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Water management of a solar-powered irrigation system: a case study in Vale do Cavaco in Benguela, Angola

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Abstract: The use of clean and renewable energy sources, such as solar PV, can help mitigate the effects on climate change, reduce pollution, energy dependence on fossil fuels, help restore degraded land and boost agricultural production. The main objective of this research work is to evaluate the uniformity of the discharge of the emitters for different irrigation conditions. The experiment was carried out in Vale do Cavaco, Benguela province, Angola, located at 12º 36' south latitude and 13º 53' east longitude, with an altitude of 26 m above mean sea level. The soil of the experimental area is of the clayey type that corresponds to the Chromic Luvisol according to the World Soil Resource Reference Base. With regard to solar energy, it has usable power on a large scale with availability of up to 7 hours solar peak, being one of the highest globally, the weather data were obtained through the Weather and Windy application, which coincides with those obtained on the website PVGIS (January 2015). The treatment applied to the soil was leaf composting in the entire plot of the experimental area. The coefficient of uniformity was based on the selection of 16 emitters evenly distributed within the subunit on four sides: the closest, the farthest and those located at 1/3 and 2/3 of the length of the tertiary tube, in which four emitters were selected following the same criteria. The measurement of the emitters was carried out with the help of plastic funnels to improve the accuracy of water collection. This was measured with 10 mL samples and precision timers. During the measurement, all emitters in operation were observed to determine the existence of obstructions. The value of the flow uniformity coefficient was determined from the mean value of the four emitters with the lowest flow rate and the mean flow rate of all emitters in the subunit. The irrigation system was highly uniform in its different modes of operation, and the moisture stored in the soil profile during the rainy season affected irrigation.

Key-words: Effectiveness; Discharge uniformity.

Gestão da água através da avaliação da uniformidade de descarga dos emissores de um sistema de irrigação movido a energia solar. Um estudo de caso no Vale do Cavaco em Benguela, Angola

Resumo: O uso de fontes de energia limpas e renováveis, como a energia solar fotovoltaica, pode ajudar a mitigar os efeitos sobre as mudanças climáticas, reduzir a poluição, a dependência energética de combustíveis fósseis, ajudar a restaurar terras degradadas e impulsionar a produção agrícola. O presente trabalho de investigação tem como objectivo principal avaliar a uniformidade da descarga dos emissores para diferentes condições de irrigação. O experimento foi realizado no Vale do Cavaco, província de Benguela, Angola, localizado a 12º 36' de latitude sul e 13º 53' de longitude leste, com uma altitude de 26 m acima do nível médio do mar. O solo da área experimental é do tipo argiloso que corresponde ao Luvisolo crômico de acordo com a World Soil Resource Reference Base. No que tange a energia solar tem potência aproveitável em grande escala com disponibilidade de até 7horas solar pico sendo uma das mais altas a nível global, os dados climatéricos foram obtidos por intermédio do aplicativo Weather e Windy, que coincide com os obtidos no site PVGIS (Janeiro de 2015). O tratamento aplicado no solo foi compostagem de folhas em toda parcela da área experimental. O coeficiente de uniformidade foi determinado com base na seleção de 16 emissores uniformemente distribuídos dentro da subunidade em quatro lados: o mais próximo, o mais distante e aqueles localizados a 1/3 e 2/3 do comprimento do tubo terciário, nos quais quatro emissores foram selecionados seguindo os mesmos critérios. A aferição dos emissores foi realizada com a ajuda de funis plásticos para melhorar a precisão na coleta de água. Este foi medido com amostras de 10 mL e cronômetros de precisão. Durante a aferição, todos os emissores em operação foram observados para determinar a existência de obstruções. O valor do coeficiente de uniformidade de fluxo foi determinado a partir do valor médio dos quatro emissores com a menor vazão e da vazão média de todos os emissores da subunidade. O sistema de irrigação quanto a sua descarga resultou ser altamente uniforme em seus diferentes modos de operação, e quanto a umidade armazenada no perfil do solo durante a estação chuvosa afetou a irrigação.

Palavras-chave: Eficácia. Uniformidade de descarga.

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1. INTRODUCTION

The lack of rainfall, lack of surface water sources, lack of conventional sources of electricity for the operation of irrigation systems, lack of infrastructure generated by secular poverty in rural areas and the consequences of the civil war that the country suffered, justify the development of photovoltaic systems for crop irrigation. The objective of this work is to evaluate the uniformity of discharge of the emitters in different modalities of planned operation through a drip irrigation system powered by photovoltaic solar energy for tomato production according to the water, agronomic, edaphic and climatic needs of the locality. Where the research was carried out i.e. the Cavaco Valley, municipality of Benguela, province of Benguela, Republic of Angola.

When the factor of water availability is decreasing and its demand is increasing, it becomes necessary to sustain irrigated agriculture, with adequate management, but also of soil, energy and environment and for the system to respond better it is convenient to carry out studies on Irrigation Systems Audit through the calculation of Christiansen's uniformity coefficients (CUC) and distribution uniformity coefficient (CUD) and, then calculation of the cultural evapotranspiration (ETc) and comparison with the appropriations applied (JIMÉNEZ et al., 2014; NUNCIO AND ARRANGEMENT, 2017; OLIVEIRA, 2011; PEREIRA, 2004; PEREIRA, 2017; UN WATER, 2012; MELO, et al., 2021). What we have just mentioned coincides with Vélez and Mujica (2007) who define that the depletion of water resources, the high costs of water and energy, and the globalization of markets require improvements in the use of water for irrigation.

Over the years, several methods have been developed to estimate ETo. The creation of several methods is justified due to the need to make estimates simpler and/or due to limitations in the availability of climate data that are necessary for calculations (PAREDES et al., 2020, 2021; PEREIRA, 2004; PEREIRA & ALVES, 2016).

Crop development studies are identified, the appropriate crop coefficients (Kc) are selected, the crop coefficient in the early development phase (Kc ini) is adjusted for the soil wetting fraction, the crop coefficients in the middle (Kc mid) and final (Kc end) phase of development are adjusted for the local climatic conditions, which allows the Kc curve to be constructed and, finally, to calculate the ETc (ALLEN et al., 2005; ALLEN & PEREIRA, 2009; RALLO et al., 2021). All these Kc values are tabulated in FAO 56 (ALLEN et al., 1998; PEREIRA et al., 2020, 2021 a,b; RALLO et al., 2021; ALLEN & PEREIRA, 2009; ROSA et al., 2012a; PAÇO et al., 2019; RALLO et al., 2021). Originally, drip irrigation systems were used to develop agriculture in areas with scarce water resources (BRESLER, 1977).

Later, the advantages of High Frequency Localized Irrigation translated into increased yields, less harmful salinity distributions in plant roots, water savings, and lower energy costs allowed these irrigation systems to achieve greater coverage (ELFVING, 1982).

Localized irrigation facilitates fertigation that can save between 50 and 70% of fertilizer and even more than 50% of water when compared to conventional agriculture, it also allows the use of treated wastewater or water with salinity, this is because, as the soil moisture in the root zone is always high, due to the water supply being frequent or continuous, soil water potentials are low, which reduces the risk of adverse effects due to salinity (MOSSANDE., 2015, 2019; MINHAS et al., 2020; YANG et al., 2020).

Irrigation programming is commonly carried out with the nominal flow of each emitter defined by the manufacturer, however, the flow rate may vary due to the effects of pressure, temperature, clogging (physical, biological or chemical) and flaws in the design of irrigation systems, so that usually the actual flow differs from the nominal flow (VILLAVICENCIO & VILLABLANCA, 2010).

In drip irrigation systems, several water losses can occur due to the uniformity of discharge of the emitters (SOLOMON, 1984); the variability between emitters, their obstruction, the topography of the terrain, and the pressure losses in the network (NAKAYAMA & BUCKS, 1986).

Increasing discharge uniformity saves water, improves fertilization when carried out via fertigation, and reduces environmental impacts associated with groundwater contamination (SOUTH, 1994). In a fertilization and nitrogen irrigation test, designed with drip tapes, the uniformity of discharge of the emitters in the different operating modalities established was studied and the performance of the nitrogen fertilization and watering treatments of the plants was evaluated.

According to Pizarro (1996), the uniformity of irrigation in high-frequency localized irrigation "RLAF" should exceed 90%, but this result is altered by processes associated with variations in the manufacture of emitters and sometimes inadequate hydraulic designs of systems that provide different flow rates for similar working pressures (ARVIZA, 1989).

Researchers from the University of California, Davis, analyzed the effect of irrigation and fertigation on the in-ground tomato crop, at the various stages of its cycle, and concluded that the main factors affecting tomato yield and quality are water management, soil fertility and lack of irrigation uniformity. which may also be linked to clogs (MARTÍNEZ & RECA, 2014; PHENE et al., 2018; YU et al., 2019; SOUZA et al., 2020; PIMENTA et al., 2022).

For these reasons, the uniformity and efficiency of water application can be greatly affected by emitter performance (CLARK et al., 2007; PEREIRA, 2004; PHENE et al., 2013; SMAJSTRLA et al., 2018) Uniformity is especially important when the irrigation system is used to apply chemicals, which will be applied as evenly as irrigation water (EVANS et al., 2013; HEERMANN & SOLOMON, 2007; HAMAN, 2017; SMAJSTRLA et al., 2018; LORD et al., 2007; PEREIRA, 2004).

2. MATERIAL AND METHODS

The research was carried out in an experimental area occupying an area of 0.23 ha in Vale do Cavaco, Benguela province, Angola, located at 12º 36' south latitude and 13º 53' east longitude, with an altitude of 26 m above mean sea level (INAMET, 2013). The soil of the experimental area is of the clayey type that corresponds to the Chromic Luvisol according to the World Soil Resource Reference Base (WRB, 2007). With regard to solar energy, it has power that can be used on a large scale with availability of up to 7 hours solar peak, being one of the highest globally, the weather data were obtained through the Weather and Windy application (Play Store Android 2021), which coincides with those obtained on the website (PVGIS, January 2015).

It was carried out during the years 2021 and 2022, where a photovoltaic solar drip irrigation system was installed consisting of 6 photovoltaic panels of the Kyocera brand, with power per unit of 54 Wp, a submersible solar centrifugal pump of the Lorentz model that works with direct current, load between 0-30 m and flow of 4 m^3 h^{-1}. The pump motor is of the ETADRIVE HR 600W/1200W model with PS600/PS1200 charge controller (LARA., 2007).

An irrigation system with integrated drippers of the Uragota brand, with low pressure and low sensitivity to clogging, with a diameter of 16 mm, distance between emitters of 1.0 m, nominal flow of 3.5 L h-1 per emitter was used for a pressure of 49.20 kPa and a discharge equation of the potential type that responds according to the manufacturer's data to the equation q = 0.506h 0.498, the same used in Mossande (2015).

The experimental design consisted of strips (Figure 1) formed by two irrigation subunits of 0.115 ha configured by 20 laterals of 50 m in length; 50 emitters per side; side flow of 0.20 m^3/h; subunit flow rate 4.0 m^3/h; side volume of 380 L and subunit volume of 7600 L.

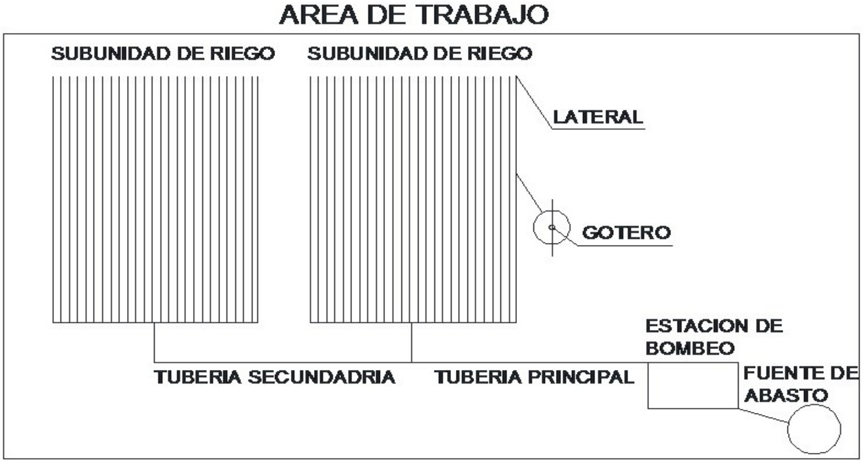

Figure 1. Schematic of the irrigation system.

The coefficient of uniformity was determined according to (CHRISTIANSEN, 1942; MERRIAM & KELLER, 1978; PIZARRO, 1996) based on the selection of 16 emitters evenly distributed within the subunit on four sides: the closest, the farthest away, and those located 1/3 and 2/3 of the length of the tertiary tube, in which four emitters were selected following the same criteria.

The measurement of the emitters was carried out with the aid of plastic funnels to improve the accuracy of water collection. This was measured with 10 mL test tubes and precision stopwatches (LOBOA et al., 2011).

During the measurement, all emitters in operation were observed to determine the existence of obstructions. The flow rate was expressed in L h^{-1} by the following expression:

$$q = \frac{3.6V}{t} \tag{1}$$

Where q the flow rate of the emitter (L h^{-1}); V The volume measured in a cylinder 'beaker'" (mL); t the measurement time of the collected volume (s).

The value of the flow uniformity coefficient was determined from the mean value of the four lowest flow emitters and the average flow of all subunit emitters, using the following equations:

$$q_{25\%} = \frac{\sum_{1}^{4} q_i}{4} \tag{2}$$

$$q_m = \frac{\sum_{1}^{16} q_i}{16} \tag{3}$$

$$CU = \frac{q_{25\%}}{q_m} 100 \tag{4}$$

Where q25% is the average flow received by the 25% of the emitters with the lowest flow rate in the test (L h^{-1}); qm the average of all emitters tested in the test (L h^{-1}); CU The coefficient of flow uniformity (%).

The interpretation of the results of the values of the coefficient of uniformity was performed according to the criteria of Bralts (1987), which classifies uniformity based on the value of the coefficient of variation of the flows into five categories: excellent (0.0 -0.1); very good (0.1-0.2); acceptable (0.2-0.3); low (0.3-0.4) and unacceptable (>0.4) and the Vermeiren and Jobling (1986) criterion, which considers the topography of the study area and classifies uniformity as: excellent (> 94%); Good (86-94%); acceptable (80-86%) and poor (<80%). The coefficient of variation and the deviation of the mean flow rate from the nominal flow rate were determined using the following equations:

$$C_v = \frac{S}{q_m} \tag{5}$$

$$Dq_m = \frac{|q_m - q_n|}{q_n} \tag{6}$$

Where Cv is the coefficient of variation; Dqm the deviation of the average flow from the nominal flow (L h^{-1}) which was evaluated according to the categories proposed by the ASAE (1989); qm the average flow obtained in the laboratory (L h^{-1}); qn the nominal flow rate indicated by the dripper manufacturer (L h^{-1}); S the standard deviation of flow rates (L h^{-1}).

In each irrigation subunit, the variation of the uniformity coefficient in relation to the irrigation time was evaluated to determine the effect of this parameter on the behavior of the emitter (LOBOA et al., 2011). Pressure was measured with metal Bourdon pressure gauges at the inlet of the irrigation subunits to ensure uniform hydraulic conditions according to the design.

The similarity of the flow of the emitters in the irrigation subunits was verified by means of the hypothesis test, considered an alternative of general inequality. The null hypothesis has been formulated (H0) and the alternative (H1) So yes the statigraph T-Student deliberate (T) is greater than its critical value (Tc) or the probability (P) is lower than the significance level (α) if the decision is made to reject Ho and accept H1; demonstrating that the compared means differ statistically.

$$H_0 : \mu_1 = \mu_2$$
$$H_1 : \mu_1 \neq \mu_2 \quad (7)$$

The total efficiency of the system was determined through an empirical-analytical procedure from the following equations:

$$E_t = E_{fu} . E_{pp} \quad (8)$$

$$E_{fu} = \frac{q_{25\%}}{q_m} \quad (9)$$

Where Et is the total efficiency of the system (%); Efu the efficiency due to lack of uniformity of the irrigation installation (%) e Epp Percolation Loss Efficiency (%). This value according to FAO (1986) It varies depending on the following types of soils: Sandy (0,91); medium or silty "slime" (0,96) and clayey or "slime" (1,00).

The soil moisture content was determined by the gravimetric method at the beginning, middle and end of the central side of each subunit, collecting samples the day after the application of the irrigation dose, to ensure the distribution of the infiltrated water in the profile. Moisture samples were collected by stratum at depths of 10, 20, 30 and 40 cm on the vertical axis and at distances of 0, 15, 30, 45 and 60 cm on the horizontal axis (GENOA et al., 2013), obtaining a data grid that allowed the characterization of the moisture distribution in the wet bulb and the construction of moisture isolines by the Kriging method (MURILLO et al., 2012) with the use of Golden Surfer software, version 10 of the year 2011.

The area wetted by the emitter was obtained under field conditions, placing stations spaced every 15 cm from the center of the dripper at three points on the central side of both irrigation subunits, both in the lateral direction and perpendicular to it, measuring the length of the wetted strip and determining its depth by analyzing the gravimetric humidity up to 40cm. This process allowed us to know the conformation of the wet bulb in the times of 30, 60, 90, 120 and 150 minutes based on the volume applied by the dropper. The distribution of the root system was performed at 95 days after transplanting (DDT) in the central furrows of each irrigation subunit at distances of 10, 20 and 40 m from its beginning by the monolithic method (Böhm, 1979) consisting of the extraction of roots from a rectangle with dimensions of 1.00 m x 1.20 m by soil strata of 10 cm at a depth of 100 cm. separately.

The soil of the experimental area is of the clayey type that corresponds to the Chromic Luvisol according to the World Soil Resource Reference Base (WRB, 2007). The treatment applied to the soil was leaf composting in the entire plot of the experimental area.

The fruits were harvested from the maturation of the first bunch and then repeated once a week. Harvest yield in kg m-2, as well as diameter in cm and fruit weight in kg, was evaluated in one square meter of surface area at 95 days after transplanting (DDT) in the three central furrows of the subunits at distances of 10, 20, 30 and 40 m from its beginning to obtain a total of 12 observations. Fuentes (2014) evaluated different tomato cultivars for fresh consumption in the Zapotitlán Valley, El Salvador, with total yields similar to those obtained in the present investment; therefore, the results presented can be considered favorable for the area under study. The tomato variety used was Heat Master, with a row spacing of 1.00 between plants 0.50m and the treatment applied to the soil was leaf composting in the entire plot of the experimental area.

3. RESULTS AND DISCUSSION

Figure 1 shows the average values of the climatic variables in the period analyzed, it is observed that the maximum temperature exceeded 30 °C in the months of February, March and April, the minimum temperature reached the lowest values in June, July and August with 17 °C., Wind speed was the most uniform variable in terms of value, with a monthly average of 5.03 m s-1. Rainfall was very scarce with the highest values in the months of December, February and March ranging from 6.10 to 13.0 mm (MOSSANDE, 2015).

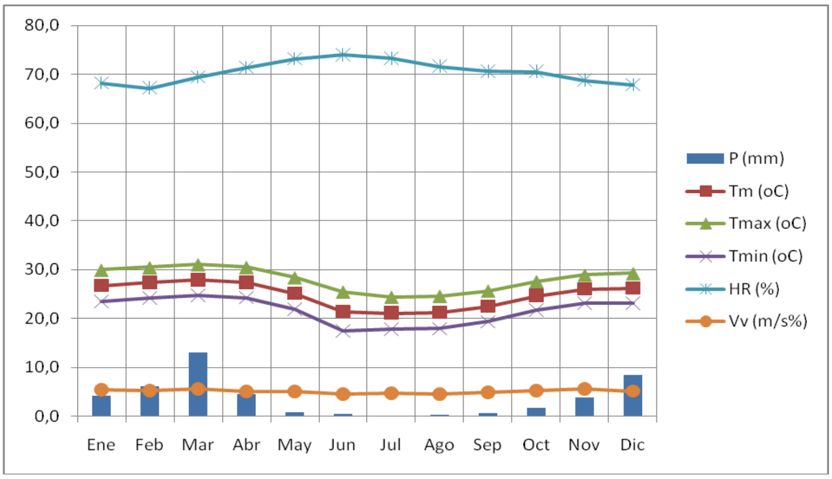

Figure 2. Mean values of climatic variables.

The curve that represents the flow discharged by the dripper as a function of the working pressure is shown in Figure 2. Good self-compensation behavior of the emitter is observed in the pressure range from 53.9 to 68.6 kPa with flow rates ranging from 3.67 y 3.83 L h^{-1} with a flow difference of 0.16 L h^{-1}. The characteristic equation of the emitter obtained in the practical operating conditions of the designed photovoltaic system was of the potential type with a high coefficient of determination (R2).

$$q = 1.55h^{0.215}$$

$$R^2 = 0.962 \tag{10}$$

Where q es the flow rate discharged by the emitter (L h^{-1}); h Work Pressure (kPa).

The value of the discharge exponent indicates that it is a self-compensating dripper when it reaches values between 0 and 0.3 (FERREYRA et al., 2000); On the other hand, Uralita (2003) points out that at low pressure the flow rate of this type of emitter never exceeds the nominal level; they only increase until they reach the minimum working pressure. The potential-type model is the most widely used in pressurized irrigation engineering to represent the mathematical relationship between flow and head, since it clearly defines the cost coefficient and the flow exponent. This type of model was calibrated by Carmenate et al., (2011) and Rodríguez & Puig (2011) in investigations carried out in a drip irrigation system for citrus and banana trees in the conditions of Cuba, which is very similar to the conditions of Angola since both countries have a tropical climate.

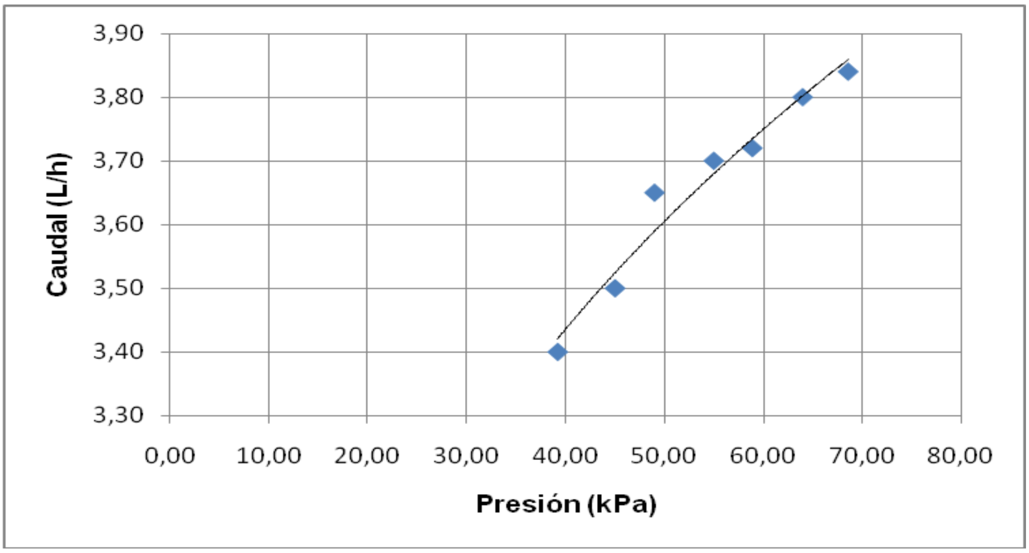

Figure 3. Dripper flow curve in relation to working pressure.

Table 1 shows that in both subunits studied, an average flow rate of 3.45 L.h^{-1} was achieved for the evaluations carried out at the beginning and end of the tomato crop with a mean standard deviation of 0.096 L h^{-1}, and presents 2.88 L.h^{-1} as the average flow received by 25% of the emitters with the lowest flow in the test (Table 1). The statistical analysis showed the similarity of the dripper flow by not detecting significant differences between the values of the average flow in the two irrigation subunits evaluated.

Table 1. Emitter flow rates and standard deviation of the flow rate.

Subunit	Evaluation	qm (L h^{-1})	q25% (L h^{-1})	S (L h^{-1})	P	T	Tc
A	Campaign Initiation	3,48	2,87	0,101	0.897	0.147	4.303
	End of campaign	3,43	2,89	0,086			
B	Campaign Initiation	3,46	2,84	0,103			
	End of campaign	3,44	2,91	0,092			
Average		**3,45**	**2,88**	**0,096**			

Table 2 shows that the average coefficient of variation obtained experimentally was 0.028 and influenced the flow uniformity coefficient of the emitters to be excellent in each irrigation subunit according to Bralts & Kesner (1983). Fontella et al. (2009) confirm that it is possible to achieve high values of UC in drip irrigation systems under farm conditions, in studies carried out in the province of Mendoza, Argentina, finding that in 17 farms evaluated the uniformity coefficient was excellent (45%); very good (23%); acceptable (15%) and only 17% obtained the low and unacceptable categories. In this investigation the system operated with an average total efficiency of 0.91.

Table 2 shows that the deviation from the mean flow rate reached a value of 0.014 L h^{-1}; Therefore, it was evaluated as excellent according to the categories proposed by the ASAE (1989). This result was similar to that obtained by Rodríguez & Puig (2011) in a similar study where they evaluated a surface drip irrigation system with pressures of up to 500 kPa, we also evaluated the coefficient of variation (Cv) and the coefficient of flow uniformity (CU).

Table 2. Coefficient of uniformity and flow deviation.

Subunit	Evaluation	CU (%)	Cv	Dqm (L h^{-1})
A	Campaign Initiation	92,72	0,029	0,006
	End of campaign	90,75	0,025	0,020
B	Campaign Initiation	91,26	0,030	0,011
	End of campaign	89,93	0,027	0,017
Average		**91,165**	**0,028**	**0,014**

Figure 3 shows that in no case were uniformity coefficient values lower than 80% achieved. The most favorable uniformity coefficient (CU) values were reached during the first 60 minutes of system operation, where values between 91.60% and 92.72% were reached; Then they drop to 89.48 and 89.20% in 90 and 120 minutes, respectively. During the entire irrigation period, no obstructions were observed in the emitters. A second-order polynomial mathematical expression was found that correctly relates the uniformity coefficient to the irrigation time (TR) in minutes.

$$CU = 0.000008T_R^3 - 0.001T_R^2 + 0.041T_R + 92.67$$

$$R^2 = 0.984 \tag{11}$$

In studies carried out in Colombia by Loboa et al. (2011) for the evaluation of the coefficient of uniformity in different emitters, they found in all cases a decrease in UC as the irrigation time increased. The best behavior occurred in the self-compensated drippers with values close to 90.8% at 120 minutes, remaining around this value for 48 hours of irrigation. The irrigation ribbon reached a value of 84.88% in 120 minutes of irrigation; but in general it presented low performance during almost the entire irrigation period, with UC values between 70% and 80% for 156 hours.

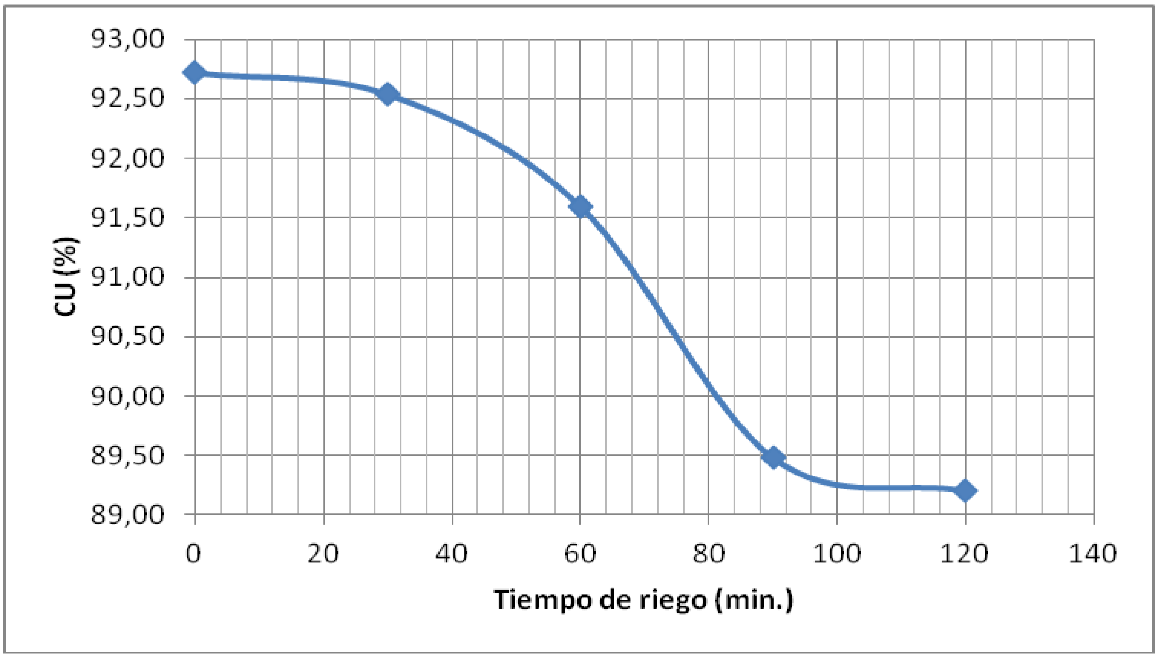

Figure 4. Coefficient of uniformity in relation to irrigation time.

Table 3 shows the results of the humem bulb study. It was shown that taking into account the spacing of 1.00 m between emitters and 1.20 m between laterals, the wetting radius of the wet bulb (RB) reached an overlap of 36% and 14% respectively, which corroborated the absence of dry areas in the planting framework observed in the investigation based on the dose of irrigation applied by drippers.

Regarding the wetting depth of the wet bulb (HB) It was found that the wetting profile after 150 minutes of irrigation reached a depth of 57.2 cm, much higher than the effective depth established for tomato cultivation; therefore, the loss of flow below the root system was evident. This type of behavior is common in surface drip irrigation characterized by water losses by deep percolation, which has been demonstrated by different authors such as Rodríguez and Puig (2011) in the conditions of Cuba, Genoa et al. (2013) in Argentina, Moreno & Villafañe (2005) in Venezuela.

The irrigation interval was 2 days, according to Mossande (2015), the irrigation time showed a linear relationship in relation to the wetting radius of the wet bulb and the wetting depth of the wet bulb as shown in the following equations:

$$R_B = 0.428t + 2.207$$
$$R^2 = 0.987 \tag{12}$$

$$H_B = 0.369t + 0.745$$
$$R^2 = 0.992 \tag{13}$$

Table 3. Wetting radius and depth of wet bulb.

TR (min)	V (L)	RB (cm)	HB (cm)
30	1.8	17.5	13.1
60	3.5	27.1	22.8
90	5.2	36.8	31.5
120	7.0	54.25	45.5
150	8.7	68.2	57.2

A dose of 8.13 L plant was applied to each irrigation día-1, equivalent to a 7.86 mm net irrigation sheet. Slightly acidic groundwater was used with pH de 6,48 and electrical conductivity. de 0.18 dS m^{-1} determined at the water quality laboratory of the Methodist University of Angola (UMA). It is classified according to Matheus (2011) as non-saline with negligible effects on crops.

The behavior of moisture in the soil profile is shown in figure 4. It is observed that the volumetric humidity in the first three strata remains high above the field capacity, especially up to the distance of 30 cm from the emitter, which indicates that slight water leaks occurred from the stratum corresponding to the depth of 30-40 cm. Regarding the flooding of the upper strata in drip irrigation, Rodríguez and Puig state that this behavior affects the presence of air and favors the rate of evaporation from the soil surface; However, it benefits the uptake of water and nutrients by the crop which contributes to its growth and development.

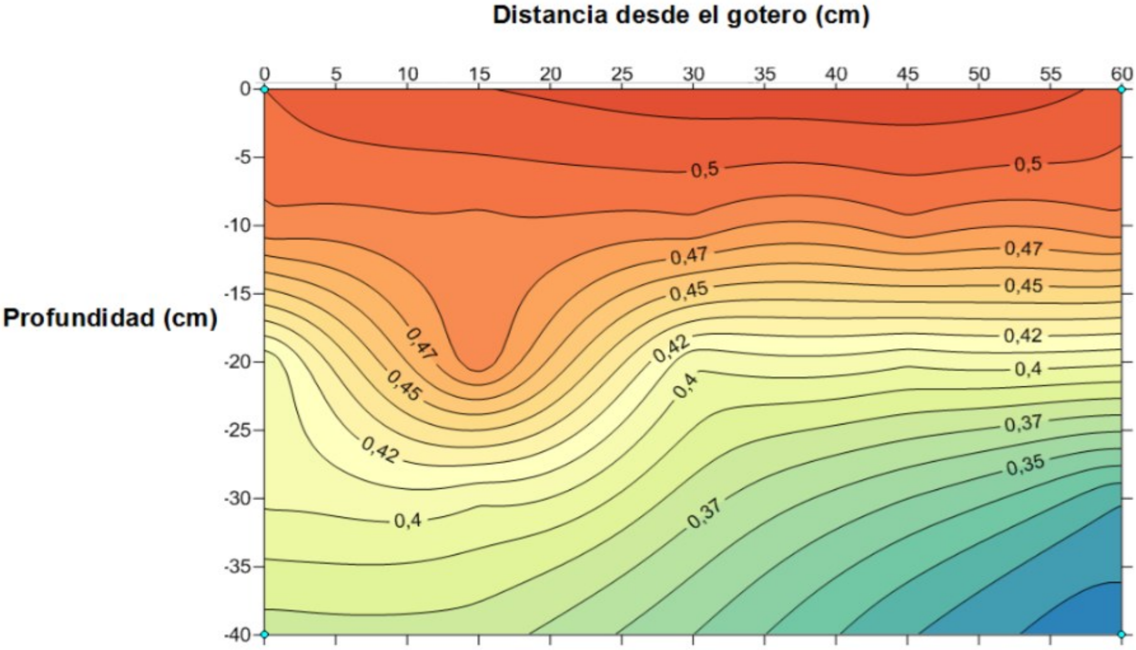

Figure 5. Isolines of Average Volumetric Humidity (cm3 cm-3).

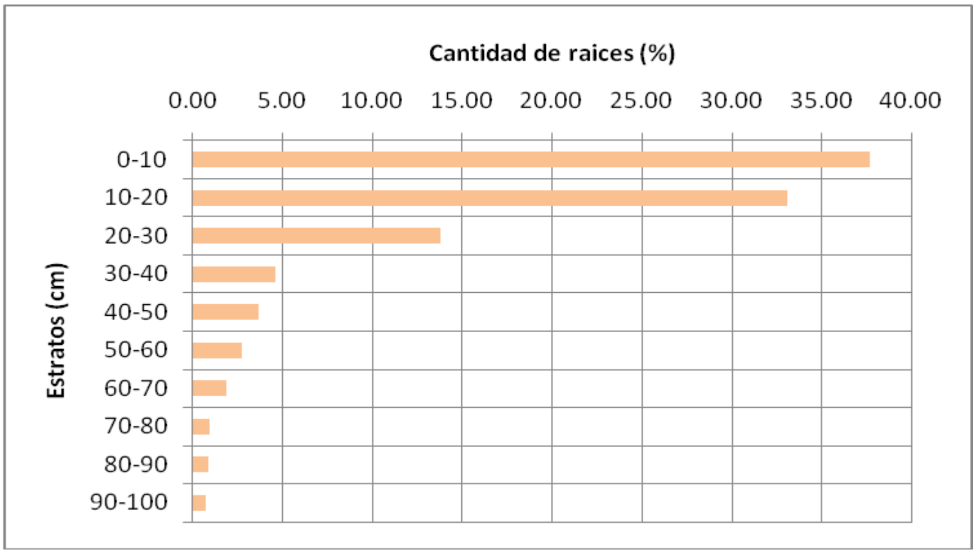

Figure 6. Distribution of the root system in the soil profile.

Figure 5 shows that the highest percentage of roots was located in the superficial stratum, which has a depth of 0-10 cm (37.72%), followed by the 10-20 cm stratum (33.12%) and then decreased significantly. visible in the lower strata. At the depth of 0-20 cm only 71% of the root system is reached; however, at the depth of 0-30 cm the root system reached a development of 84.64%; Therefore, the effective depth of the root system of the tomato crop was 30 cm for these conditions. This result confirms what was expressed by Noordwijk (1983) that the effective depth is the one where 80% of the roots are concentrated.

Regarding this aspect, Pérez et al. (2003) pointed out that the root system of tomato is made up of a main root and secondary and adventitious roots that usually reach more than 50 cm in depth; however, 70% are located less than 20 m from the ground surface.

The growth dynamics of tomato cultivation during the studied period showed that the crop manifested intense vegetative activity from 40 to 60 days after planting (DDP) and stabilized in the physiological maturity stage, reaching a plant height of 90 cm and with a vegetative cycle until harvest of 120 days. This development was associated with the prevailing edaphoclimatic conditions and the water tables applied through the irrigation system, which provided a moisture content very suitable for the development and growth of the crop.

Table 5 shows the average harvest values of the tomato cultivar Heat Master at 95 DAT. The evaluated photovoltaic drip irrigation system produced yields higher than 11 t ha-1 in both subunits with no statistically significant differences. The fruits reached 7.92 cm and 18.95 g for the diameter and weight of the fruit, respectively, these results correspond to the performance parameters found by other authors such as Petit (2009) and Fuentes (2014).

Table. 4. Components of tomato yield.

Sampling point	Subunit A	Subunit B	Average	Sx	P	T	Tc
Average Tomato Weight (g)	21,87	22,37	21,97	2,61	0,95	0,07	2,78
Number of tomatoes/plant	28	26	27	1,06	0,42	0,98	4,30
Yield (t ha^{-1})	33,54	33,12	33,33	1,01	0,32	1,12	2,73

4. CONCLUSIONS

The system was fairly uniform within each fertigation and irrigation treatment, and within each mode of operation, indicating that variation between emitters due to manufacturing and other factors that may influence discharge uniformity did not affect the uniformity of water application in the system.

The discharge uniformity values of the emitters in the different modes of operation of the system ruled out the need for covariance in the irrigation and test treatments.

The irrigation treatments did not affect the fruit production, possibly due to variations in the moisture reserves contained in the profile, not associated with irrigation, and due to the irregular redistribution of irrigation water on the soil surface.

The behavior of the drippers in relation to the uniformity coefficient indicated that the one with the best performance corresponded to the Lyn emitters, followed by the self-compensating and microjet drippers, and the one with the lowest performance corresponded to the irrigation tape.

Among the drippers evaluated, the irrigation ribbon showed the lowest percentage of variation in the uniformity coefficient. The percentage of variation in the uniformity coefficient of the drippers increased in the following order: Lyn, self-compensating and microjet.

The Lyn dripper obtained the best behavior regarding the uniformity coefficient when using the FGAC filtration method.

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REFERENCES

ALLEN, R. G.; PEREIRA, L. S. Estimating crop coefficients from fraction of ground cover and height. **Irrigation Science**, v.28, n.1, p.17–34, 2009.

ALLEN, R. G.; PEREIRA, L. S.; RAES, D.; SMITH, M. **Crop Evapotranspiration** (guidelines for computing crop water requirements). FAO Irrigation and Drainage, 56, Roma, Itália. 300p. 1998.

ALLEN, R. G.; PEREIRA, L. S.; SMITH, M.; RAES, D.; WRINGHT, J. L. FAO-56 dual crop coefficient method for estimating evaporation from soil and application extensions. **Journal of Irrigation and Drainage Engineering** , v.131, n.1, p.2–13, 2005.

ARVIZA, J. **Evaluación de sistemas de riego localizado. I curso de riego localizado**. Valencia, España: Universidad Politécnica de Valencia, 1989.

ASAE (American Society of Agricultural Engineers). **Design and Installation of Micro irrigation Systems**, 627-630. ASAE EP409, Standards, Engineering Practices and Data, 38th Edition, USA, 1989.

BÖHM, W. Methods of studying root systems. **Ecological Studies** 33 ed. Springer- Verlag, p. 188, Berlin, Germany, 1979.

BRALTS, V.; EDWARDS, D.; WU, I. Drip irrigation design and evaluation based on stadistical uniformity concept. **Advances in Agronomy**, v.4, p.67-117, 1987.

BRESLER, E. Trickle-drip irrigation: Principles and application to soil-water management. **Advances in Agronomy**, v. 29, n. 3, p. 343-393, 1977.

CARMENATES, H. D.; MUJICA, A; PANEQUE, P. **Influencia de las obturaciones de los emisores en los sistemas de microirrigación en el rendimiento del cultivo de los cítricos**. Vol. 20, No. 4, Habana, Cuba, 2011.

CHRISTIANSEN, J.E. Irrigation by Sprinkling. California Agric. Exp. Bull. No. 570; Univ. of Calif.: Berkeley, CA, 1942; 94, alimentos da agricultura familiar no DF. **Revista de Política Agrícola**, n.1, p.117-129, 2021.

CLARK, G. A.; HAMAN, D. Z.; PROCHASKA, J. F.; YITAYEW, M. General system design principles. **Developments in Agricultural Engineering**, v.13, p.161–220, 2007.

EMBRAPA. **A real contribuição da agricultura familiar no Brasil**. 2017. Disponivel:https://www.embrapa.br/agropensa/busca-de-noticias/-/noticia/27405640/a-real-contribuicao-da-agricultura-familiar-no-brasil.

ESTEVÃO, A.T.A. **Avaliação do sistema de rega subterrânea na cultura do tomate de indústria (Solanum lycopersicum L.) na região do Vale do Tejo**. Dissertação (Mestrado). Instituto Politécnico de Santarém Escola Superior Agrária de Santarém, Portugal, 2022

EVANS, R., WU, I.-P. SMAJSTRALA, A. G. Microirrigation Systems. In: **Design and operation of farm irrigation systems**, 2nd Edition. American Society of Agricultural and Biological Engineers, 633-683. FAO. (2013).

FAO. **Evapotraspiracion del cultivo:** Guías para la determinación de los requerimientos de agua de los cultivos. Manual No. 56 Serie Riego y Drenaje, Roma, Italia, 2006.

FERREYRA, R.; SELLÉS, G.; PIMSTEIN, A. Diseño, manejo y mantención de equipos de riego localizado de alta frecuencia. **Boletín INIA**., p. 55, Chile, 2001.

FONTELA, C.; SALATINO, S.; MORÁBITO, J.; MIRÁBILE, C.; MAFFEI, J.; MASTRANTONIO, L. Riego por goteo en Mendoza, Argentina: evaluación de la uniformidad del riego y del incremento de salinidad, sodicidad e iones cloruro en el suelo. **Revista FCA UNCuyo**, Tomo XLI. n.1, p.135-154, 2009.

FUENTES, F. E. Evaluación de cultivares de tomate para el consumo fresco, en Valle de Zapotitán, El Salvador. **Revista Manejo Integrado de Plagas**. CATIE. 2021.

GÉNOVA, L.; ANDREAU, R.; ETCHEVERS, P.; ETCHEVERRY, M.; CHALE, W.; ZABALA, S. M. Alimentos da agricultura familiar no DF. **Revista de Política Agrícola**, n.1, p.117-129, 2021.

HAMAN, D. Z. Causes and prevention of emitter plugging. In: **Microirrigation Systems**. Department of Agricultural and Biological Engineering, UF/IFAS Extension, University of Florida, 1–11. Heermann, D. F. (2017).

HRISTIANSEN, J. Hydraulics of sprinkling systems of irrigation. **Transaction of American Society Civil Engineering**, v.107, p.221-239, 1942.

HUANG, J.K. Impacts of COVID-19 on agriculture and rural poverty in China. **Journal of Integrative Agriculture**, v.19, n.12. p.2849–2853, 2020.

IBGE, Instituto de Geografia e Estatística. Agricultura Familiar. **Censo agropecuário 2017**. Disponível em https://censoagro2017.ibge.gov.br/templates/censo_agro/resultadosagro/pdf/agricultura_familiar.pdf

INAMET. **Boletín informativo de las variables meteorológica**. Instituto Nacional de Meteorología y Geofísica. Delegación de Benguela, Benguela, Angola, 2013.

JIMÉNEZ, B., ARNELL, N., OKI, T. ARNELL, N. Climate change impacts, adaptation, and vulnerability. **Agricultural Water Management**, v.203, p.53-62, 2014. https://doi.org/10.1017/CBO9781107415379.008

LARA, F. A. **Diseño de un sistema de riego por medio de energía solar, a través de paneles fotovoltaicos**. Tesis de Ingeniería Mecánica. Universidad Austral de Chile, p.146, Valdivia, Chile, 2007.

LEITE, J.B.L.; CARNEIRO, A.; CARVALHO, G.; SIQUEIRA, K.; STOCK, L.; AGUIAR, L.; HOTT, M.; BOA, J; RAMIREZ, S; DIAZ, J. D. Evaluación del coeficiente de uniformidad en cuatro emisores de riego usando filtración gruesa de flujo ascendente en capas. **Revista EIA**, v.16, p.29-34, 2011.

LORD, J. M., JMLORD, J., ARS, J. E. A. **Evaluating performance. in design and operation of farm irrigation systems**. ASABE St. Joseph, MI, EUA, 791-803. 2007.

MATHEUS, F. **Diseño de un sistema de riego por aspersión para el cultivo de la papa (*Solanum tuberosum*) en un sector de la finca "Estapape" sector Estapape, Parroquia La Quebrada, Municipio Urdaneta, Estado Trujillo**. Universidad de Los Andes, 77p, Venezuela, 2011.

MELO, M. A.; ALVES, I.M.; PAREDES, P. C. **Avaliação de dois sistemas de rega localizada**. Instituto Superior de Agronomia da Universidade de Lisboa, Portugal, 2021.

MERRIAN, J; KELLER, J. **Far irrigation system evaluation: a guide for management**. Third Edition. Utah StateUniversity, Logan Utah, USA, 1978.

MINHAS, P. S.; RAMOS, T. B.; BEN-GEL, A.; PEREIRA, L. S. Coping with salinity in irrigated agriculture: Crop evapotranspiration and water management issues. **Agricultural Water Management**, v.227, p.105832, 2020.

MOSSANDE, A. R. Requerimientos hídricos del tomate en el valle de Cavaco en Benguela, Angola. **Revista Ciencias Técnicas Agropecuarias**, v.24, n.2, 2015.

MOSSANDE, A. R. **Uso de energía solar fotovoltaica para sistemas de riego por goteo:** riego solar fotovoltaico para el cultivo de tomate: Editorial académica espñola. 2019.

MOSSANDE, R. A. Sistema de riego por goteo com bombeo solar para el tomate en Cavaco, Benguela, Angola. **Revista Ciências Técnicas Agropecuárias**, p.11, 2015.

MURILLO, D.; ORTEGA, I.; CARRILLO, J. D.; PARDO, A.; RENDÓN, J. Comparación de métodos de interpolación para la generación de mapas de ruido en entornos urbanos. **Ingenierias USBMed**, v. 3, n. 1, p. 62-68, 2012.

NAKAYAMA, F.; BUCKS, D. **Trickle irrigation for crop production**. Design operation and management. Elsevier Science Publishers B. V. Amsterdam. The Netherlands. pp. 383, 1986.

NOORDWIJK, M. Root ecology and its practical application. **Symposium Bundesanstalt Gumpenstein**, A-8952, Irdning, p. 207-226, 1983.

NUNCIO, J.; ARRANJA, C. Regadio: binómio água e energia. **Revista Recursos Hídricos**, v.38, n.2, p.17–23, 2017.

PAÇO, T. A.; PAREDES, P.; PEREIRA, L. S.; SIVESTRE, J.; SANTOS, F. L. Crop coefficients and transpiration of a super intensive Arbequina olive orchard using the dual Kc approach and the Kcb computation with the fraction of ground cover and height. **Water**, v.11, n.2, p.383, 2019.

PAREDE, P.; PEREIRA, L.S.; AlMOROX, J.; DAROUCHI, H. Reference grass evapotranspiration with reduced data sets: Parameterization of the FAO Penman-Monteith temperature approach and the Hargeaves-Samani equation using local climatic variables. **Agricultural Water Management**, v.240, p.106210, 2020.

PAREDES, P., TRIGO, I., de BRUIN, H., SIMÓES, N., PEREIRA, L.S., 2021. Daily grass reference evapotranspiration with Meteosat Second Generation shortwave radiation and reference ET products. Agric Water Manage. 106543 https://doi.org/10.1016/j.agwat.2020.106543

PASQUALOTTO, N.; KAUFMANN, M.P.; WIZNIEWSKY, J.G. Agricultura familiar e desenvolvimento rural sustentável [recurso eletrônico], 2019.

PEREIRA, L. S. **Necessidades de Água e Métodos de Rega**. Europa-América. Lisboa, 313 p. 2004.

PEREIRA, L. S. Water, agriculture and food : challenges and issues. **Water Resources Management**, v.31, p.2985–2999, 2017. https://doi.org/10.1007/s11269-017-1664-z

PEREIRA, L. S.; PAREDES, P.; LÓPEZ-URREA, R.; HUNSAKER, D. J.; MOTA, M.; MOHAMMADI SHAD, Z. Standard single and basal crop coefficients for vegetable crops. Update of FAO56 crop water requirements approach. **Agricultural Water Management**, v.243, n.1, p.106466, 2021.

PÉREZ, J.; HURTADO, G.; APARICIO, V.; ARGUETA, Q.; LARÍN, M. A. **Guía Técnica. Cultivo de Tomate**. Centro Nacional de Tecnología Agropecuaria y Forestal (CENTA), pp. 48, El Salvador, 2003.

PHENE, C. J.; HUTMACHER, R. B.; DAVIS, K. R. Two hundred tons per hectare of processing tomatoes can we reach it? **HortTechnology**, v.2, n.1, p.16–22, 1992. https://doi.org/10.21273/horttech.2.1.16

PIZARRO, F. **Riegos localizados de alta frecuencia (RLAF):** Goteo, microaspersión, exudación. 3ª ed. Madrid: Mundi-Prensa. 513 p. 1996.

PVGIS. (2016), http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?map=africa

RALLO, G.; PAÇO, T.; PAREDES, P.; PUIG, A.; PROVENZANO, G.; MASSAI, R.; PEREIRA, L.S. Updated single and dual crop coefficients for trees and vine crops. **Agricultural Water Management**, v.250, p.106645, 2021.

RODRÍGUEZ, M.; PUIG, O. Comportamiento hidráulico de los sistemas de riego por goteo superficial y subsuperficial. **Revista Ciencias Técnicas Agropecuarias**, v. 20, n. 4, p. 36-41, 2011.

ROMAY, C. Diseño y operación de tres modalidades de riego por goteo de tomate y sus respuestas productivas. **Revista Argentina de Ingeniería**, v.1, n.1, p.85-90, 2013.

ROSA, R. D.; PAREDES, P.; RODRIGUES, G. C.; FERNANDO, R. M.; ALVES, I.; PEREIRA, L. S.; ALLEN, R. G. Implementing the dual crop coefficient approach in interactive software: 2. Model testing. **Agricultural Water Management**, v.103, p.62–77, 2012.

SAMPSON, R. Microirrigation. In OWENS, L.; PIERCE, W.; SELF, S. (Eds.). **Irrigation National Engineering Handbook** (Issue October). Natural Resources Conservation Service (NRCS), 2013.

SMAJSTRLA, A. G., BOMAN, B. J., HAMAN, D. Z., PITTS, D. J. ZAZUETA, F. S. **Field Evaluation of Microirrigation Water Application**. Agricultural and Biological Engineering Department, UF/IFAS Extension,1–8. 2018

SOARES, P. M.; BRITO, M. C.; CARETO, J. A. **Persistência do alto potencial solar na África em um clima em mudança. Instituto Dom Luiz (IDL)**, Faculdade de Ciências da Universidade de Lisboa, Portugal, 2019.

SOLOMON, K. H. Efficiency and uniformity. in design and operation of farm irrigation systems 5, 108-119. (2007). ASABE, St. Joseph, MI, EUA. http://web.catie.ac.cr/informacion/RMIP/rmip53/redca4- a.htm consultado 07 de julio del 2021; http://www.saude.mt.gov.br/painelcovidmt2/ Acesso: 18/10/2022.

SOUTH, D. Managing pesticides and nitrogen insouthern pine nurseries and some ways to reduce the potential for groundwater contamination. **Alabama Agricultural Experiment Station (AAES) Reports**, n. 14, p.18, 1994.

TANG, P.; LI, H.; ISSAKA, Z.; CHEN, C. Effect of manifold layout and fertilizer solution concentration on fertilization and flushing times and uniformity of drip irrigation systems. **Agricultural Water Management**, v.200, p.71–79, 2018. https://doi.org/10.1016/j.agwat.2018.01.010

TAVANTI, T.R.; TAVANTI, R.F.R.; RIBEIRO, L.F.C.; SILVA, E.P. Análise multitemporal do uso e cobertura do solo em áreas de preservação permanente em assentamento rural no norte de Mato Grosso, utilizando geotecnologias. **Anais...** In: XXXV Congresso Brasileiro de Ciência do Solo. RN, 2015. Disponível em: https://www.eventossolos.org.br/cbcs2015/arearestrita/arquivos/800.pdf

VELIZ, R.; MUJICA, A. **Mejoramiento de la tecnología de microirrigación en el cultivo del banano en suelos ferralíticos rojos de la provincia de Ciego de Ávila**, Informe para la propuesta a Premio CITMA Provincial, CEH, Universidad

VERMEIREN, L.; JOBLING, G. A. Riego localizado. **Serie Riego y Drenaje**, N° 36. Roma: FAO. 203 p. 1986.

VILLAVICENCIO, A.; VILLABLANCA, A. Determinación del coeficiente de uniformidad de riego. INIA – URURI. **Informativo Nº 17**, Mayo de 2010.

WARRICK, A. Interrelationships of irrigation uniformity terms. **Journal of Irrigation and Drainage Engineering**, v.109, p.317-332, 1983.

WINDY (**loja Play Store Android 2021**)

WRB. Base Referencial Mundial del Recurso Suelo. Primera actualización. **Informes sobre Recursos Mundiales de Suelos**, n.103, FAO, Roma, 2007.

YANG, Q.; ZHU, Y.; WANG, J. Adoption of drip fertigation system and technical efficiency of cherry tomato farmers in Southern China. **Journal of Cleaner Production**, v.275, p.123980, 2020.

YU, L.; LI, N. A.; LIU, X.; YANG, Q.; LI, Z.; LONG, J. U. N. Influence of dentation angle of labyrinth channel of drip emitters on hydraulic and anti-clogging performance. Irrigation and Drainage, v.68, p.256–267, 2019. https://doi.org/10.1002/ird.2

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