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Monitoring urea concentration at different slope angles in drip fertigation

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ABSTRACT

The use of statistical process control tools in irrigation is becoming widespread as it allows for quick and effective investigation and detection of possible problems with drippers, especially when fertilizer is used in irrigation water and different slopes. Therefore, the research used statistical quality control charts to monitor urea concentration at different inclinations of the lateral line. The experiment was conducted in a protected environment at the Irrigation and Fertigation Laboratory - LIF) in the city of Cascavel, Paraná State, Brazil. It followed a randomized block design, in a 4x3 factorial arrangement, in which fertilizer concentrations were evaluated at three slope angles. Experimental plots were divided into two factors. The first is the type of water (clean water from an artesian well and water with a nitrogen fertilizer at 44% N) subdivided into four subplots, representing concentrations of urea (0, 2, 4, and 6 g L^{-1}). The second factor was slope angle and represented the sub-plots: uphill (2%), level (0%), and downhill (2%). The results show that Shewhart's statistical control charts were sensitive in observing the change in uniformity due to the increase in fertilizer concentration. Water with fertilizer (4 gL^{-1}) affected uniformity at all studied slope levels. The results also show that high concentrations of fertilizers change the pH of the water. The lowest urea concentrations showed the best distribution uniformity results.

Keywords: control charts, drip irrigation, Shewhart, uniformity.

Monitoramento da concentração de ureia em diferentes inclinações na fertirrigação por gotejamento

RESUMO

A utilização de ferramentas de controle estatístico de processo na irrigação vem se difundindo por propiciar a investigação e detecção rápida e eficaz dos possíveis problemas ocasionados aos gotejadores, em especial, quando se utiliza fertilizante na água de irrigação e diferentes inclinações. Desse modo, a pesquisa teve como objetivo utilizar cartas de controle estatístico de qualidade no acompanhamento da concentração de ureia em diferentes inclinações da linha lateral. O experimento foi desenvolvido em ambiente protegido no Laboratório de Irrigação e Fertirrigação (LIF), Cascavel-, PR. O delineamento experimental ocorreu em blocos casualizados em esquema fatorial 4x3, no qual foi avaliada a concentração de fertilizante em três níveis de declividade: com parcelas divididas em dois fatores, sendo o principal fator o tipo de água, representado por quatro parcelas: água limpa (proveniente de poço artesiano) e água com fertilizante nitrogenado, ureia (44% N) em três concentrações (2 g L^{-1}; 4 g L^{-1}; 6 g L^{-1}); e como segundo fator, os níveis de declividade, representado pela sub parcela: aclive (2%), nível (0%) e declive (2%). Os resultados mostram que as cartas de controle estatístico de Shewhart foram sensíveis na observação da modificação da uniformidade pelo acréscimo da concentração de fertilizante. A água com fertilizante (4 gL^{-1}) afetou a uniformidade em todos os níveis de declividade estudado. Os resultados também mostram que altas concentrações de fertilizantes alteram o pH da água. As menores concentrações de ureia apresentaram os melhores resultados de uniformidade de distribuição.

Palavras-chave: irrigação por gotejamento, gráficos de controle, Shewhart, uniformidade.

1. INTRODUCTION

Fertigation is the supply of dissolved mineral fertilizers through irrigation water (Shirgure, 2013). The use of fertigation with drip irrigation systems has become increasingly popular in agricultural production. As an efficient fertilizer application technology that saves water, labor, fertigation increases the efficiency of nutrient use by plants, in addition to improving distribution in the soil profile, due to the application being punctual and close to the roots (Pereira *et al.*, 2019). The uniformity of water and fertilizer distribution are important considerations for the design and operation of drip fertigation systems, as they directly influence management, quality, efficiency and cost, as well as crop performance in the field. Li and Rao, (2003), Zhao *et al.* (2012), Wang *et al.* (2014), Azevedo *et al.* (2014)

Uniformity is crucial for irrigation systems to apply water evenly across the irrigated area (Mohamed *et al.*, 2019). This measure can be evaluated through uniformity coefficients (Frizzone, 1992) and has great importance (Freitas *et al.*, 2013).

In fertigation, factors such as concentration and solubility of fertilizers can affect the uniformity of application of the system. According to (Fan *et al.*, 2017) different variations in fertilizer concentration can affect fertilizer uniformity. Another factor to be considered in evaluating the uniformity of water and fertilizer distribution in drip fertigation systems is the slope of the lateral line. This is because topography has an influence on the uniformity of flow and pressure, as well as on pH, electrical conductivity, among others (Souza *et al.*, 2018). According to (Szekut *et al.*, 2018) the operation of lateral drip lines is affected by the topography of the irrigated area and represents, depending on the type of water applied, changes in the discharge characteristics of emitters. For example (Lopes *et al.*, 2021a) found excellence in flow uniformity at all slope levels when evaluating fertigation with MPK.

The performance of new irrigation system configurations can be evaluated by applying statistical process control (SPC) techniques. Gomes *et al.* (2020) emphasize that this tool will provide guidance for preventive maintenance in the irrigation system.

SPC techniques can be used to analyze parameters like application uniformity (Andrade *et al.*, 2007). Some studies, such as those of Frigo *et al.* (2016), Hermes *et al.* (2015), Zocoler *et al.* (2015), Andrade *et al.* (2007), Siqueira *et al.* (2018), and Lopes *et al.* (2021b), have used this technique to understand the behavior of different irrigation designs. One of the techniques that can be used to analyze parameters, such as application uniformity, is the Shewhart Chart (Andrade *et al.*, 2007). According to Ribeiro and Catena (2012), the analysis of the Christiansen Uniformity Coefficient (CUC) (Christiansen, 1942) and Distribution Uniformity Coefficient (DUC) through SPC provides a radiograph of the process, identifying its variability and enabling its control over time. Moreover, continuous data collection and analysis can prevent potential system instability, which impairs irrigation uniformity. Therefore, a Shewhart individual control chart is useful for the analysis of manufacturing processes and irrigation systems.

Another SPC tool is the analysis of process capability through indices, which reflects the ability to manufacture products whose inherent variation is within the specified tolerance range in the product design (Borges *et al.*, 2008). It can also be useful in monitoring irrigation systems, as already stated by Mercante *et al.* (2014). In this sense, the use of control tools in identifying problems caused based on the slope and water quality in irrigation is extremely important, since the methodology used to evaluate uniformity may be subject to errors (Silva *et al.*, 2016).

Therefore, in view of the potential of statistical process control, the aim was to investigate changes in the application uniformity of a fertigation project configuration that is still little studied. In this way, the objective will be to evaluate whether the control charts are effective in identifying anomalies in irrigation management considering different concentrations of nitrogen fertilizer combined with different slopes of the lateral line.

2. MATERIAL AND METHODS

2.1. Research site characterization

The experiment was carried out in a protected environment at the Irrigation and Fertigation Laboratory - LIF (in Portuguese). It is located at the experimental campus of the Faculty of Agricultural Engineering, Western Paraná State University (UNIOESTE), in the city of Cascavel, Paraná State, Brazil. The area lies at the geographic coordinates of 24°54’0” South and 53°31’48” West.

2.2. Equipment and procedures for testing

The experiment was conducted using a 5-m drip irrigation bench with the following features: a pulley system as a return for the lateral line, resulting in a length of 10 m; a bench width of 1.55 m, with space for four lines; channels for water return to a reservoir; and a motor pump (ACQUAPUMP, Ferrari™) with a 0.5 cv power, maximum flow rate (Q) of 1.8 $m^3 h^{-1}$, and maximum manometric height (Hm) of 2.16 bar.

The platform was constructed using steel profiles and cables to enable elevation, which allowed for the creation of slopes for the lateral line. Figure 1 illustrates the perspective layout of the testing bench.

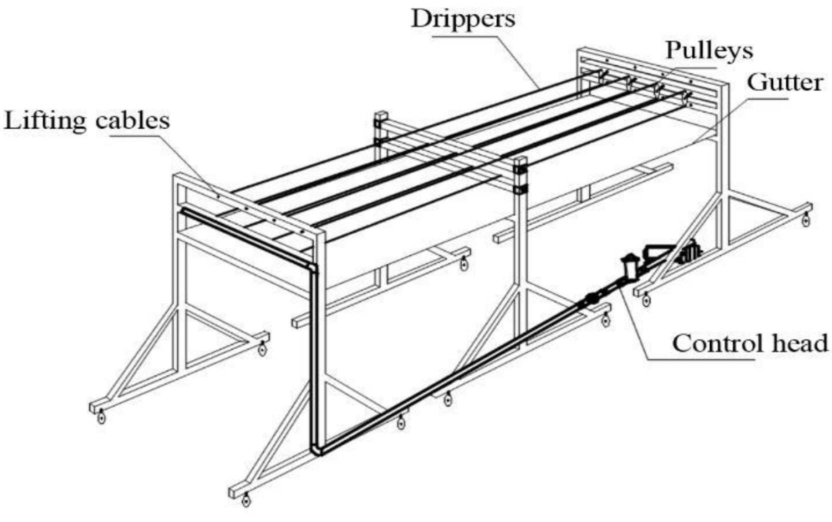

Figure 1. Perspective layout of the testing bench for drip irrigation system.
Source: Szekut *et al.* (2018).

In this study, we used Pantanal model drip emitters from the brand Brasil Drip™. These non-self-compensating emitters feature labyrinth-type emitters with turbulent flow and are designed for both surface and subsurface irrigation. The emitters were spaced 0.20 m apart and attached to the pipe wall with a mechanism to prevent the suction of debris. The emitter's wall has a thickness of 0.15 mm, a maximum working pressure of 0.78 bar, and a flow rate of 1.67 L h^{-1}, as specified by the manufacturer. The emitter discharge equation is proportional to the flow rate, with a coefficient (K) of 0.182 and a discharge exponent (x) of 0.52.

The drip irrigation flow rate was measured following the method by Keller and Karmelli (1975). The method consists of measuring flow rates at four emitters per lateral line in four lines, as follows: the first emitter, the emitters located at 1/3 (17th emitter) and 2/3 (34th emitter) of the line length, and the last emitter (50th). The position of these emitters varies according to the total number of emitters present along the predetermined length of the lateral line in the design.

The data were gathered by collectors positioned near the outlets determined above (Keller and Karmelli, 1975), with the volume collected from emitters for 3 minutes as recommended by NBR 9261 (ABNT, 2006). We performed twenty-five trials for each treatment [slopes of 2% (uphill), 0% (level), and 2% (downhill)] (ASABE, 1996). The number of samples falls within the ideal limit for quality control tests stated by Montgomery (2016). We performed a backwash of the system after the end of each trial by inclination.

We also used a 120 mesh IRRITEC™ disc filter, FLD model, and two digital INSTRUTEMP™ pressure gauges, Model 8215 (100 mwc), as other equipment in the drip irrigation system.

In the tests, urea 45% N, a CO(NH2)2 soluble nitrogen fertilizer, was used. They were solubilized for the tests (200, 400 and 600g) of N for 100 liters of water. The dilution of the fertilizer in the tank was performed manually before the beginning of the tests Borssoi *et al.* (2012), Lopes *et al.* (2021a).

2.3. Experimental design

The experiment was conducted in randomized block design and 4x3 factorial scheme, consisting of 4 blocks (fertilizer concentrations) at three slope angles: uphill (2%), level (0%), and downhill (2%) (ASABE, 1996), with plots divided into two factors. The main factor was the type of water and represented the four plots: clean water (from an artesian well) and water with nitrogen fertilizer, in this case, urea (44% N) at three concentrations (2 g L^{-1}, 4 g L^{-1}, and 6 g L^{-1}). These concentrations were used since Borges and Costa (2009) recommended not exceeding 7 g L^{-1} urea in drip irrigation systems. The second factor was slope degree and represented the subplots: uphill, level, and downhill. A total of 12 treatments were then applied, with 25 replicates, thus resulting in 300 trials.

2.4. Flow rate, pH, electrical conductivity, and uniformity coefficients

Emitters were measured for flow rate by the gravimetric method. It consists of weighing a certain water volume taken within a certain time to reach greater precision in volume determination. As recommended by NBR 9261 (ABNT, 2006), emitter flow was calculated as in Equation 1:

$$q = \frac{v}{1000t} 60 \quad (1)$$

Where in:

q – drip emitter flow, L h^{-1};

V – sampled solution volume, mL;

t – sampling time, min.

The hydrogen potential (measured with a Tec-3MP pH meter) and electrical conductivity (measured with a Tec-4MP conductivity meter) of both clean water and water with fertilizer were determined in the laboratory. One sample per treatment per assay was collected to optimize analysis time for the variables.

The Christiansen Uniformity Coefficient (CUC), proposed by Christiansen (1942), and the Distribution Uniformity Coefficient (DUC) were calculated using Equations 2 and 3, respectively, and determined based on the flow rate from the 16 drippers per assay:

$$CUC = 100\left(1 - \frac{\sum_{i-1}^{n}|x_i - x_{med}|}{n.x_{med}}\right) \quad (2)$$

Where in: CUC: Christiansen Uniformity Coefficient (%); xi: individual values of water volume contained in collectors (mm); X_{ave}: overall average of collected water volume (mm); and n: number of collectors in the test area.

$$DUC = 100\left(\frac{X_{25}}{X_{med}}\right) \quad (3)$$

Where in: DUC: Distribution Uniformity Coefficient (in %); X_{25}: average of the lowest quartile of water volumes in collectors (mm); and X_{ave}: overall average of the collected water volume (mm).

Frizzone *et al.* (2012) proposed classifying CUC and DUC as a function of the values obtained to identify the efficiency of the irrigation system, as shown in Table 1.

Table 1. Classification of the coefficients CUC and DUC for drip irrigation systems.

Class	CUC (%)	DUC (%)
Excellent	> 90	> 90
Good	90 – 80	90 – 80
Regular	80 – 70	80 – 70
Bad	70 – 60	70 – 60
Unacceptable	<60	<60

Source: Frizzone *et al.* (2012).

In each test, the pressure was measured at 8 points, 4 times at the beginning of the system and 4 times in the end; the 1st at the beginning of irrigation, the 2nd at 1 minute, the 3rd at 2 minutes, and the 4th at 3 minutes. With the pressure data, the pressure uniformity coefficient (PUC), described in Equation 4, was calculated.

$$PUC(\%) = (1 - CV) * 100 \quad (4)$$

Where in:

PUC – Pressure Uniformity Coefficient (%)

CV – Coefficient of variation (dimensionless)

Pressure uniformity coefficients (PUC) were classified according to Table 2.

Table 2. Pressure uniformity coefficient (PUC).

Class	PUC (%)
Excellent	> 94
Good	86 – 94
Regular	80 – 86
Bad	70 – 80
Unacceptable	<70

Source: Frizzone *et al.* (2012).

2.5. Control chart and process capability index

Shewhart Control Charts were used to monitor DUC focusing on individual means. To create and interpret these charts, we calculated the Upper Control Limit (UCL) and Lower Control Limit (LCL) using Equations 5 and 6.

$$UCL = \underline{x} + 3\frac{R}{d_2} \tag{5}$$

$$LCL = \underline{x} - 3\frac{R}{d_2} \tag{6}$$

Where in: $\underline{x}$: process average; $\underline{R}$: moving range of observations; and d2: predetermined value according to the number of repetitions.

Process capability was assessed using the method proposed by Montgomery (2009), which involves calculating the process capability index (PCI) when the process is stable, i.e., under statistical control and with the variable having a distribution close to normal. When a process is stable, Cpk (unilateral processes) is applied. Equation 7 expresses the calculation of PCI.

$$PCI = \frac{\underline{x} - LIC}{3\sigma} \tag{7}$$

When uniformity values are available, a Cp value of 1.25 or greater is considered capable or adequate for the process classification because the drip emitter being used has unilateral specifications (Montgomery, 2009). In this research, the focus of control was on the lower unilateral values, specifically 80% and 86%, and 90% and 94%, which were classified as good or excellent uniformity, respectively. The Cpi value was used as a reference.

Clean water and fertilizer solutions for irrigation were analyzed in the Laboratory of Environmental Sanitation of Western Paraná State University. The physical-chemical analysis followed the APHA *et al.* (2012) methods. The data were subjected to the Anderson-Darling and Kruskal-Wallis normality tests at 5% significance. Then, multiple comparisons were made using the Mann-Whitney test at 5% significance. All statistical analyses and chart building were conducted using MINITAB 16 software.

3. RESULTS AND DISCUSSION

The results of the physical-chemical analysis for water with three concentrations of urea are presented in Table 3. According to Nakayama and Bucks (1986), Capra and Scicolone (1998), all the physical-chemical parameters analyzed present a low risk of clogging.

The pH values of clean water and water with fertilizer were on average above the predicted limits. According to Nakayama and Bucks (1986), pH values above 7.2 favor the precipitation of elements, such as calcium and magnesium, in filters, pipes, and emitters, contributing to drip emitter clogging. Thus, the increase in urea concentration by 6 g L^{-1} influenced pH (7.75). The pH results found by (Szekut *et al.* 2018) when evaluating water with nitrogen fertilizer at a concentration of 3 g L^{-1} were higher, which, on average, obtained 8.50 for this parameter.

On the other hand, electrical conductivity (EC) remained within the values indicated by Nakayama and Bucks (1986), who recommend not using water with EC above 3.0 dS m¹ for irrigation.

Table 3. Physical-chemical parameters for clean water and water with different concentrations of urea.

Parameter	Clean water	2 g L^{-1} urea	4 g L^{-1} urea	6 g L^{-1} urea
Total iron (mg L^{-1})	0.02*	0*	0*	0*
Manganese (mg L^{-1})	0.06*	0.02**	0.02**	0.04**
Suspended solids (mg L^{-1})	40*	236	60	292
Electrical conductivity (dS m^{-1})	0.058	0.070	0.072	0.076
pH	7.41*	7.51*	7.43*	7.75*
Calcium (mg L^{-1})	2.95*	0	0	0
Magnesium (mg L^{-1})	0.77*	0.78*	0.79*	0.80*
Total nitrogen (mg L^{-1})	0.06	8.77	18.19	25.52

Total iron (mg L^{-1}): Low (< 0.2 mg L^{-1}); Medium (0.2-1.5 mg L^{-1}); High (> 1.5 mg L^{-1}).
Clogging risk level: *Low, ** Moderate, and ***High.
Source: Nakayama and Bucks (1986).

To ensure an accurate sample description and subsequent analysis, normality tests using the Anderson-Darling method were conducted on the CUC (%) and DUC (%) parameters for all concentrations applied at the lateral line slope. While one of the parameters showed a normal distribution in the dataset evaluated in Table 4, some groups had p-values below 0.05, prompting the use of Kruskal-Wallis for nonparametric data analysis. The results from Table 4 indicated a statistical difference between urea concentrations and slope angles, with changes in urea concentration affecting the distribution uniformity of the nitrogen solution in the fertigation system. Therefore, the Mann-Whitney test was used for nonparametric data comparison at a 5% level of significance, with the results presented in Table 5.

Using the multiple comparison test, it can be seen that the application of 2 g L^{-1} differed statistically for all slope levels tested (Table 4). Such behavior can be observed in (Figure 2), the smaller amplitude of the uniformity variation between the slope levels stands out when compared to the control treatment, and the concentrations 4 g and 6 g L^{-1}. Uphill and downhill systems stand out for the 4 g L^{-1} concentration, where greater variability in fertilizer distribution is found, with a median below 80% for the uphill, considered bad for irrigation according to Frizzone *et al.* (2012), followed by the downhill.

On the other hand, the downhill system for application of 6 g L^{-1} showed less amplitude for uphill and downhill in relation to all concentrations. While the control treatment (water) performed >90% at all slope levels for CUD. Therefore, according to the descriptive statistics of the data, the treatments of clean water (at all levels of slope), 2 g L^{-1} and 6 g L^{-1} are recommended on downhill because they present CUD >90%.

Table 4. Descriptive analysis of DUC and CUC for different urea concentrations applied on three slopes of the lateral line.

Variable			Data normality (p-value)	Min	1 Quartile	Median	3 Quartile	Max	Kruskal-Wallis (p-value)
DUC	Level system	0	0.009	93.39	95.12	96.31	96.78	97.47	<0.005
		2	0.008	78.95	84.73	86.56	87.59	96.85	
		4	0.756	79.89	83.21	84.49	85.80	87.40	
		6	0.089	63.11	76.98	80.13	85.28	90.83	
CUC	Level system	0	0.007	93.39	95.11	96.27	96.80	97.47	<0.005
		2	0.007	88.41	91.97	93.15	93.51	95.11	
		4	0.560	89.76	91.57	92.20	92.95	93.63	
		6	<0.005	64.65	88.29	89.75	92.16	95.07	
DUC	Uphill system	0	<0.005	95.51	96.66	97.26	97.44	97.70	<0.005
		2	<0.005	71.88	86.57	88.38	90.38	93.04	
		4	0.171	86.70	89.16	89.91	92.43	93.73	
		6	0.358	91.80	93.51	94.18	95.07	96.54	
CUC	Uphill system	0	<0.005	92.97	93.99	95.50	95.93	96.32	<0.005
		2	<0.005	85.94	92.86	93.94	94.72	95.66	
		4	0.075	86.70	89.16	89.91	92.43	93.73	
		6	0.879	91.80	93.51	94.18	95.07	96.54	
DUC	Downhill system	0	<0.005	83.59	92.46	93.47	93.78	96.13	<0.005
		2	0.020	83.42	89.09	91.12	92.04	93.11	
		4	0.171	74.33	80.16	81.58	86.12	87.93	
		6	0.011	86.94	90.17	90.70	91.63	92.74	
CUC	Downhill system	0	<0.005	91.70	95.37	96.04	96.26	97.17	<0.005
		2	0.074	91.42	94.09	95.22	95.69	96.44	
		4	0.075	86.70	89.15	89.91	92.43	93.73	
		6	<0.005	93.16	94.97	95.26	95.49	96.19	

Table 5. Multiple comparison of data for level, uphill and downhill.

Comparison			$0\ g\ L^{-1}$	$2\ g\ L^{-1}$	$4\ g\ L^{-1}$	$6\ g\ L^{-1}$
			P – Valor			
UD (%)	Level	Uphill	0.0003	0.0074	0.0040	0.0000
	Level	Downhill	0.3125	0.0000	0.0416	0.0000
	Uphill	Downhill	0.0000	0.0055	0.2443	0.7415

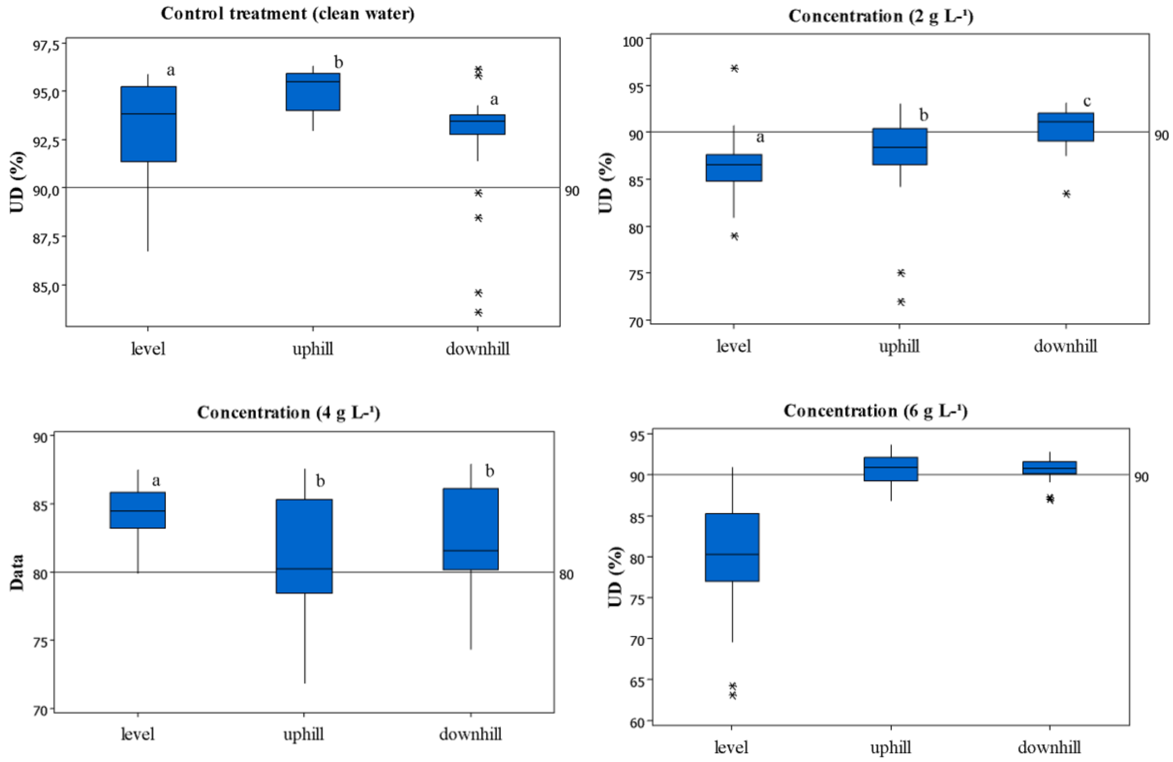

Figure 2. Box-plot for UD (%) in concentrations 0 gL^{-1}, 2 $g L^{-1}$, 4 $g L^{-1}$ e 6 $g L^{-1}$.

To ensure statistical control, Shewhart Charts were used to monitor the variability in distribution uniformity of CUC (%) and DUC (%) during 25 trials with different fertilizer concentrations and slopes. According to Montgomery (2009), data must meet normality specifications and not show autocorrelation for the application of Shewhart Charts and Process Capability Index. As presented in Table 4, only treatments with p-values > 0.05 were considered in the analysis, according to the Anderson-Darling test.

Considering autocorrelation (Table 6), only the 2 $g L^{-1}$ concentration for DUC in the downhill slope was not analyzed. The Shewhart Control Charts and Process Capability Index were determined for the remaining treatments, following Montgomery (2009).

Table 6. Data normality and autocorrelation.

Variável			Normality (p-value)	Autocorrelation
DUC	LEVEL	4	0,756	No
		6	0,089	No
CUC	LEVEL	4	0,560	No
DUC	UPHILL	4	0,171	No
		6	0,358	No
CUC	UPHILL	4	0,075	No
		6	0,879	No
DUC	DOWNHILL	4	0,075	No
CUC	DOWNHILL	2	0,074	Yes
		4	0,075	No

Figure 3 displays individual Shewhart Control Charts for CUC (%) uniformity indices, focusing solely on the system with a 4 g L^{-1} fertilizer concentration. The chart illustrates the sample points within the control limits, indicating that the process is statistically under control. Points beyond the limits would reject this hypothesis, following Montgomery (2016).

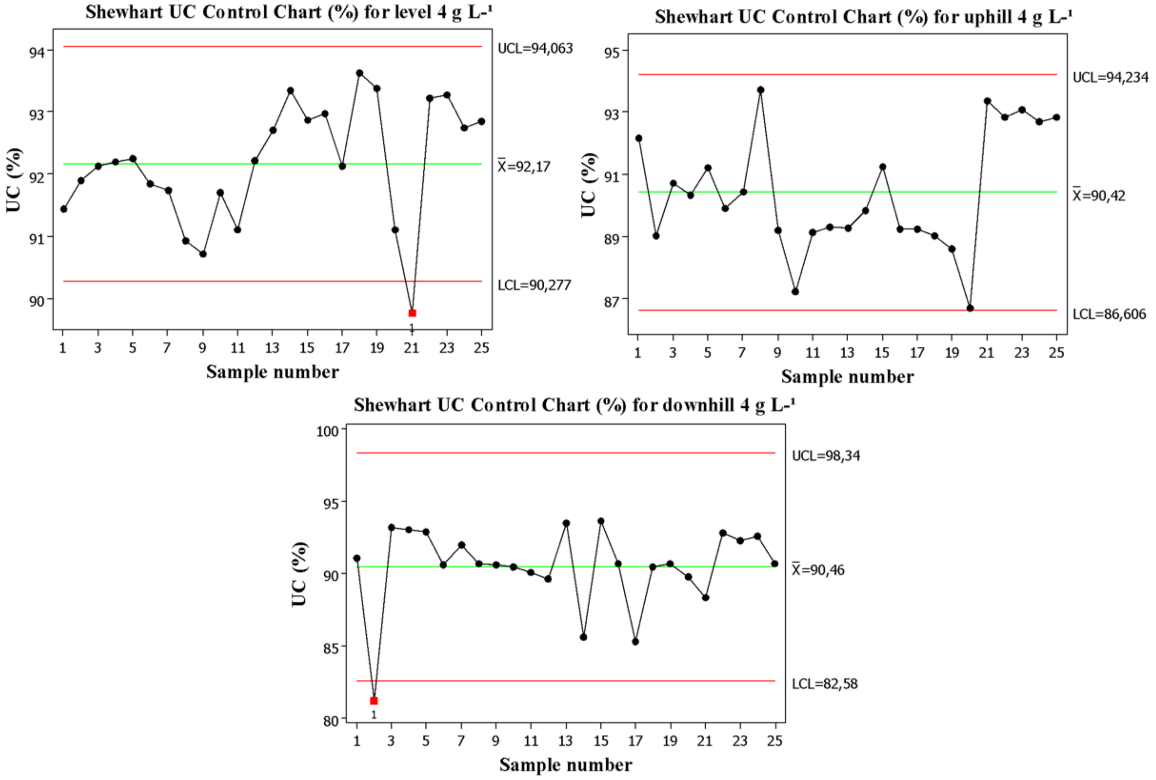

Figure 3. Shewhart Control Chart for CUD (%) in level, uphill, and downhill for 4 g L^{-1}.

Analyzing the Shewhart Chart for CUC (%), at a concentration level of 4 g L^{-1} (Figure 3), there is a point outside the control limits, non-randomness around the average, as well as increasing trend lines between evaluations (11 to 15) and descending from (5 to 9), characteristics that configure a system outside the control limits. However, although the points do not comply with quality control characteristics, all points showed high uniformity rates >90%.

Similar behavior is observed for the uphill system with the same concentration, although the points are within the control limits, it presents non-randomness around the mean, in addition to a greater range of data between 86% and 93%.

Compared to the level system, its performance was not satisfactory, since, among tests (9 to 19), with the exception of Test 15, there is a greater drop in uniformity (<90%). Hermes *et al.* (2013; 2014; 2015) also observed events below the lower control limit when discussing drip irrigation through the Shewhart Chart.

Still, for the same concentration, the downhill system showed better behavior when compared to the uphill system, as it presents less variability for the data set.

Lopes *et al.* (2021a) obtained satisfactory results for flow uniformity when applying a concentration of 3 g L^{-1} of MPK.

Consecutive points above or below the mean line were observed for uphill and downhill slopes (Figure 4), indicating a trend in the data. According to Montgomery (2009), when seven values exhibit such behavior, there is a lack of statistical control. Only the downhill system remained within the control limits, but a decreasing sequence was identified from 8 to 12. Szekut *et al.* (2018) reported better working conditions for irrigation lines positioned on downhill slopes compared to systems on the level and uphill slopes.

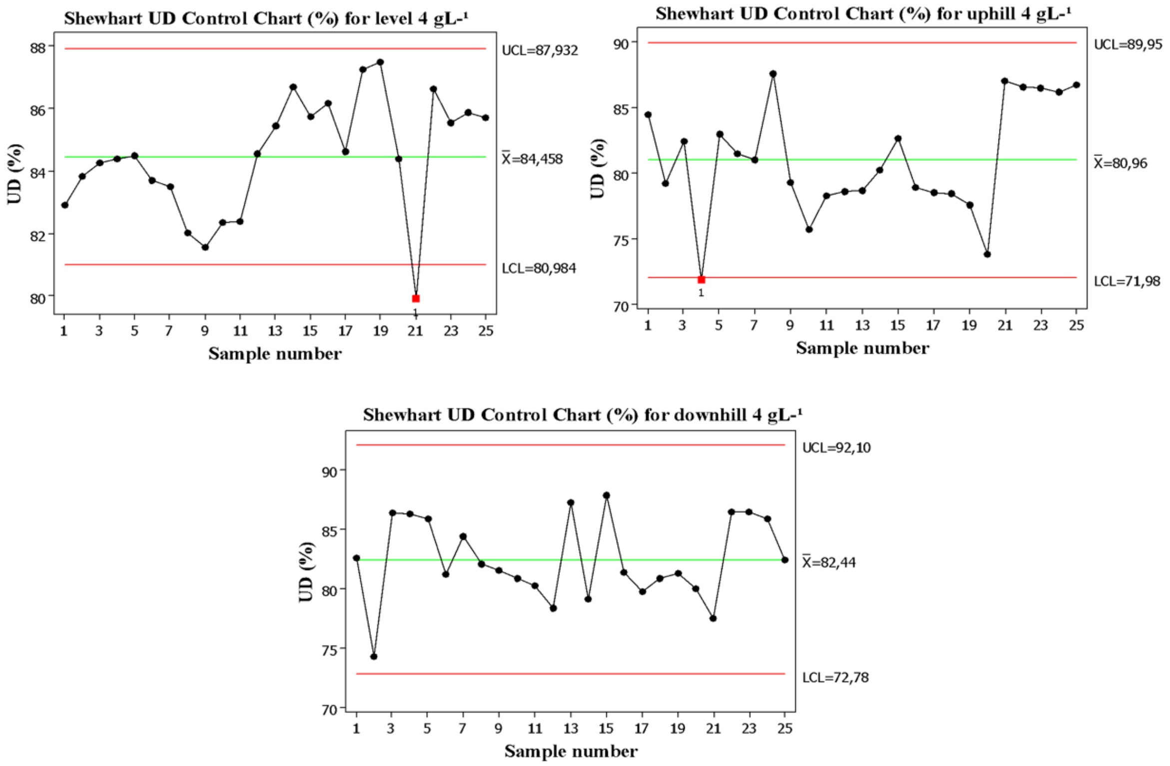

Figure 4. Shewhart Control Chart for CUD (%) of systems on level, uphill, and downhill with water with 4 g L^{-1} urea.

Regarding uniformity values, all slope angles presented values <90% when compared to CUC results (Figure 3). Ribeiro *et al.* (2012) also obtained lower DUC values than CUC, attributing this to inherent variables of the equations used to calculate DUC, which consider 25% of the area that received the lowest flows, which is not a rule for datasets (Zhang *et al.*, 2013). The worst performance was verified for the system on the downhill slope, with values below 75% for DUC, which can be classified as regular by Frizzone *et al.* (2012).

According to Frizzone *et al.* (2012), a minimum irrigation uniformity below the 70% line is considered poor. In (Figure 5), Points 9, 17, and 23 fall below this line for DUC (%), indicating inadequate spacing. Furthermore, increasing the urea concentration to 6 g L^{-1} affected uniformity for the level system, as shown in the Shewhart Control Chart (Figure 5), with DUC values above 70%.

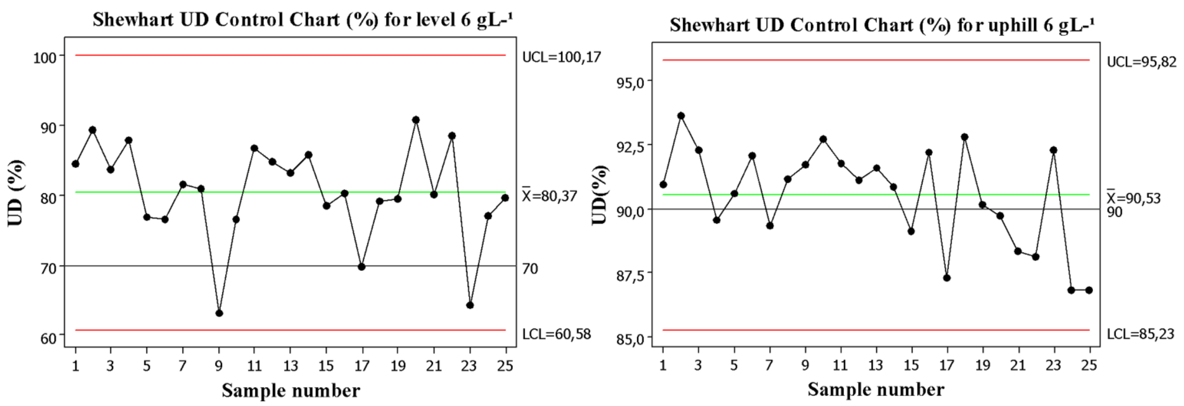

Figure 5. Shewhart Control Chart for CUD (%) of the level system with water with 6 g L^{-1} urea.

Regarding the uphill system (Figure 6), the uniformity achieved minimum values (>90%). According to Frizzone *et al.* (2012), these results indicate good uniformity for the uphill system. The points remained random around the mean line for both CUC (%) and DUC (%) graphs, even though values below the average line were observed in assays 17 to 25. This is not considered a trend according to Montgomery (2009). A similar result was obtained by Andrade (2007), who observed points above the midline when applying the Shewhart Control Charts for micro sprinkler spacing. Szekut *et al.* (2018) report that lines positioned on downhill indicate better working conditions compared to a level and uphill system for fertigation.

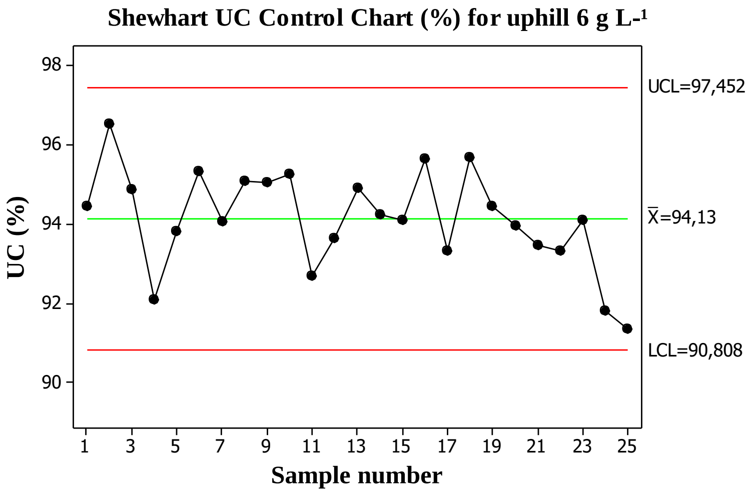

Figure 6. Figura 6. Shewhart Control Chart for UC of the uphill system with water with 6 g L^{-1} urea.

Table 7 shows the flow and pressure uniformity results. The highest uniformity values were observed in the level system (99.18%) followed by the uphill system (99.04%) at control conditions (0 g L^{-1}). Despite uniformity being excellent on all slopes, small pressure variations can occur due to head loss and level variation (Lima *et al.*, 2003).

Increasing urea concentration reduced CUp in all treatments except for downhill with a concentration of 6 g L^{-1} (99.04%). The greatest pressure difference was observed in the level system with 2 g L^{-1} (95.86%) and the downhill system (96.97%). Similar results were reported by Lopes *et al.* (2021b).

Table 7. Flow and pressure uniformity.

Treatment	Urea concentration	CUp
Level	0 g L^{-1}	99.18
Uphill		99.04
Downhill		98.64
Level	2 g L^{-1}	95.86
Uphill		98.66
Downhill		96.97
Level	4 g L^{-1}	98.54
Uphill		98.93
Downhill		96.97
Level	6 g L^{-1}	98.92
Uphill		98.32
Downhill		99.04

The process capability index (PCI) was calculated using only the lower control limit (LCL), with 80% and 90% adopted as good and excellent, respectively, following Frizzone *et al.* (2012) for CUC and DUC classification (Table 8). According to Montgomery (2009), processes with values equal to or above 1.25 can remain under control for unilateral specifications. The table shows that for CUC, the system on level ground was considered adequate for LCL = 90%, but the means were not within pre-established limits for LCL = 80%. No evaluation was performed for DUC, as the values did not show normality or correlation, as required by Montgomery (2009). Previous studies have reported higher PCI values for irrigation systems, with Hermes *et al.* (2015) obtaining a PCI of 2.04 for CUC above 80%, Juchen *et al.* (2013) reporting a PCI of 2.87 for drip irrigation with dairy and slaughterhouse effluents, and Justo *et al.* (2010), concluding that PCI is a powerful tool for classifying irrigation system uniformity.

Table 8. Process capability index of drip irrigation system with different urea concentrations.

Treatment	Concentration	CUC	DUC	CUC	DUC
		PCI LCL = 90%	PCI LCL = 80%	PCI LCL = 90%	PCI LCL = 80%
Level	2 g L^{-1}	2.86	*	*	*
Level	4 g L^{-1}	1.15	*	*	1.28
Uphill		0.11	2.73	*	0.11
Downhill		0.06	1.33	*	0.11
Level	6 g L^{-1}	*	0.50	*	*
Uphill		1.24	4.25	0.10	1.99

*Process capability index could not be calculated, and averages were not within the pre-established limits.

Table 8 shows the results for the process capability index (PCI) using the lower control limit of 80% for good and 90% for excellent uniformity, based on the criterion of Frizzone *et al.* (2012) for CUC and DUC classification. According to Montgomery (2009), for LCL = 80%, both uphill and downhill systems were suitable for CUC; however, for DUC, only the level system is within specifications with LCL = 80%. Therefore, the best performance was observed for the uphill system, whereas no system was capable of LCL = 90%, which is the minimum value of irrigation uniformity classified as excellent according to Frizzone *et al.* (2012).

For the concentration of 6 g L^{-1}, only the lower control limit was considered, with a value of 80% considered good and 90% considered excellent for CUC and DUC, according to Frizzone *et al.* (2012). At LCL = 80%, only the uphill system showed an average within the established limits and proved capable with a value of 4.25 for CUC. When analyzing the DUC parameter at LCL = 80%, the uphill system was adequate, while with LCL = 90%; none of the slopes were found to be adequate.

4. CONCLUSIONS

The Shewhart Control Chart was effective in identifying change in the behavior of irrigation uniformity for different concentrations of nitrogen fertilizer in the slope of the lateral line.

The addition of urea concentration by 4 g L^{-1} showed greater variability in the amplitude of fertilizer distribution uniformity.

The application of lower concentrations showed less variability in uniformity.

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