0.01 \tag{32}$$

$$Kc = 0.4144\,LAI + 0.1691\quad R^2 = 0.93,\quad n = 8\quad P < 0.01 \tag{33}$$

These relations indicate that the husk tomato K_c can be estimated from LAI data. Based on the results, when LAI is equal to one, the crop coefficient approaches one in absence of plastic mulching (Figure 6), and even tends to be greater than one, which indicates that the ET_c is greater than the ET_0. However, Bandyopadhyah et al. (2005) determined for the peanut (*Arachis hypogaea* L.) crop that when the *LAI* is greater than three, K_c values are greater than one.

These results also demonstrated that plastic mulching reduces the crop coefficients and, therefore, the crop evapotranspiration, particularly during the reproductive and maturation stage, which translates into water savings during crop irrigation scheduling.

The method used for calculating *LAI* and the Penman-Monteith ET_o to evaluate the crop resistance simplifies the most complex processes of evapotranspiration; also, it is precise and reliable for evaluating crop water productivity with plastic mulching (Lovelli et al., 2008; Li et al., 2008).

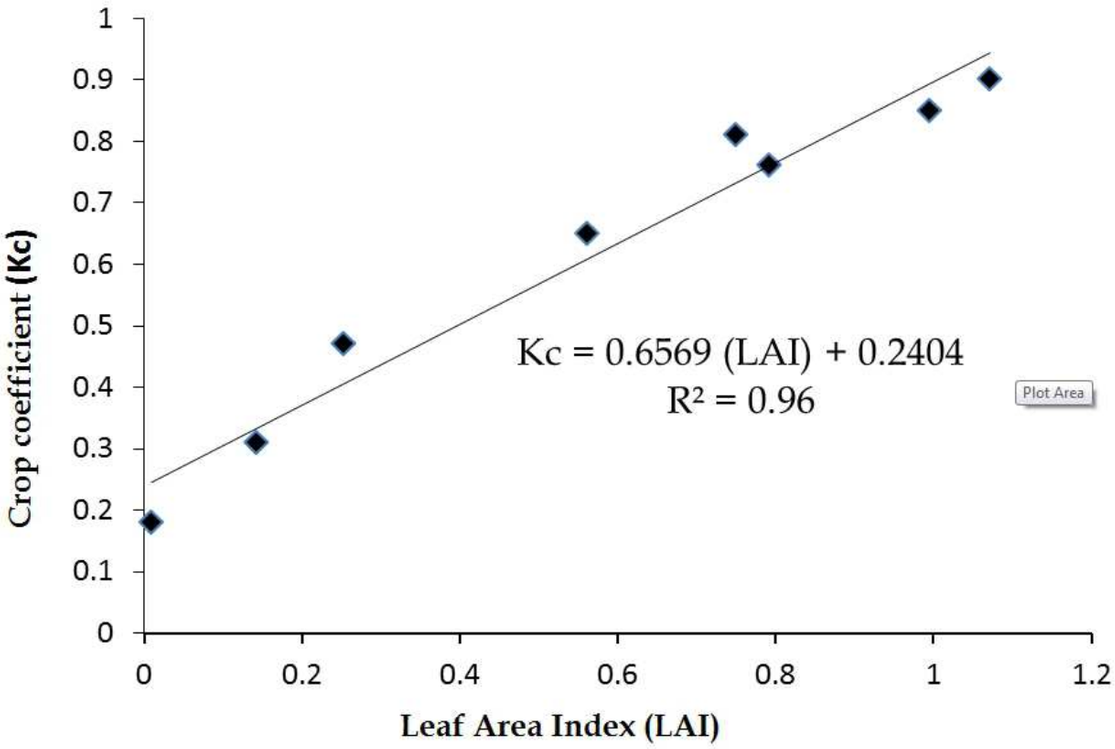


Fig. 8. Crop coefficients in husk tomato as a function of the Leaf Area Index without plastic mulching under drip irrigation.

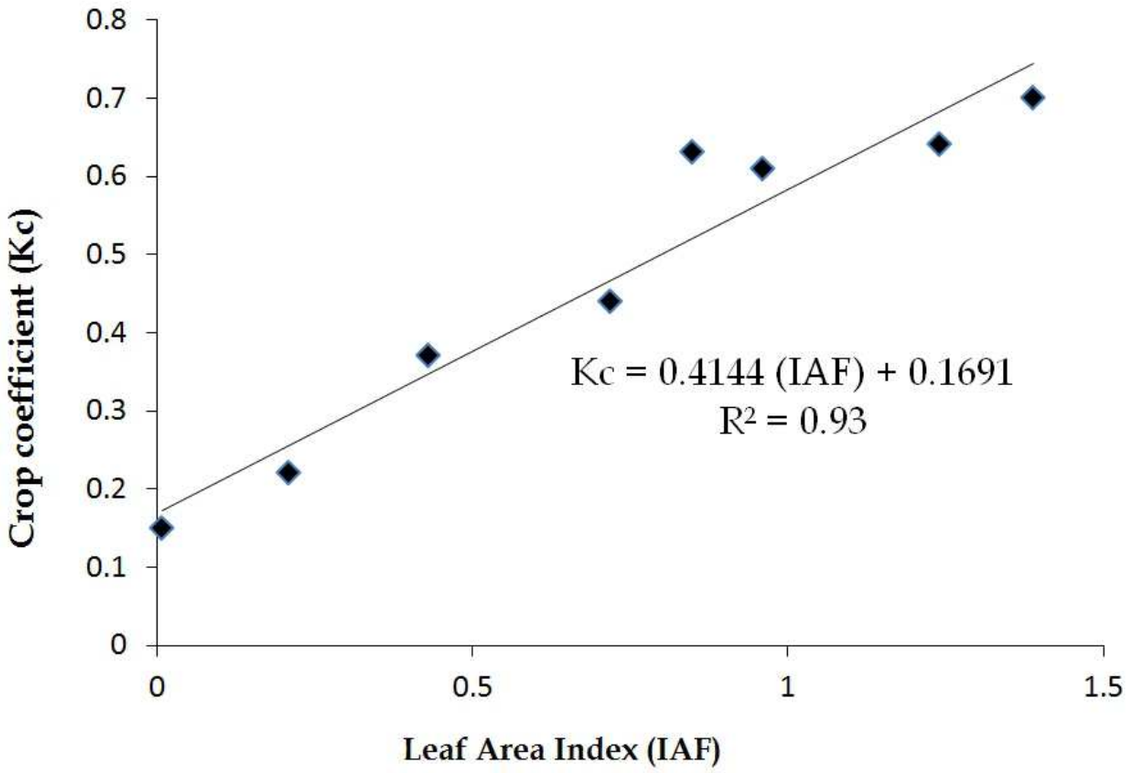


Fig. 9. Crop coefficients in husk tomato under drip irrigation as a function of the Leaf Area Index with plastic mulching.

5. Conclusions

The study's conclusions were the following: i) the use of infrared thermometry to calculate the *CWSI* is a reliable technique to schedule irrigation using the determined upper and lower *CWSI* baselines in the husk tomato crop. Its use in the initial phase of the crop is limited due to the size of the canopy. ii) The *CWSI* values close to zero corresponded to the treatments in which the totality of the irrigation depth was replaced (100 and 120 % of the ET_0) during the crop season. As the water availability decreased, the *CWSI* value increased until reaching 0.7 in the treatment with severe irrigation restrictions (40 % ET_0) without plastic mulching. The models that predict the *CWSI* from the irrigation depth are acceptably adjusted to the *CWSI* observed values. iii) Daily measurements of the matric potential level allowed estimating the losses in soil moisture in a reliable manner, as well as calculating the crop's evapotranspiration. iv) The crop coefficients (K_c) for husk tomato grown without plastic covering were estimated with a value of 0.3 in the vegetative, of 1.1 in the reproductive, and of 0.86 in maturation stage. When the crop is covered with plastic mulching, the crop coefficients were estimated with a valued of 0.2, 0.71 and 0.56 for the vegetative, reproductive and maturation stages, respectively. v) The K_c for husk tomato without mulching can be estimated from the leaf area index (*LAI*) through the equation $K_c = 0.6569(LAI) + 0.2404$, and with plastic mulching through the equation $K_c = 0.4144\ (LAI) + 0.1691$, under well irrigated conditions.

6. Acknowledgements

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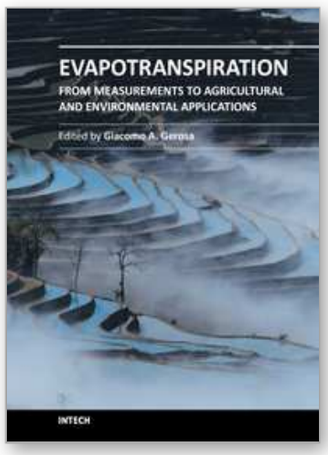

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This book represents an overview of the direct measurement techniques of evapotranspiration with related applications to the water use optimization in the agricultural practice and to the ecosystems study. Different measuring techniques at leaf level (porometry), plant-level (sap-flow, lysimetry) and agro-ecosystem level (Surface Renewal, Eddy Covariance, Multi layer BREB), are presented with detailed explanations and examples. For the optimization of the water use in agriculture, detailed measurements on transpiration demands of crops and different cultivars, as well as results of different irrigation schemes and techniques (i.e. subsurface drip) in semi-arid areas for open-field, greenhouse and potted grown plants are presented. Aspects on ET of crops in saline environments, effects of ET on groundwater quality in xeric environments as well as the application of ET to climatic classification are also depicted. The book provides an excellent overview for both, researchers and student,s who intend to address these issues.

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