

Comparative study of drip irrigation systems using indoor amorphous photovoltaic panels

Estudo comparativo de sistemas de irrigação por gotejamento com uso de painéis fotovoltaicos amorfos *indoor*

Estudio comparativo de sistemas de riego por goteo mediante paneles fotovoltaicos amorfos de *indoor*

Received: 08/10/2021 | Reviewed: 08/19/2021 | Accept: 08/23/2021 | Published: 08/25/2021

Vander Fabio Silveira

ORCID: <https://orcid.org/0000-0002-5725-0591>
Universidade Estadual do Oeste do Paraná, Brazil
E-mail: vfabios@hotmail.com

Jair Antonio Cruz Siqueira

ORCID: <https://orcid.org/0000-0002-8140-444X>
Universidade Estadual do Oeste do Paraná, Brazil
E-mail: jair.siqueira@unioeste.br

Laís Fernanda Juchem do Nascimento

ORCID: <https://orcid.org/0000-0002-3790-5896>
Universidade Estadual do Oeste do Paraná, Brazil
E-mail: laisfjuchem@gmail.com

Luciene Kazue Tokura

ORCID: <https://orcid.org/0000-0001-9758-0141>
Universidade Estadual do Oeste do Paraná, Brazil
E-mail: lucienetokura@gmail.com

Alessandra Mayumi Tokura Alovisi

ORCID: <https://orcid.org/0000-0003-4236-4446>
Universidade Federal da Grande Dourados, Brazil
E-mail: alessandraalovisi@ufgd.edu.br

Marcio Antonio Vilas Boas

ORCID: <https://orcid.org/0000-0003-3444-8164>
Universidade Estadual do Oeste do Paraná, Brazil
E-mail: marcio.vilasboas@unioeste.br

Carlos Eduardo Camargo Nogueira

ORCID: <https://orcid.org/0000-0003-3886-9118>
Universidade Estadual do Oeste do Paraná, Brazil
E-mail: cecn1@yahoo.com.br

Marta Mitiko Kubota de Siqueira

ORCID: <https://orcid.org/0000-0002-0006-6750>
Universidade Estadual do Oeste do Paraná, Brazil
E-mail: martamks@gmail.com

Carlos Adriano Bohn

ORCID: <https://orcid.org/0000-0001-8099-126X>
Universidade Estadual do Oeste do Paraná, Brazil
E-mail: bohncarlos@yahoo.com

Renan Marques

ORCID: <https://orcid.org/0000-0003-0058-8062>
Universidade Estadual do Oeste do Paraná, Brazil
E-mail: renan-marques@hotmail.com

Soni Willian Hauptenthal

ORCID: <https://orcid.org/0000-0003-2598-4133>
Universidade Estadual do Oeste do Paraná, Brazil
E-mail: soniwillian@hotmail.com

Cristiano Fernando Lewandowski

ORCID: <https://orcid.org/0000-0001-5944-5723>
Universidade Estadual do Oeste do Paraná, Brazil
E-mail: cristiano@aceletric.com

Gilson Debastiani

ORCID: <https://orcid.org/0000-0003-3429-4257>
Universidade Estadual do Oeste do Paraná, Brazil
E-mail: gilsondebastiani2013@gmail.com

Abstract

Solar energy is a clean and renewable energy production option and can be applied to pumping water. Pumping water with photovoltaic solar energy is one of the technologies that has stood out in the country. In this context, the work aimed to evaluate the different methods of a drip irrigation system as a function of the use of an indoor amorphous photovoltaic pumping system, without electrical energy storage. The study was installed at the State University of Western Paraná. Voltage and current data were generated by the photovoltaic panels; solar irradiation was measured by the pyranometer device; the water pump flow rate was determined using the flow meter and in-line drip tube types. Irrigation performance was determined by the water distribution uniformity coefficients (CUD) and Christiansen's uniformity coefficient (CUC). Tests were performed on open and partially cloudy days. The experiment totaled 40 sampled data, half being collected on sunny days and the other half on partially cloudy days, at 9:45 am; 11:00 am; 1:30 pm and 3:00 pm. The methodology had the greatest influence on the CUD value. For the CUC parameter, the values were approximately 89% for the studied methods. Values remained under control for the Shewhart graph, but with the process capacity index affected.

Keywords: Drip irrigation system; Photovoltaic pumping system; Photovoltaic systems; Shewhart chart; Sunny and partially cloudy days.

Resumo

A energia solar é uma opção limpa e renovável de produção de energia e pode ser aplicada no bombeamento de água. O bombeamento de água com energia solar fotovoltaica é uma das tecnologias que tem se destacado no país. Neste contexto, o trabalho teve como objetivo avaliar os diferentes métodos de um sistema de irrigação por gotejamento em função da utilização de um sistema de bombeamento fotovoltaico amorfo *indoor*, sem armazenamento de energia elétrica. O estudo foi instalado na Universidade Estadual do Oeste do Paraná. Os dados da tensão e corrente elétrica foram gerados pelos painéis fotovoltaicos; a irradiação solar foi medida pelo aparelho piranômetro; a vazão da bomba d'água foi determinada usando o medidor de vazão e os tipos de tubos de gotejamento em linha. O desempenho da irrigação foi determinado pelos coeficientes de uniformidade de distribuição de água (CUD) e pelo coeficiente de uniformidade de Christiansen (CUC). Os testes foram realizados em dias de céu abertos e parcialmente nublados. O experimento totalizou 40 dados amostrados, sendo metade coletados em dias ensolarados e a outra metade em dias parcialmente nublados, às 9h45; 11h00; 13h30 e 15h00. A metodologia apresentou maior influência no valor do CUD. Para o parâmetro CUC, os valores foram de aproximadamente 89% para os métodos estudados. Os valores permaneceram sob controle para o gráfico de Shewhart, mas com o índice de capacidade do processo afetado.

Palavras-chave: Sistema de irrigação por gotejamento; Sistema de bombeamento fotovoltaico; Sistemas fotovoltaicos; Gráfico de Shewhart; Dias de sol e parcialmente nublados.

Resumen

La energía solar es una opción de producción de energía limpia y renovable y se puede aplicar al bombeo de agua. El bombeo de agua con energía solar fotovoltaica es una de las tecnologías que se ha destacado en el país. En este contexto, el trabajo tuvo como objetivo evaluar los diferentes métodos de un sistema de riego por goteo en función del uso de un sistema de bombeo interior amorfo fotovoltaico, sin almacenamiento de energía eléctrica. El estudio se instaló en la Universidad Estatal del Oeste de Paraná. Los datos de voltaje y corriente fueron generados por los paneles fotovoltaicos; la irradiación solar se midió mediante el dispositivo de piranómetro; el caudal de la bomba de agua se determinó utilizando el medidor de flujo y los tipos de tubo de goteo en línea. El rendimiento del riego se determinó mediante los coeficientes de uniformidad de distribución del agua (CUD) y el coeficiente de uniformidad de Christiansen (CUC). Las pruebas se realizaron en días abiertos y parcialmente nublados. El experimento totalizó 40 datos muestreados, la mitad recolectados en días soleados y la otra mitad en días parcialmente nublados, a las 9:45 am; 11 a.m; 1:30 pm y 3:00 pm. La metodología tuvo la mayor influencia en el valor CUD. Para el parámetro CUC, los valores fueron aproximadamente del 89% para los métodos estudiados. Los valores permanecieron bajo control para la parcela de Shewhart, pero con el índice de capacidad del proceso afectado.

Palabras clave: Sistema de riego por goteo; Sistema de bombeo fotovoltaico; Sistemas fotovoltaicos; Gráfico de Shewhart; Días soleados y parcialmente nublados.

1. Introduction

The importance drip irrigation is a localized technology that significantly increases crop yields (Grant, 2019; Zocoler et al., 2004). The autonomous photovoltaic system for pumping water in drip irrigation systems has become an economically competitive option for family farming, as well as populations located in remote areas, mainly because it is a technology with low operational and maintenance costs. Crops such as orchards, vegetables and organic crops need appropriate nutrients and uniformity in their irrigation, and this irrigation system allows for greater collection and rational use of water, avoiding harvest losses due to water stress. Thus, with the optimization of photovoltaic energy, all kinds of competitive crops can be made

viable in the consumer Market (Alvarenga et al., 2014; Chandel et al., 2015; Vick & Neal, 2012; Valer et al., 2016; Yu et al., 2018).

Solar power to pump water is a viable option when compared to pumping based on electricity and diesel (Li et al., 2017). And among the autonomous photovoltaic systems, systems with and without energy storage are mentioned. Systems with energy storage can be used to charge electric vehicle batteries, public lighting and small portable appliances, while systems without energy storage are often used in water pumping, presenting greater economic feasibility, as they are not possess instruments for energy storage. In this system, the photovoltaic panel generates electrical energy in direct current and, after converting it to alternating current, it is injected directly into the electrical energy network of the energy distributor (Rawat et al., 2016; Villalva & Gazoli, 2012).

Give the need for development, and different modes for agricultural production, it is interesting to study a method of irrigation using renewable energy (Zago, 2017).

Localized irrigation is identified as an efficient method in using water. Water is applied by drippers or microsprinklers in a punctual way, were only the root region is wet. Losses of water through evaporation or drift is minimized, as well as fungicidal diseases. The volume of water for localized irrigation is smaller when compared to other application methods, being an advantage for places where water resources are scarce or that face conflicts over water use (Grah et al., 2012).

Vilas Boas (2016) also states that localized irrigation is based on the application of water on the surface or below the ground, using pressurized pipes and emitters, in order to water only a region, close to the plant, known as the wet bulb. Drip is the most widespread irrigation system among localized irrigation systems and is mainly used in crops with wide spacing. In this system, the water circulates under pressure until it reaches the emitters, whose function is to reduce the speed of the water and allow it to flow out drop by drop.

It is indicated that before and after the installation of an irrigation system, its evaluation is carried out by means of tests to guarantee its maximum efficiency (Duarte et al., 2012). The evaluation of a localized irrigation system consists of the collection of slides applied with the aid of test tubes and subsequent analyzes of the results using mathematical equations. The collected data can be used to calculate different uniformity coefficients, that express the variability of application of irrigation depths (Mantovani, 2000).

The use of control charts can be used to evaluate irrigation systems with uniform photovoltaic pumping. These charts are used to monitor irrigation systems and signal if adjustments are needed. Thus, the Shewhart charts are able to detect small variations in the studies evaluated. The process capacity index is another parameter that serves to classify the processes used (Andrade et al., 2017).

There are few scientific articles on photovoltaic pumping without the use of battery systems, which makes the study relevant in relation to the intermittency of solar energy combined with irrigation.

Give the above, the aim of the study was to determine the water distribution uniformity coefficients (CUD) and the Christiansen uniformity coefficient (CUC), without energy storage with an indoor experiment to evaluate the irrigation performance on days characterized as of open skies and partially cloudy skies, using the methods proposed by Keller & Karmeli (1974) e Denículi et al. (1980) and Total.

2. Material and Methods

2.1 Study area and description of materials used in the experimental implementation

Work was developed at the Center of Analysis of Alternative Systems (CASA), State University of Western Paraná - UNIOESTE, located in the Campus of Cascavel-Paraná. The drip irrigation system was assembled indoor from the CASA laboratory near the same the geographical location is defined by the South Latitude (S) 24°59' and West Longitude 53°27' (W)

and average altitude of 750 meters. According to the SUNDATA Program (Reference Center for Solar and Wind Energy Sergio de Sálvio Brito – Cresesb, 2019) average radiation of 4.80 kWh/m²/day.

The methodology used to design the experiment was based on the methodology proposed by Zago (2017).

In order to generate electrical energy to the pump motor system, a set of two photovoltaic modules (Solarterra Model JN40F) were used in parallel of amorphous silicon, as shown in Figure 1. Each module has a rated power of 40 Wp and a maximum nominal voltage of 46 V, the open-circuit voltage (VOC) is 61 V, nominal current of 0.87 A and the short circuit current (ISC) of 1.00A. The photovoltaic modules were associated in parallel, forming a photovoltaic panel of 120 WP. Amorphous silicon photovoltaic panel was installed for the experiment at 35 degrees slope and geographic north.

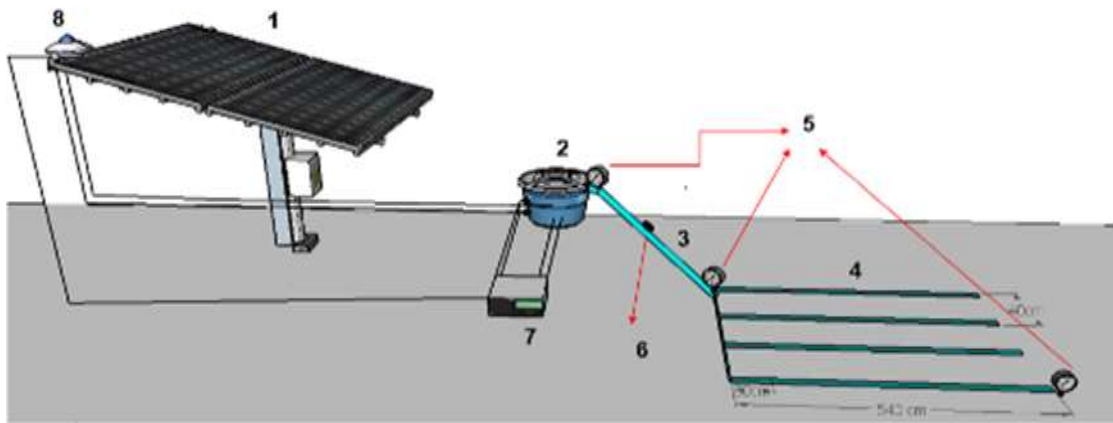
Figure 1. Amorphous silicon photovoltaic panel.



Source: Authors.

The assembly of the experiment was composed by the pyranometer (brand Kipp and Zonen, model CMP3, with 15.3 $\mu\text{V W}^{-1} \text{m}^2$ sensitivity), photovoltaic modules, sectioning and sensing circuit for the datalogger (brand Campbell Scientific, model CR 1000) and feeding of the water pump (Solarjack brand, model SDS-D-228 diaphragm type), in addition to all the hydraulic system composed by the storage and pumping of water to the irrigation system and pressure sensing and flow of pumped water (Yifa brand, model Yf-s201 with 1/2") (Figure 2).

Figure 2. General diagram of the experimental setup. Where: (1) photovoltaic panel; (2) water tan and submersible water pump; (3) Connecting tube between pump and irrigation system; (4) irrigation system.; (5) pump outlet manometer; (6) water flow sensor; (7) sectioning circuit + sensing for datalogger; (8) Pyranometer.



Source: Authors.

2.2 Experimental setup and techniques

The operation of the pump occurred only at the times of solar irradiation on the panels, that is, no energy storage system was used for the system to operate during night or overcast days.

The drip irrigation system was tested in the CASA project laboratory. Four drip tapes of 5.4 m in length were spaced 40 cm apart, with drippers spaced every 30 cm. Figure 3 shows the irrigation system composed of 18 collectors per line, totaling 72 collectors.

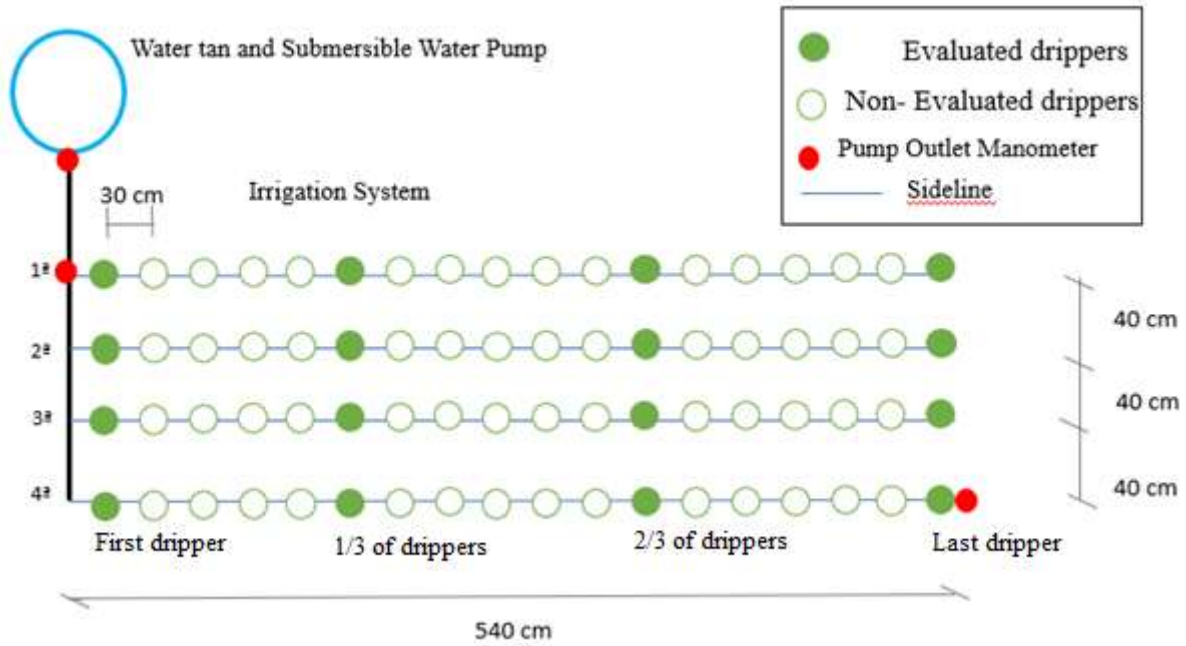
Figure 3. Drip irrigation system implanted inside Center of Analysis of Alternative Systems (CASA).



Source: Authors.

The inline drip tubes used in the experiment were of the Netafim brand, Micro Drip model, as shown in Figure 4.

Figure 4. Measurement scheme using the Keller & Karmeli (1974) methodology with 16 drippers.



Source: Authors.

The data collection of the experiment was carried out in 10 days of open sky and 10 days of partly cloudy sky, both for the indoor drip irrigation system. The periods collected were 9:45 am; 11:00 am; 1:30 p.m. and 3:00 p.m. Each trial had duration of 5 minutes for each hour. The collections started in May and were completed in November.

The chosen schedules were in function of the indices of greater irradiance that occur between the interval of 9:45 and 15:00 hours. The experiment was performed in the indoor system, in order to demonstrate a controlled system, simulating a protected environment, and in loco to field, respectively.

The criteria used to evaluate the system were the coefficient of variation (CV) of the lateral emitter, the uniformity of emission (CUD) and the coefficient of uniformity of Christiansen (CUC). A comparison of the Keller & Karmeli (1974), Denículi et al. (1980) method and the total measurement of all collectors for irrigation were also performed.

The uniformity of water application was expressed by Christiansen's uniformity coefficient (CUC) (Christiansen, 1942), which is one of the most used, since it adopts the absolute mean deviation as a dispersion measure, as can be seen in Equation 1.

$$CUC = \left\{ 1 - \frac{\sum_{i=1}^{n_e} |q_i - \bar{q}|}{n_e \bar{q}} \right\} 100 \quad (1)$$

Where q_i : Flow of each dripper ($L h^{-1}$), \bar{q} : Average flow of drippers ($L h^{-1}$), n_e : Number of drippers.

From this, the CUC data were classified according to the criteria shown in Table 1.

Table 1. Criteria for classification of CUC (%).

Ranking	CUC (%)
Great	90-100
Good	80-90
Regular	70-80
Bad	60-70
Unacceptable	< 60

Source. American Society of Agricultural and Biological Engineers - ASABE (1996).

In order to evaluate the uniformity according to the areas that receive less water, it is necessary to use the distribution uniformity coefficient (CUD), proposed by Kruse (1978) and also recommended by Normative 12 (Brazilian Association of Technical Standards – ABNT, 1985), which is given in percentage (%) and expressed by Equation 2.

$$CUD = \frac{q_{25\%}}{\bar{q}} 100 \quad (2)$$

Where $q_{25\%}$ = mean value of 25% of the lowest flows ($L h^{-1}$).

This coefficient is defined as the water distribution measure that relates the fourth part of the total area and receives less water with the applied average blade.

After the data obtained, the American Society of Agricultural and Biological Engineers (ASABE, 1996) standard, presented in Table 2, was used and the recommended classification for the distribution uniformity coefficient values was determined.

Table 2. Criteria for CUD classification (%).

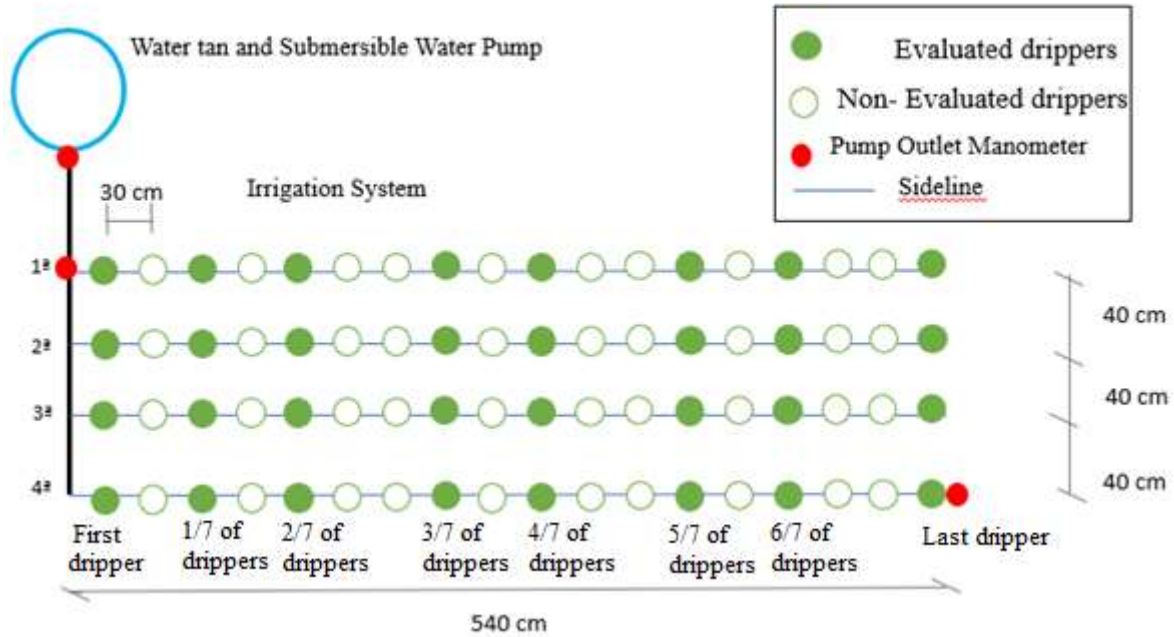
Ranking	CUD (%)
Great	> 90
Good	75 – 90
Regular	62 – 75
Bad	50 – 62
Unacceptable	< 50

Source. American Society of Agricultural and Biological Engineers – ASABE (1996).

According to the methodology of Keller and Karmeli (1974) the flow rates were determined in 16 drippers within the irrigation system, selecting four lateral lines to the logo of the branch line, which are: the first one 1/3 and 2/3 of the branch line length and the last lateral line (Figure 4).

According to Denículi et al. (1980), the flow rates are determined in 32 drippers within the irrigation system. Eight collectors were selected per lateral line: first dripper, drippers located at 1/7, 2/7, 3/7, 4/7, 5/7 and 6/7 and the last dripper (Figure 5). In addition, all flow rates were collected from all collectors and compared to the other methodologies cited.

Figure 5. Measurement scheme using the Denículi et al. (1980) methodology with 32 drippers.



Source: Authors.

For the comparison was used the chart of Shewhart that were successful due to its simplicity because they present facility of decision rule is based only on the examination of the last observed point. Therefore, they investigate the presence of special causes in the process. However, this can be a disadvantage by ignoring any data reported by the previous sequence of points. In this way, it is said that the graph "has no memory" making the Shewhart type insensitive to small changes in the process, of the order of 1.5σ (standard errors) or less (Montgomery, 2009).

The purpose of the control chart for individual observations is to observe out-of-control points. These are those that are off limits and also evaluate the occurrence of undesirable settings such as trends, points very close to the boundaries or the midline.

The upper control limit (UCL) and lower central limit (LCI) can be statistically determined by the mean amplitude of the samples, and are dependent on the process variability, according to Equations 3 and 4 (Montgomery, 2009).

$$UCL = \bar{x} + 3 \cdot \frac{\overline{MR}}{d_2} \quad (3)$$

$$LCI = \bar{x} - 3 \cdot \frac{\overline{MR}}{d_2} \quad (4)$$

Where x_i : average, d_2 : constant, depends on the number of repetitions per test, for $r = 1$, the value of the constant is 1.128. Being \overline{MR} : mean amplitude, \bar{x} : overall average (Equation 5).

$$\overline{MR} = \frac{\sum |x_i - x_{i-1}|}{n-1} \quad (5)$$

The process capacity index (Cp) is a dimensionless parameter that indirectly measures how much the process can meet the specifications, and the higher its value, the better the process can meet the requirements (Costa et al., 2008).

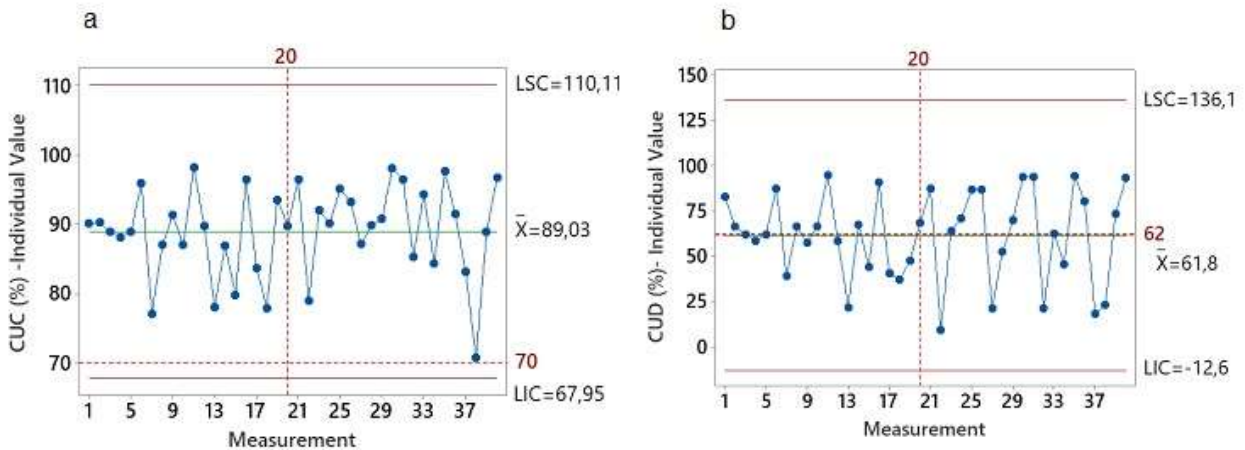
3. Results and Discussion

3.1 CUC and CUD variation according to the evaluated methodologies

The data of Figures 6, 7 and 8 refer to 40 sample values collected in 4 daily schedules, being (1-20) days characterized as open skies and (21-40) partly cloudy.

The values of Figure 6, by the Keller and Karmeli (1974) collection method, were controlled when the limits described by Shewhart were analyzed. It was observed that the CUC presented a mean of 89.82%. Differently from the CUD, where the mean was 64.9% and exhibited several trials, both on open and partly cloudy days.

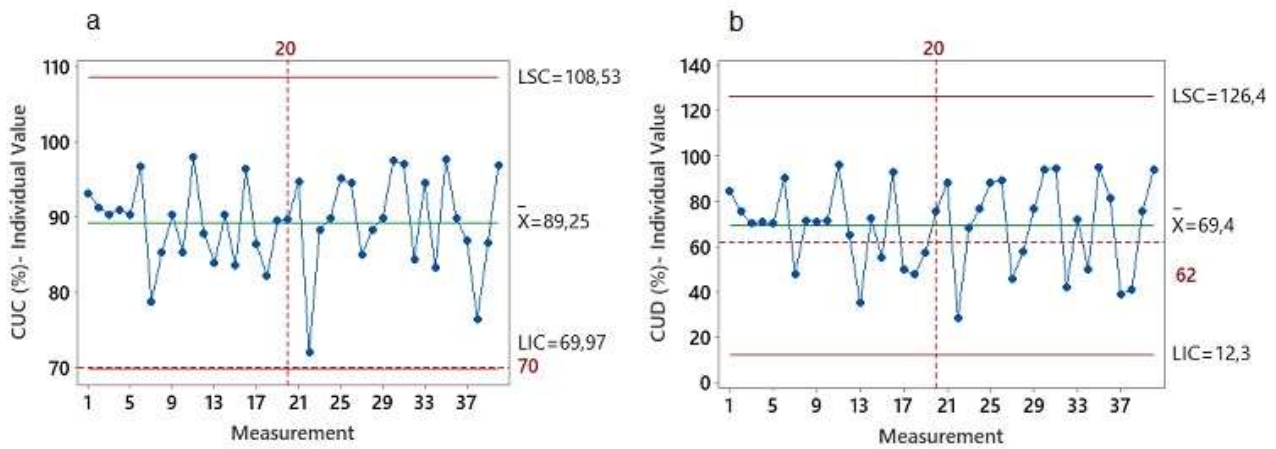
Figure 6. Shewhart control chart for irrigation uniformity, according to the Keller and Karmeli (1974) methodology. a) uniformity coefficient of Christiansen (CUC) and b) coefficients of water distribution uniformity (CUD).



Source: Authors.

For the method Denículi et al. (1980), Figure 7, shows an outlier point below the lower control limit that occurred on days considered as partially cloudy, but the sample was under uniformity control and within the established by American Society of Agricultural and Biological Engineers (ASABE, 1996). The average for CUC was 89.25% considered as good. Justi et al. (2010) found a maximum value of 89.25% for analysis of irrigation quality by sprinkling.

Figure 7. Shewhart control plot for irrigation uniformity, according to the Denículi et al. (1980). a) uniformity coefficient of Christiansen (CUC) and b) coefficients of water distribution uniformity (CUD).



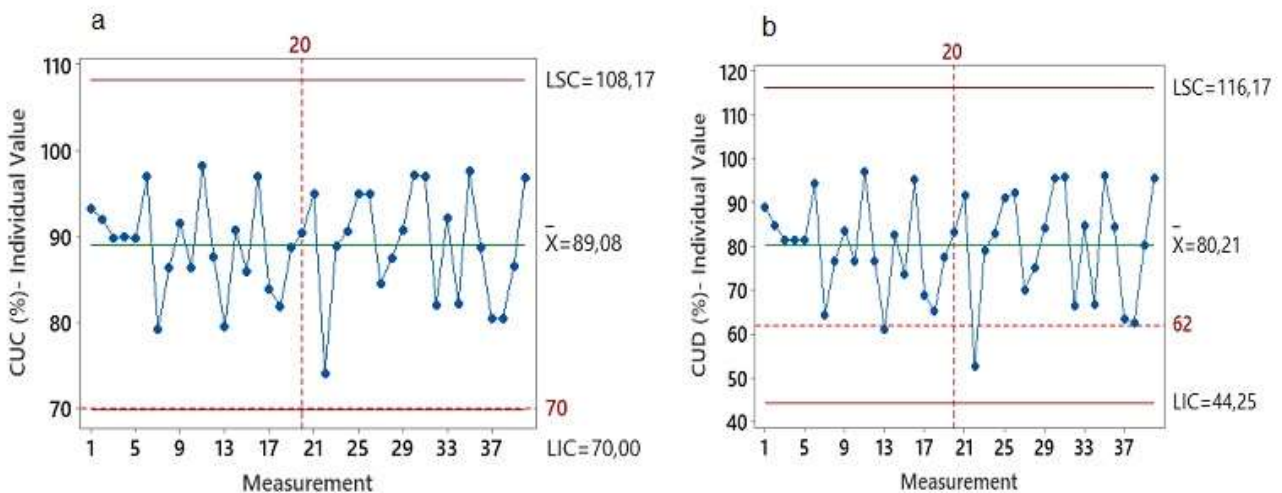
Source: Authors.

Santos et al. (2016) also studied the two sampling methodologies: Keller and Karmeli (1974) with 16 points and Denículi et al. (1980) with 32 points, obtained CUC values higher than 89.08%, so the system was classified as good.

An increase in the value of the center line is observed for 69.4% for the CUD value in Figure 7 and 80.21% in Figure 8. According to Vieira et al. (2003), although CUD is more used for CUC is still the best-known coefficient for technicians and producers in general. According to Mantovani (2000) this is due to CUC values having greater stability due to being less affected by the extreme conditions, being one of the reasons why it is more used to define the irrigation efficiency in the estimation of the gross blade of irrigation. In this way, this work also obtained similar results regarding the oscillation of values for CUC that was smaller when compared to CUD for all the mentioned types of methodology.

The value of CUC was 89.08% when we analyzed all the emitters percentage lower than that found by Haupenthal et al. (2018) of 98.92% that used the same indoor irrigation system, however with polycrystalline photovoltaic pumping.

Figure 8. Shewhart control plot for irrigation uniformity, measuring the flow rate of all emitters. a) uniformity coefficient of Christiansen (CUC) and b) coefficients of water distribution uniformity (CUD).



Source: Authors.

Fernandes et al. (2012) applied the two methodologies cited in a drip irrigation system. The uniformity of the irrigation system was rated as 78% reasonable for Keller and Karmeli (1974) and regulated 77% for Denículi et al. (1980). They also concluded that when the length of the lateral lines is over 100m, it is recommended to use 32 points (Deniculi et al., 1980 Method) as a way to assure results that are more representative of the uniformity of water distribution.

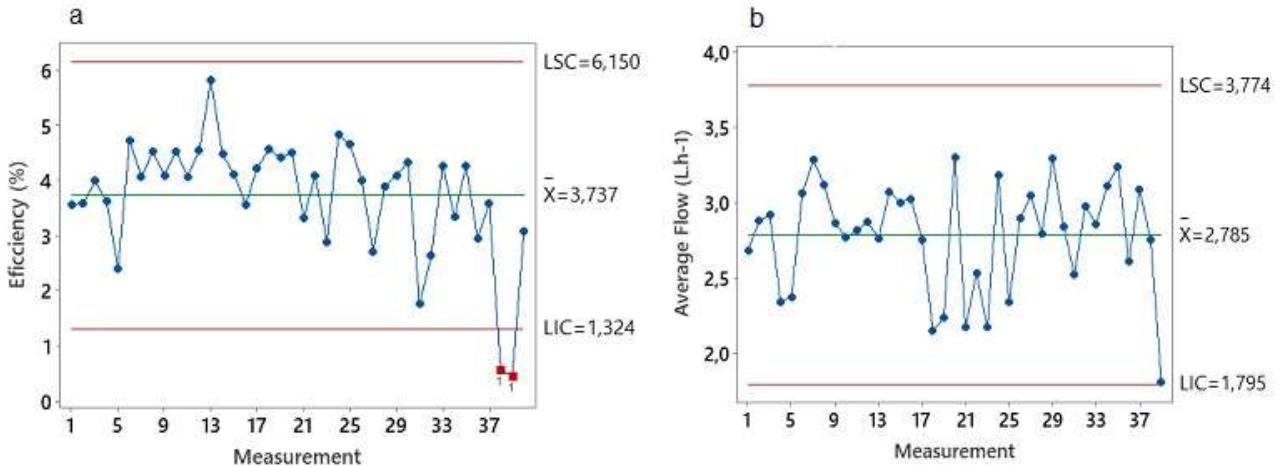
For Vieira and Mantovani (2004) both for the calculation of CUD and CUC, under conditions where the irrigation system has a constant maintenance, it is permissible to carry out evaluations of only 16 drippers. However, when the irrigation system is in trouble, such as clogging of the drippers, it is necessary to make a larger sampling with 32 points. Differently from this work that for the value of CUD it was necessary the verification of all emitters to understand the quality of the system.

The results found were similar with Andrade et al. (2016) who pointed 90% linear values for variable values of CUC and CUD, 91 to 71.55% for different spaces in their study. Demonstrating a higher sensitivity for the CUD parameter (%).

For the authors Lopes et al. (2019), declining irrigation was more uniform (CUC = 99.03% and CUD = 98.45%), however, for all the studied graphs, it was out of statistical control, unlike the data found in this work. They reached higher values of excellence in irrigation, but without statistical control.

The photovoltaic solar efficiency graph showed two random points samples: trial 38 with 0.57% and trial 39 with 0.74%, both found in the 3 pm in conditions of partly cloudy sky. Note that trial 38 for an average flow of 1.81 L h⁻¹ tends to be out of control due to be close to the center line (Figure 9).

Figure 9. Charts of individual controls a) efficiency of the solar system photovoltaic (%) and b) average flow (L h⁻¹) for open days (1 to 20) and partially cloudy (21 to 40) of the indoor drip irrigation system mounted in the autumn season.



Source: Authors.

It is observed that for partially cloudy days, Figure 9, two collections were out of control for the Shewhart chart in relation to the general sample. However, without direct reference to the average flow of the drip irrigation system, which remained under control, but with great variability around the average of 2,785 L h⁻¹.

The influence of the solar photovoltaic energy in the drip irrigation system was divided into two samples: open-pit days (p-value 0.637) and partially cloudy (p-value of 0.507) for CUC (%); (p-value 0.505) and partly cloudy (p-value 0,159) for CUD (%).

Andrade (2013) when evaluating the process of localized irrigation using statistical quality control.

When Cpk assumes negative signal, the mean will be outside the tolerance field and the larger the negative Cpk negative number module will be the average tolerance limit considered (Table 3).

Table 3. Process capacity of CUC and CUD (indoor).

Parameter	Index	60-70	70-80	80-90	90-100
CUC (%)	Cp	0.28	0.28	0.28	0.28
Clear sky	Cpk	-1.07	-0.51	0.06	-0.06
CUC (%)	Cp	0.24	0.24	0.24	0.24
Partly cloudy	Cpk	-0.92	-0.44	0.04	-0.04
CUD (%)	Cp	0.15	0.15	0.15	0.15
Clear sky	Cpk	-0.30	0.01	-0.01	-0.31
CUD (%)	Cp	0.12	0.12	0.12	0.12
Partly cloudy	Cpk	-0.26	-0.01	0.01	-0.23

Source: Authors.

Szekut et al. (2014) which analyzed index of process capacity in drip irrigation for family farms to below 85% for CUC and 90% CUD presented negative Cpk values. The Cpk indices were negative in all percentages of this study, where values below 0 may be considered as 0.

Regarding the Cp all were below 1.25 established by Montgomery (2009), which shows instability in the pumping process without energy storage. Andrade et al. (2017) pointed out the process capacity index was relevant in his work, in which he studied the evaluation of the uniformity of the micro sprinkler irrigation with photovoltaic solar energy with and without energy storage, to classify the processes used, demonstrating the storage treatments the value of the process capability index.

4. Conclusions

The use of the Total methodology was more efficient for the CUD analysis. The CUC values were not affected by the three methodologies studied.

For the CUC, the average values were 89.08% when all issuers were analyzed, 89.25% by the methodology of Denículi et al. and 89.03% for Keller & Karmeli methodology. Only two points were observed to be out of control on the Shewhart chart.

As for CUD, although all are under control for Shewhart, the averages varied widely from 80.21% total, 69.4% Denículi et al. and 61.8% for Keller & Karmeli. Great variation was demonstrated in the analysis of the irrigation standard.

The capacity index proved to be insufficient for analysis without energy storage.

The amorphous photovoltaic solar system had no direct influence on the behavior of the drip irrigation system, being the hydraulic parameters more effective in the overall behavior of the system.

It is suggested for future work the development of research using different types of drippers and different photovoltaic modules, to assess whether these changes affect the performance of the irrigation system.

Acknowledgments

The authors thank the State University of Western Paraná, Cascavel campus, for their support in the study.

References

- Alvarenga, A. C., Ferreira, V. H., & Fortes, M. Z. (2014). Energia solar fotovoltaica: uma aplicação na irrigação da agricultura familiar. *Sinergia*, 15 (4), 311-318.
- American Society of Agricultural and Biological Engineers. ASABE. (1996). *Field evaluation of micro-irrigation Systems*, St. Joseph, USA.
- Andrade, M. G. (2013). *Efeito de um sistema de bombeamento de água fotovoltaico na operação de um microaspersor*. Dissertação de mestrado. Universidade Estadual do Oeste do Paraná, Cascavel, Brazil.
- Andrade, M. G., Vilas Boas, M. A., Siqueira, J. A. C., Dieter, J., Sato, M., Hermes, E., Mercante, E., & Tokura, L. K. (2017). Statistical quality control for the evaluation of the uniformity of microsprinkler irrigation with photovoltaic solar energy. *Renewable and Sustainable Energy*, 78, 743-753. 10.1016/j.rser.2017.05.012
- Andrade, M. G. D., Vilas Boas, M. A., Siqueira, J. A. C., Sato, M., Dieter, J., Hermes, E., Mercante, E. (2017). Uniformity microsprinkler irrigation system using statistical quality control. *Ciência Rural*, 47, e20160546. 10.1590/0103-8478cr20160546.
- Brazilian Association of Technical Standards. ABNT. (1985). *System central sprinkler irrigation, characterization and performance - test method: 1st Draft Standards*. River of January. 22p.
- Chandel, S. S., Nagaraju Naik, M., & Chandel, R. (2015). Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies. *Renewable and Sustainable Energy Reviews*, 49, 1084-1099. 10.1016/j.rser.2015.04.083
- Christiansen, J. E. (1942). *Irrigation by sprinkling*. University of California, 124p.
- Costa, A. F. B., Epprecht, E. K., & Carpinetti, L. C. R. (2008). *Controle Estatístico de Qualidade* (2nd ed.). Editora Atlas.
- Denículi, W., Bernardo, S., Thiébaud, J. T. L., & Sediya, G. C. (1980). Uniformidade de distribuição de água, em condições de campo num sistema de irrigação por gotejamento. *Revista Ceres*, 27 (150), 155-162.
- Duarte, K. A., Pereira, M. M., Souza, J. M., Pereira, M. K. M., Gomes, G. P., & Xerez, F. N. F. B. (2012). Desempenho de um sistema de irrigação por microaspersão na cultura da Atemóia (*Annona ssp.*). INOVAGRI International Meeting, <http://www.inovagri.org.br/meeting2012/wp-content/uploads/2012/06/Protocolo289.pdf>.
- Fernandes, A. I., Carvalho, M. A. R., Carvalho, L. C. C., & Santos Neto, A. M. (2012). Avaliação de um sistema de irrigação pelas metodologias de Keller e Karmeli, e de Denículi em citros irrigados por gotejamento. *Revista Brasileira de Agricultura Irrigada*, 6 (2), 74-80. 10.7127/rbai.v6n200085
- Grah, V. F., Botrel, T. A., Ponciano, I. M., Damasceno, A. P. A. B., Salvador, C. A., & Alves, D. G. (2012). Solução alternativa para bombeamento de água e automação da irrigação sem o uso de energia elétrica. *Irriga*, 1 (1), 309-323. 10.15809/irriga.2012v1n01p309
- Grant, F. (2019). *Development and validation of a systems-level cost optimization tool for solar-powered drip irrigation systems for smallholder farms*. Doctoral thesis. Massachusetts Institute of Technology.
- Hauptenthal, S. W., Siqueira, J. A., Tokura, L. K., Nogueira, C. E. C., Vilas Boas, M. A., Nascimento, L. F. J., & Rocha, E. O. (2018). Evaluation of a Photovoltaic Energy System Applied to a Drip Irrigation System. *Journal of Agricultural Science*, 10 (8), 43-55. 10.5539/jas.v10n8p43
- Justi, A. L., Vilas Boas, M. A., & Sampaio, S. C. (2010). Índice de capacidade do processo na avaliação da irrigação por aspersão. *Engenharia Agrícola*, 30 (2), 264-270. 10.1590/S0100-69162010000200008
- Keller, J., & Karmeli, D. (1974). Trickle irrigation design parameters. *Trans. ASAE*, 17, 678-684. Saint Joseph.
- Li, G., Jin, Y., Akram, M. W., & Chen, X. (2017). Research and current status of the solar photovoltaic water pumping system - A review. *Renewable and Sustainable Energy Reviews*, 79, 440-458. 10.1016/j.rser.2017.05.055.
- Lopes, A. R., Vilas Boas, M. A., Pazuch, F. A., Dalla Corte, L., Ostroski, D. A., Remor, M. B., Mohr, F. B. M., Dotto, M., Zanella, A. P., Carvalho, A. F. G., Freddo, A. R., Bertoldo, I. C., Pirola, K., & Giarola, C. M. (2019). Statistical Quality Control in Uniformity of Drip Irrigation With Different Slopes. *Journal of Agricultural Science*, 11 (16), 195-205. 10.5539/jas.v11n16p195
- Mantovani, E. C. (2000). *A Irrigação do cafeeiro*. In: Zambolim, L. Café: produtividade, qualidade e sustentabilidade, UFV.
- Mantovani, E. C. (2000). *Café: produtividade, qualidade e sustentabilidade* (Eds: L. Zambolim), UFV.
- Montgomery, D. C. (2009). *Introdução ao controle estatístico de qualidade*, (4th ed.), (Eds: Farias AML, Flores VRLF, Laurencel LC). Rio de Janeiro: Editora LTC.
- Rawat, R., Kaushik, S. C., & Lamba, R. (2016). A review on modeling, design methodology and size optimization of photovoltaic based water pumping, standalone and grid connected system. *Renewable and Sustainable Energy Reviews*, 57, 1506-1519. 10.1016/j.rser.2015.12.228
- Reference Center for Solar and Wind Energy Sergio de Sálvio Brito. CRESESB. (2019). Presented at the SUNDATA, Brazil, July.
- Santos, M. A. L., Santos, D. P., Silva, D. S., Santos Silva, M., & Cavalcante, P. H. S. (2016). Avaliação da uniformidade de distribuição de um sistema de irrigação por gotejamento em inhame (*Dioscorea cayennensis* L.). *Revista Ciência Agrícola*, 13 (1), 7-12.
- Szekut, F. D., Klein, M. R., Suszek, F. L., Vilas Boas, M. A., & Zuculotto, T. (2014). *Índice de capacidade de processo na irrigação por gotejamento destinado à agricultura familiar*. In: II Brazilian Symposium on Salinity & II Brazilian Meeting on Irrigation, 2014, Fortaleza - CE. II INOVAGRI International Meeting. 10.12702/ii.inovagri.2014-a429.

- Valer, L. R., Melendez, T. A., Fedrizzi, M. A., Zilles, R., & Moraes, A. M. (2016). Variable-speed drives in photovoltaic pumping systems for irrigation in Brazil. *Sustainable Energy Technologies and Assessments*, 15, 20-26. 10.1016/j.seta.2016.03.003.
- Vick, B. D., & Neal, B. A. (2012). Analysis of off-grid hybrid wind turbine/solar pv water pumping systems. *Solar Energy*, 86, 1197-1207. 10.1016/j.solener.2012.01.012
- Vieira, G. H. S., & Mantovani, E. C. (2004). *Estudo comparativo da avaliação de sistemas de irrigação por gotejamento com medição da vazão de 16 e 32 gotejadores*. XIV Congresso Nacional de Irrigação e Drenagem, Porto Alegre, RS. Brazil.
- Vieira, G. H. S., Mantovani, E. C., & Cordeiro, E. A. (2003). *Estudo comparativo da avaliação de sistemas de irrigação por gotejamento utilizando os métodos propostos por Keller e por Deniculi*. Paper presented at the Congresso Brasileiro de Pesquisas Cafeeiras, Araxá, MG. Brazil.
- Vilas Boas, M. A. (2016). *Fundamentos de irrigação localizada*, Edunioeste.
- Villalva, M., & Gazoli, J. (2012). *Energia solar fotovoltaica: conceitos e aplicações*, Érica.
- Yu, Y., Liu, J., Wang, Y., Xiang, C., Zhou, J. (2018). Practicality of using solar energy for cassava irrigation in the Guangxi Autonomous Region, China. *Applied Energy*, 230, 31-41. 10.1016/j.apenergy.2018.08.060
- Zago, E. A. (2017). *Desempenho de um sistema de irrigação por gotejamento utilizando energia fotovoltaica*. Dissertação de mestrado. Universidade Estadual do Oeste do Paraná.
- Zocoler, J. L., Cesar, L. E. V., & Vanzela, L. S. (2004). Efeito da posição relativa da linha lateral de um equipamento de irrigação do tipo pivô central na uniformidade de distribuição de água e eficiência de irrigação. *Engenharia Agrícola*, 12 (4), 290-297.