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Statistical process control in pulsed drip irrigation systems

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ABSTRACT

Pulse drip application is a management option to prevent clogging and improve water-use efficiency. The measurement of distribution uniformity is opportune for pulse irrigation projects to ensure efficiency since the shorter the pulse time, the more negative influence the transition periods have. The objective of the present work was to monitor the quality of a drip irrigation system with different emitter models and different pulse times. The experiment was conducted under laboratory bench conditions, and 25 tests were performed for each pulse application (2, 3, 6 and 12 minutes) and emitter model (non-compensated and auto-compensated). Uniformity was determined using Christiansen's uniformity coefficient (CUC) and distribution uniformity coefficient (DUC) and monitored by Shewhart control charts and exponentially weighted moving average (EWMA). The decrease in pulse time caused a decrease in flow rate and uniformity only in drip irrigation systems with non auto-compensated emitters. However, this decrease is subtle, to the point that uniformity presented an excellent performance for all pulses tested. The use of the Shewhart and EWMA control charts were effective in monitoring the uniformity of the pulsed drip irrigation system. The Shewhart control chart was more robust in identifying isolated non-compensated uniformities, while the EWMA control chart was more sensitive in identifying unstable propensity. In the treatments with the non-compensated emitter, the statistical process control was able to identify that shorter pulse times resulted in greater application instability. As for the auto-compensated emitters, the statistical process control highlighted the concern with application uniformity after maintenance interference.

Keywords: anti-drain emitter, high-frequency irrigation, irrigation interval, statistical quality control.

Controle estatístico de processo em sistemas de irrigação por gotejamento pulsante

RESUMO

A aplicação pulsante é uma opção de manejo para prevenir entupimento e melhorar a eficiência do uso da água na irrigação por gotejamento. A determinação da uniformidade de aplicação é oportuna para projetos de irrigação pulsante para garantir a eficiência uma vez que quanto menor o tempo de pulso maior influência negativa dos períodos de transição. O presente trabalho teve o objetivo de monitorar a qualidade de um sistema de irrigação por gotejamento com diferentes modelos de emissores e em diferentes tempos de pulso. O experimento foi conduzido em condições de laboratório, em bancada, e 25 ensaios foram realizados para cada aplicação pulsante (2, 3, 6 e 12 minutos) e modelo de emissor (normal e autocompensante). A uniformidade foi determinada utilizando-se o coeficiente de uniformidade de Christiansen (CUC) e o coeficiente de uniformidade de distribuição (CUD) e monitorada pelos gráficos de controle de Shewhart e média móvel exponencialmente ponderada (EWMA). A diminuição do tempo de pulso causou a diminuição na vazão e na uniformidade apenas nos sistemas de irrigação por gotejamento com emissores sem sistema autocompensante. Entretanto esta diminuição é sutil, ao ponto de a uniformidade apresentar um excelente desempenho para todos os pulsos testados. A utilização dos gráficos de controle de Shewhart e EWMA foram eficazes no monitoramento da uniformidade do sistema de irrigação por gotejamento pulsante. O gráfico de controle de Shewhart foi mais robusto identificando uniformidades isoladas fora do padrão, enquanto o gráfico de controle EWMA foi mais sensível, ao identificar tendências de instabilidade. Nos tratamentos com o gotejador normal o controle estatístico de processo foi capaz de identificar que em tempos de pulsos menores maior a instabilidade da aplicação. Já com os emissores autocompensantes o controle estatístico de processo realçou a preocupação com a uniformidade de aplicação após interferências de manutenção.

Palavras-chave: controle estatístico de qualidade, emissor antidrenante, intervalo de irrigação, irrigação em alta frequência.

1. INTRODUCTION

Application uniformity in drip irrigation can be compromised when emitters become clogged by organic or inorganic sedimentation from irrigation water, suction of dirt under vacuum conditions inside the hose, root intrusion and mineral accumulation in the emitter outlet channel (Abdelraouf *et al.*, 2012).

A conventional way to avoid clogging the drippers is to use chemical acids in the cleaning process of the lateral lines. According to Pitts *et al.* (1990), acid can be used to lower the pH of water and reduce the potential for chemical precipitation. Sulfuric (H_2SO_4), hydrochloric (HCl), phosphoric (H_3PO_4), and nitric (HNO_3) acids are used for this purpose.

However, the use of acids to prevent irrigation clogging is not always possible, such as in organic farming. Thus, an effective means of avoiding clogging in drip irrigation is to use emitters with larger orifices operating in pulses rather than continuously, in order to maintain an ideal application rate (Al-Amoud and Saeed, 1988). A large cross section gives more room for particles to pass through without accumulating and causing clogging.

Pulsed irrigation refers to the practice of irrigating for a short period, then waiting for another short period, and repeating this cycle until all irrigation water has been applied (Eric *et al.*, 2004). Pulse application also raises the turbulence created within the lateral line, causing suspended dirt particles to move through the emitter, decreasing the occurrence of clogging caused by sedimentation (Abdelraouf *et al.*, 2012).

Other than being a technique for preventing clogging in drip irrigation, pulsed application is capable of achieving other benefits. For example, the possibility of using water with higher electrical conductivity Cruz *et al.* (2021), Pasternak and Demalach (1995), Silva *et al.* (2022), Arriero *et al.* (2020), Almeida *et al.* (2018), improved water use efficiency Almeida *et al.* (2015), Abdelraouf (2019), Visconti *et al.* (2014), Arriero *et al.* (2020), reduced water percolation under the root zone Elmaloglou and Diamantopoulos (2009), Hicklenton and Cairns (1996), Visconti *et al.* (2014), reduced nitrate leaching (Cote *et al.*, 2003), Watts and Martin (1981), and greater nutrient accumulation within the crop (Menezes *et al.*, 2020). It is worth mentioning, that the differences in the distribution of water in the soil are visible only in the first moments after pulsed application, that is, the distribution of moisture is similar inside the wet bulb compared to continuous irrigation after a few hours Maller *et al.* (2019), Karimi and Appels (2021).

Having seen the potentialities of pulsed drip irrigation, it is important to emphasize the precautions to be taken. It should be noted that all these studies assume stable pressures throughout the irrigation pulse, which may not be entirely true for short irrigation pulses. In short irrigation pulses the influence of transition periods (pipe filling and emptying phases) is accentuated, as these have an invariable duration, independent of the duration of the pulse (Lozano *et al.*, 2014). Therefore, it is possible to find a high irrigation distribution uniformity when evaluating the installation under steady pressure, and a very low uniformity when evaluating the complete pulse of each irrigation (Goyal, 2017).

Studies have already been done considering the transition time in pulsed application. In the hypothesis that uniformity decreases with decreasing pulse time, the authors care to highlight what is the minimum time for uniformity to be greater than 90%. Lozano *et al.* (2014) for example, when evaluating different models of emitters without anti-entrainment systems, recommended minimum application times of 13 to 20 minutes. Beaza *et al.* (2014) and Lozano *et al.* (2020), in turn, found that under tilt and under pulses, which ranged from 5 to 20 minutes, no application achieved 90% uniformity.

To reach these conclusions the authors monitor the uniformity coefficients and reach conclusions using statistical techniques for comparing means and mathematical models that describe the behavior of pulse application in a generic way. However, these studies do not present how the behavior of uniformity is in a sequential perspective, that is, there is no consensus on the stability of a set of applications under a given pulse time, or if there is the presence of patterns from one application to another, and even if the variability is caused by controllable factors.

From this perspective, the hypothesis of this research is that statistical process control (SPC) tools can map the stability, trends, and causes involved in pulsed drip irrigation. According to Justi *et al.* (2010), statistical process control is adapted to the evaluation of irrigation systems, since it is composed of tools that seek to maintain variables within limits or standards pre-established by technical standards, seeking that a given process behaves adequately. Control charts, for example, have the ability to monitor the process and signal to analysts the need to investigate and adjust it, depending on the size of the deviations found (Walter, 2013).

Several authors have used the SPC tools in a drip irrigation system. Hermes *et al.* (2013; 2014; 2015), Klein *et al.* (2015), and Juchen *et al.* (2013), are further examples of works that have used the tools and reinforced the potential of the ability to monitor irrigation control within satisfactory limits, as well as contributing to the monitoring of the irrigation process.

The Shewhart control charts and exponentially weighted moving average (EWMA) control charts are among the best known and most widely used SPC tools (Frigo *et al.*, 2016). The success of the Shewhart control chart is due to its simplicity, in which the ease of the decision rule is based only on examining the last observed point. However, this is also a major disadvantage, as any information provided by the previous sequence of points is disregarded, which makes the Shewhart control chart relatively insensitive to small changes in the process (Walter, 2013).

In this sense, since small variations in a process cannot be perceived by the Shewhart control chart; it is advisable to use the EWMA control chart. This method is more sensitive in detecting small deviations from the process mean. Therefore, it offers high speed and credibility in identifying small incompatibilities in the process.

Thus, the objective of this work was to evaluate the distribution uniformity coefficient

(DUC) and Christiansen's uniformity coefficient (CUC) through the evaluation of the Shewhart and EWMA control charts, in order to diagnose possible characteristic behaviors in pulsed drip irrigation.

2. MATERIAL AND METHODS

2.1. Site characterization

The irrigation tests took place in the city of Maringá – PR (latitude 23°25′38″ South, longitude 51°56′15″ West, average altitude of 551 meters), in a laboratory, with a controlled environment, without the influence of external factors such as solar radiation and wind.

2.2. Test equipment and procedures

For the experiment, a drip irrigation bench of 7 meters long and 1.2 m wide was assembled. On this study platform were installed gutters for the return of water to a 2000 liter tank.

For the trials, we used 2 IRRITEC drippers, standard iDrop model, flow rate of $4Lh^{-1}$, and model iDrop PC – auto-compensated emitter, 6 Lh^{-1}. This model was chosen due to market availability. Figure 1 illustrates the layout of the drip irrigation system.

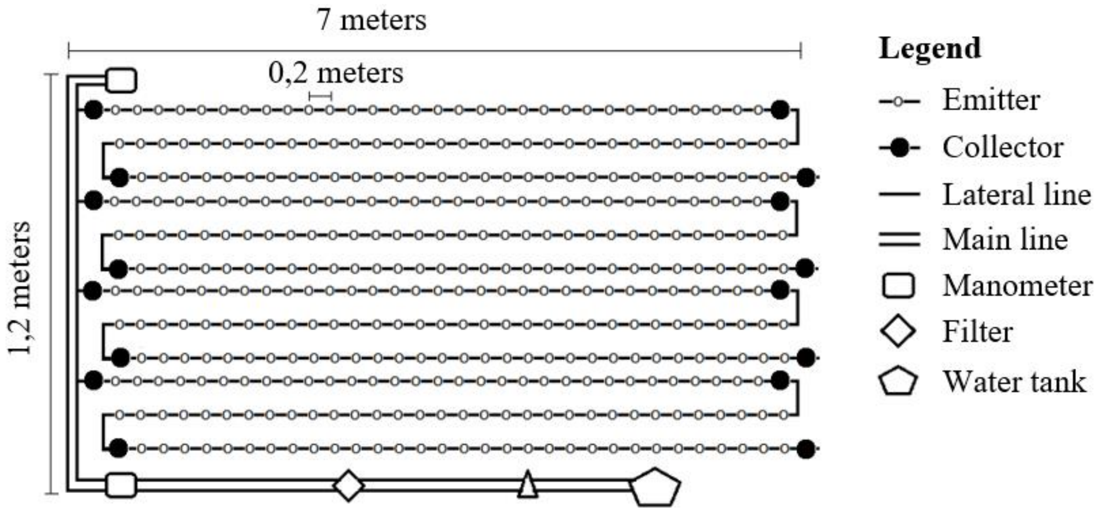


Figure 1. Sketch of the bench drip irrigation system.
Source: Created by the authors.

The remainder of the irrigation system was project based on the manufacture catalogue recommendations with a 1" 120-mesh stainless steel screen filter, 32mm polyethylene branch pipes, and 16mm diameter lateral lines. A ¾ HP motor pump was used, which met the needs of the irrigation system set up with an auto-compensated emitter, which required a flow rate in the main pipe of $2.4m^3/h$ and a pressure at the inlet of the lateral line of 18.28 m.c.a.

The length of the lateral line projected was 20 meters, i.e., below but close to the 27 meters recommended by the non auto-compensated emitter catalog, with a flow rate of 4 Lh^{-1}, in order to obtain 95% uniformity.

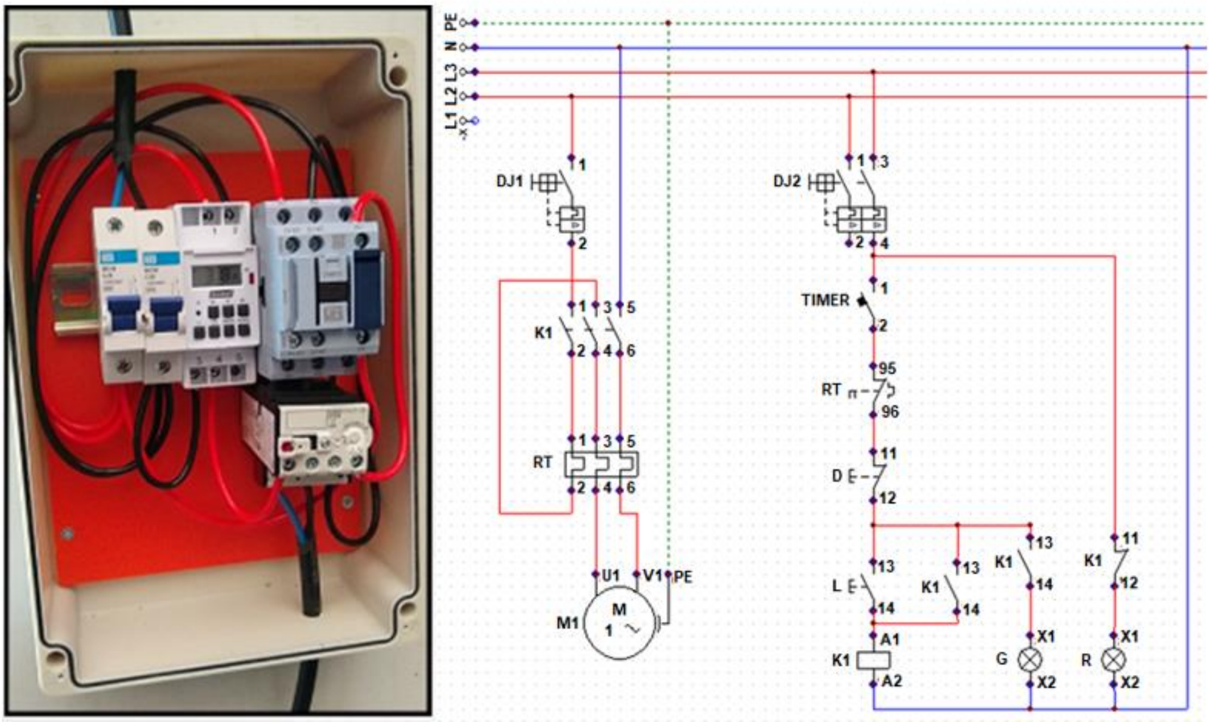
Furthermore, the entire system was mounted without any unevenness and a spacing of 0.2 meters between emitters was maintained. The pressure was measured at the beginning and end of the main pipe with two Bourbon glycerin pressure gauges from 0 to 6 bar. To collect the water from the drippers, plastic collectors were used, and later weighed on a 1g precision digital scale to measure the flow rate. The water used in the tests came from the Paraná water supply company (SANEPAR, 2020). Table 1 shows the records on the characteristics of the water distributed by Sanepar, in the months of June, July and August, when the collections were made.

Table 1. Water quality analysis.

	June Average	July Average	August Average	Minimum / Maximum Allowed	Administrative Order N5/17 MS:199
Apparent Color	2.47	2.50	2.50	15.00	uH-Um-Cor
Turbidity	0.23	0.20	0.23	5.0	NTU
Chlorine residuals	0.94	0.91	0.88	0.2 to 5.0	mg//L
Fluoride	0.77	0.80	0.79	0.6 to 1.1	mg/L
Total Coliforms	0	0	0	(0) Absent	-

Source: SANEPAR (2020).

To activate the pump, a control board was assembled in charge of making the direct start of the motor, as well as controlling the running time in a precise way. For this, two 25A single pole circuit breakers were used, responsible for protecting the motor in case of variations in the electrical network; a 12A contactor, responsible for programming the drive system; and a 5.6-8A overload relay, responsible for shutting down the system if the motor pump overloads. In Figure 2, a picture of the control cabinet and its respective electrical diagram is shown.



Legend: L – Phase; N – Neutral; PE – Protection; DJ - Circuit breaker; K – Contactor; RT - Thermal Relay; M - Motor pump; U, V - Pump phases; D, L - Pushbutton switch; G, R - Signal light;

Figure 2. Control panel and wiring diagram.
Source: Created by the authors.

Since the lateral lines are only 20 meters long and there are only 100 drippers per line, the methodology used to collect the flow rate of the drip irrigation system was that of Keller and Karmeli (1975). This methodology uses only 16 dripper samples, arranged as follows: in the four rows, located 1/3, 2/3 from the beginning of the plot and in the first and last dripper of the row.

The flow rate of the drippers was measured by the gravimetric method in order to obtain greater precision in the determination. The 3 minutes collection time recommended by NBR

9261 (ABNT, 2006) was not used, the strategy used was for all treatments to have the same total application time, so the collection time adopted of 12 minutes was the shortest multiple of 2, 3, 6 and 12.

2.3. Experimental design

Thus, except for the treatment of a 12-minute application, all had an off-time between two applications of 25 minutes, and their flow rate was counted after the 12 minutes were up. Twenty-five trials were conducted for the following treatments: T1: 6 2-minute applications with non-compensated emitter; T2: 4 3-minute applications with non-compensated emitter; T3: 2 6-minute applications with non-compensated emitter; T4: 1 12-minute application with non-compensated emitter; T5: 6 2-minute applications with auto-compensated emitter; T6: 4 3-minute applications with auto-compensated emitter; T7: 2 6-minute applications with auto-compensated emitter; T8: 1 12-minute application with auto-compensated emitter.

2.4. Measuring flow rate and uniformity coefficients

Using the volume collected by the emitters, the flow rate was determined, according to Equation 1.

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

Where in: q – drip emitter flow, L h^{-1}; V – sampled solution volume, mL; t – sampling time, min.

Next, the Christiansen Uniformity Coefficient (CUC), proposed by Christiansen (1942), and the Distribution Coefficient (DUC), proposed by Merrian and Keller (1978), were calculated, as shown in Equations 2 and 3, respectively.

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

Where in: CUC - Christiansen's Uniformity Coefficient, in %.; x_i- Individual values of the water volume contained in the collectors, in mm; x_{med} - Overall average of collected water volume values, in mm; n – Number of collectors in the testing area.

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

Where in: DUC– Distribution uniformity coefficient, in %.; x_{25}- Average of the lower quartile of water volumes contained in the collectors, mm; x_{med} - Overall average of collected water volume values, in mm.

2.5. Control chart and process capability index

Using the CUC and DUC values, mean comparisons were made; however, in order to evaluate the behavior under time control and to classify the efficiency of the proposed treatments, the Shewhart control charts and the EWMA were made. The methodology, proposed by Montgomery (2016), was adopted, in which it is necessary the normality of the analyzed data and the non auto-correlation between it.

In this design, the number of observations in the sample is n = 1, which means that the sample consists of a single individual unit. In these cases, control charts for individual measurements are used. Generally, these charts use the moving range of two consecutive observations as the basis for estimating the variability of the process. The moving range is defined as MR and is calculated by $MR_i = |x_i - x_{i-1}|$, where i is an integer representing the point being observed (Montgomery, 2016).

The control chart for individual measurements for monitoring the mean has the central line and the upper and lower control limits calculated by Equations 4 and 5, respectively (Montgomery, 2016; Minitab, 2023).

$$UCL = \bar{\bar{X}} + L\frac{MR}{d_2} \quad (4)$$

$$LCL = \bar{\bar{X}} - L\frac{MR}{d_2} \quad (5)$$

Where in: $\bar{\bar{X}}$ - Mean of the averages; L - Distance from the control limits to the central line, expressed in standard deviation units; MR - Mean of data amplitudes; d_2 - A constant equal to 1.128 when the number of observations is n = 2, considering individual measurements, according to the tabulated values described by Montgomery (2016).

For most Shewhart control charts, the control limits are calculated considering L = 3. Which represents an approximate value of 370 samples taken for a point to necessarily indicate an out-of-control condition (Montgomery, 2016).

According to the author, this definition also means that 99.73% of the samples will be within the control limits, in this scenario only common causes will be acting on the system and the distribution will be normal. However, in this study, L= 2 was used, since only 25 samples were taken. With this value of L, 95.45% of the samples will be within the control limits, which represents an approximate value of 22 samples collected for a point to necessarily indicate an out-of-control condition.

The EWMA control chart, in its turn, considers the accumulation of successive information by giving more weight to the most recent information. This method is a weighted average of all past and current observations and is therefore insensitive to the normality assumption. It is ideal for use with observations and is defined as Equation 6:

$$Z_i = \lambda x_i + (1 - \lambda)\, z_{i-1} \quad (6)$$

Where: $0 < \lambda \leq 1$; $Z_i = u_0 = X'$ (mean or target value in control xi).

The variance of variable Z is expressed as Equation 7.

$$\sigma_{zi}^2 = \sigma^2 \left(\frac{\lambda}{2-\lambda}\right) \left[1 - (1-\lambda)^{2i}\right] \quad (7)$$

Where: σ: standard deviation of the data in relation to the mean; λ: weight assigned to each sample; i: order from the sample used.

Roberts (1959) noted that the UCL and LCL of the EWMA control chart can be calculated by Equations 8 and 9, respectively.

$$UCL = X' + L\sigma\sqrt{\left(\frac{\lambda}{2-\lambda}\right)[1 - (1-\lambda)]^{2i}} \quad (8)$$

$$LCL = X' - L\sigma\sqrt{\left(\frac{\lambda}{2-\lambda}\right)[1 - (1-\lambda)]^{2i}} \quad (9)$$

Where in: $\bar{\bar{X}}$: data average; λ: weight assigned to each sample, ranging from 0 to 1; L: number of standard deviations to control the mean to be detected; i: order of the sample used. In this study, 0.25 is the weight constant of the sample, and for the width of the limits λ the factor is L = 2. This value of L was chosen in a similar way to the L of the Shewhart control chart.

In general, values of $0.05 \leq \lambda \leq 0.25$ perform well, with $\lambda = 0.05$; 0.10 and 0.20 being popular choices. A good empirical rule is to use smaller values of λ to detect smaller changes. For example, for values of λ close to 0, the previous observation has greater weight, and for $\lambda = 1$, the previous observation is canceled out, and the EWMA turns into a Shewhart chart (Crowder, 1989).

For the classification of the uniformity coefficients, the classification proposed by Frizzone *et al.* (2012) was used, as shown in Table 2.

Table 2. CUC and DUC classification 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).

The statistical comparison techniques, as well as the Shewhart and EWMA control charts were calculated using MINITAB software, Version 16.

The Anderson-Darling statistic was used to determine whether the data meet the normality assumption. To check for differences between the means of a given variable, ANOVA was used for parametric data, and the Kruskal-Wallis test was used for non-parametric data.

In case of differences between the means, for non-parametric data the Mann-Whitney multiple comparison test was used. A significance level of 5% was used in all cases.

3. RESULTS AND DISCUSSION

The results of the four monitored pressure values for each treatment (initial and final inlet and outlet of the main line), when compared, did not present statistical differences between the different pulse times. Therefore, it is emphasized that the pulsed application does not modify the service pressure in the distribution line of the proposed irrigation system.

It is worth noting that the pressures were collected when the system was stabilized, that is, after the filling phase and before the emptying phase of the hose. This shows us that all treatments were equally designed, since under constant pressure any pulse times should be equal.

Goyal (2017) states that if the pulse is considered only under its stable pressure, it is possible to find high uniformity, since the pressure and the flow rate of the system do not undergo major changes; but if the complete pulse is considered, the uniformity drops because the pressure and the flow rate go through variable stages. Thus, due to the way the pressures are collected, their values cannot explain the phases in which they are under variation; however, any variation in flow or uniformity is justified by the filling and emptying phases of the hose.

However, as can be seen in Figure 3, when comparing the different models of emitters, it is possible to notice that the inlet pressures both at the beginning and at the end of the collection were stable and concentrated at 1.2 bar for all treatments. Moreover, the occurrence of outliers is evident, with emphasis on pressures of 1.1 bar, which both occurred at the end of the pulse time. The justification for these two outliers is in the obstruction of the discharge line, since in both cases the pressure started at 1.2 bar and in a short interval of time there was a pressure drop.

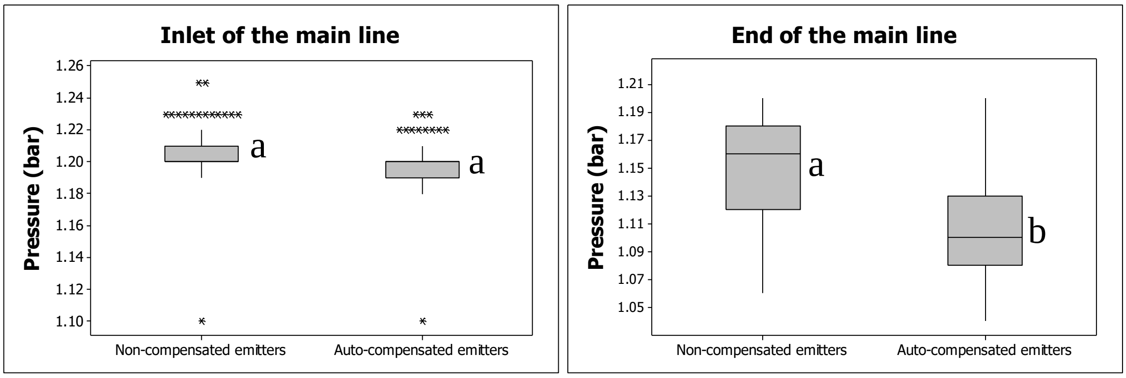


Figure 3. Box-plot of pressure values at the inlet and at the end of the main line.

Regarding the pressure values at the outlet manometer of the main line presented in Figure 3, it is possible to notice a difference between the dripper models. The median of the pressure values involving the non-compensated emitter was 1.16 bar, while the auto-compensated emitter was 1.1 bar, or 5.4% lower. This behavior occurs due to the higher pressure drop in the system with auto-compensated emitters, mainly because the total flow rate of these treatments is higher (6 Lh^{-1}). For Gomes *et al.* (2010), the higher the flow rate, the higher the head loss of the irrigation system, and when using auto-compensated drip lines, considering localized head loss is an especially relevant criterion when sizing drip lateral lines.

According to the flow behavior of the treatments, Figure 4 highlights the comparison between the different pulse times applied to each dripper model. As for the non-compensated dripline, the median of the flow rates for the 3 longest pulse times were 4.2 Lh^{-1}, and only the 2-minute pulse differed statistically at 5% significance, with a median of 4.17. This drop-in flow rate for the 2-minute pulse time may reflect transition periods (filling and emptying phases of the hose). The flow rates in the transitions are lower, so even applying a total of 12 minutes, this treatment has 1 to 3 times more this phase, and that added together ends up generating this difference.

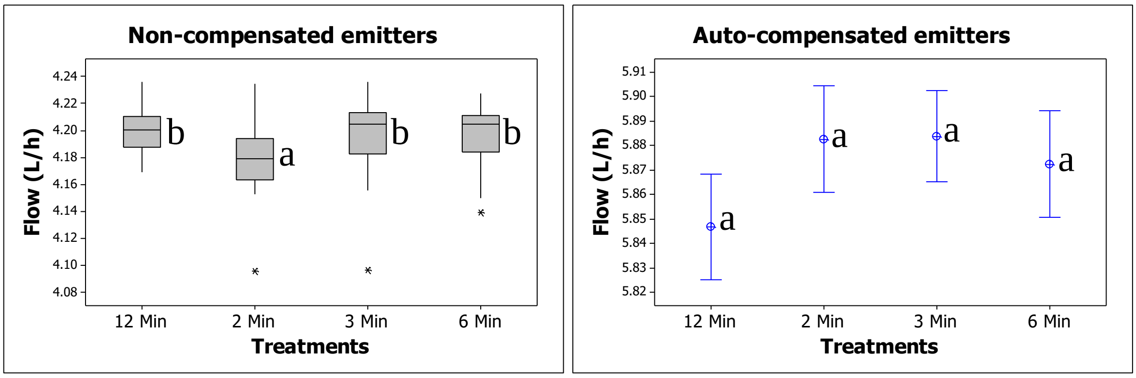


Figure 4. Box-plot of the flow rate values of the non-compensated emitter and interval plot of the flow rate values for the auto-compensated emitter.

As for the flow rate values for irrigation with the auto-compensated emitter, they were equal at 5% significance, with an average of 5.8. This evenness reveals the function of the auto-compensated emitter technology. The presence of the membrane inside the emitter delays the flow rate in the transition phases mentioned above, thus the main characteristic that can compromise the pulsed application is eliminated, or at least softened.

For the evaluation of the Christiansen uniformity coefficient (CUC), Figure 5 initially shows the comparison between means and averages for all treatments. As for the treatments with the non-compensated emitter there was a statistical difference, with the two shortest pulse times showing lower uniformity at 5% significance. As for the auto-compensated emitter, the same pattern prevailed for all pulse times.

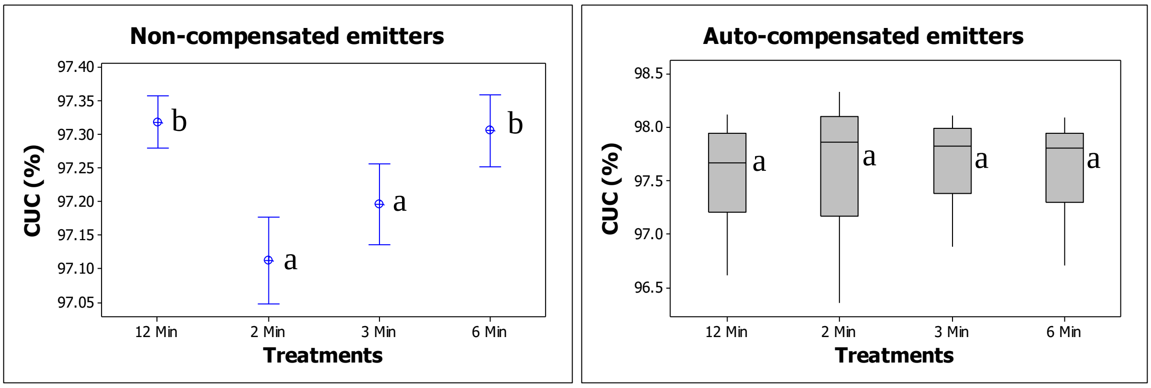


Figure 5. Interval plot for CUC values (non-compensated emitter).

It is worth noting, that if the CUC evaluation is stopped only with the comparison of averages, all treatments would have an excellent rating considering the metric proposed by Frizzone *et al.* (2012), since all treatments were above 90%. In addition, it is possible to conclude that even with the existing differences between pulse times, the fact that the CUCs lie between 96 to 98%, the pulse application in the proposed configurations, that is, at low-level and with lateral lines up to 20 meters, would be recommended to any irrigation manager.

Given the high uniformity presented by the CUC, Figure 6 shows the box-plots of all treatments for the DUC values. The DUC assessment is rather typical in drip irrigation due to the fact that drip irrigation works with lower flow rates, if compared to other irrigation methods, such as sprinkler irrigation. Hence, there is a major concern regarding emitters that apply less than the calculated flow rate, since it becomes accountable for the water deficit of the specific region, and consequently for the decrease in productivity of the crop as a whole. Moreover, the DUC can alert about some management issues, since it's sensitive to small variations in the distribution of water in a system (Souza *et al.*, 2006).

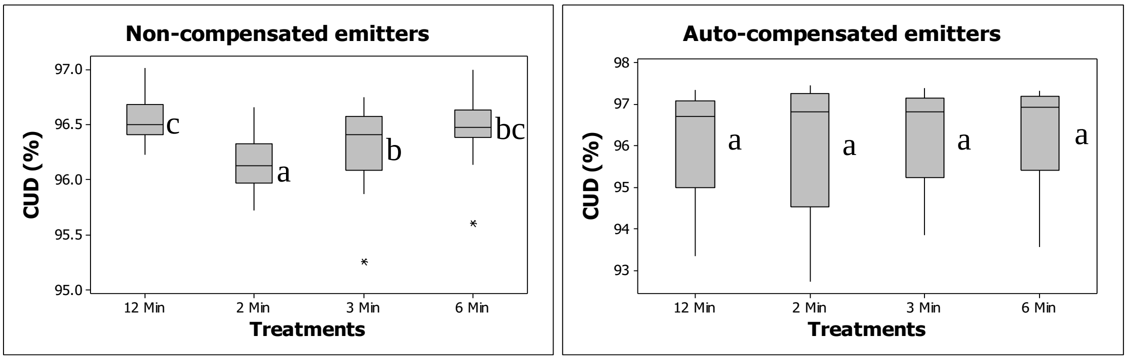


Figure 6. Box-plot of DUC values (non-compensated emitter).

As expected, the DUC proved to be more judicious than the CUC, since it further distinguished the treatments involving the non-compensated emitter, accounting nearly every pulse time for a different uniformity, as well as presenting uniformity with lower values and higher amplitudes than those recorded by the CUC involving the auto-compensated emitter, i.e., ranging from 92 to 97%. Even with the decrease in uniformity, the DUC still remains above 90%, and qualifies as excellent according to Frizzone *et al.* (2012).

These values are consistent according to previous works which involved pulsed application in drip irrigation. Beaza *et al.*, (2015) for example, reached uniformities above 90% only in low-level irrigation systems. Notably, most authors have investigated different inclinations of the system, as they consider the hypothesis that only under steep slope or slope pulse application may compromise the application uniformity (Lozano *et al.*, 2014; 2020; Zapata *et al.*, 2017).

Nevertheless, the hypothesis of this work is that statistical process control should identify behaviors that can qualify or disqualify different configurations of pulsed drip irrigation. Thus, Figures 7 and 8 show the Shewhart control charts and the exponentially weighted moving average (EWMA) for CUC and DUC of the treatments involving the non-compensated emitter.

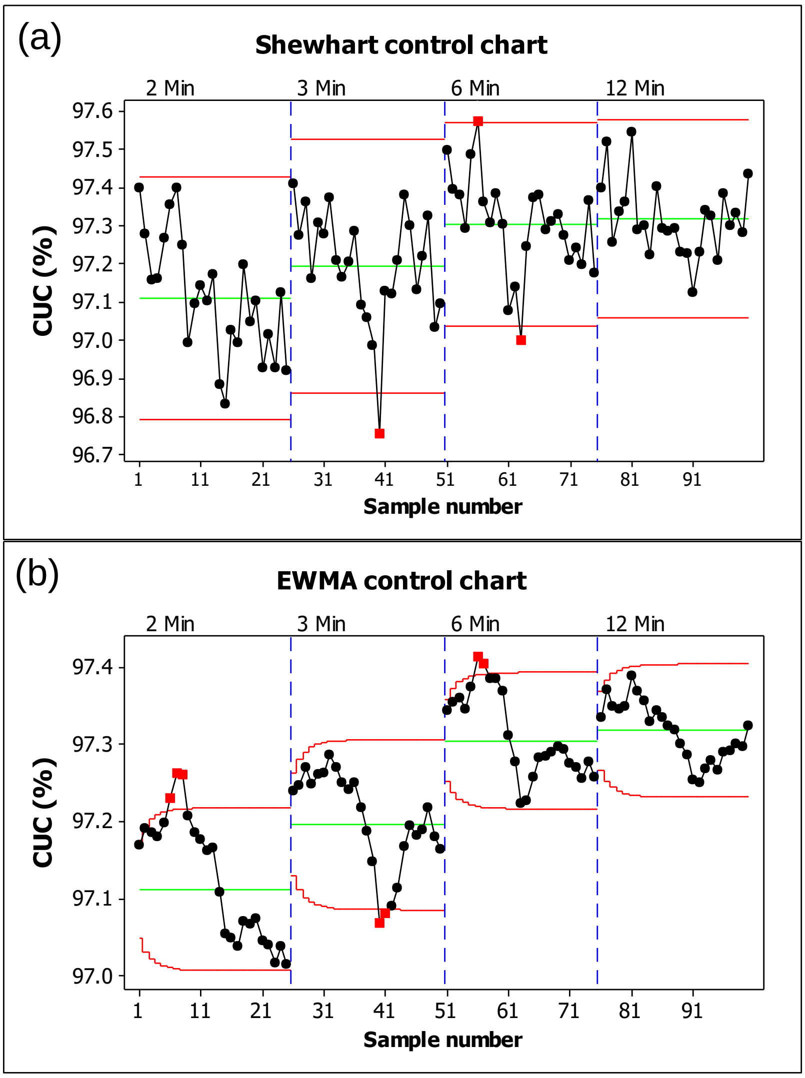


Figure 7. (a) Shewhart control chart and (b) EWMA control chart for CUC values (non-compensated emitter).

The primary noteworthy point is that in all treatments with a non-compensated emitter the data set showed a lack of normality or self-correlation. Lack of normality and self-correlation can make the use of statistical process control tools inappropriate, as they can distort the results (Montgomery, 2016). Therefore, the analyses of the graphs were done, albeit under reservations.

The Shewhart control charts involving the non-compensated emitter showed isolated points outside the control lines, with more incidence in the charts involving the DUC. These isolated points can be caused by factors such as low pressure (Saraiva *et al.*, 2014), dripper clogging, energetic fluctuations, pressure variations, and climatic factors (Justi and Saizaki, 2016).

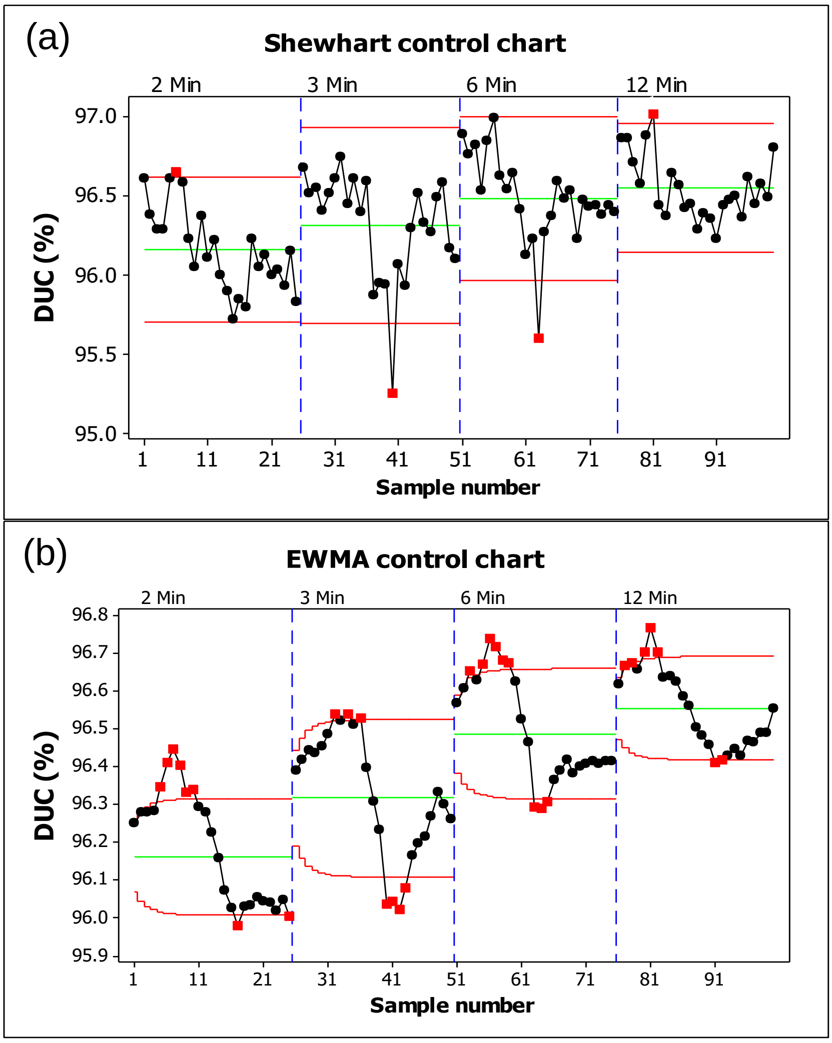


Figure 8. (a) Shewhart control chart and (b) EWMA control chart for CUD values (non-compensated emitter).

Still, by evaluating the EWMA chart it is possible to see when systematic behavior has occurred, such as having many points on one side of the mean line, or having rising, falling, or cyclical trends, as well as points outside the control limit. For Montgomery (2016), this is a nonrandom configuration, meaning that the system is sensitive to other variables to the point where uniformity changes.

For example, in Figure 7a, under the 2-minute treatment, and in Figure 8a under the 3-minute and 6-minute treatments, there were 8 consecutive points above the mean line. This lack of control was not signaled by the Shewhart chart, but was detected by the EWMA chart. The Shewhart control chart is more concise, while the EWMA control chart indicates trends and deviations not shown by the Shewhart control chart (Lopes *et al.*, 2020). The EWMA control chart is the most suitable for the evaluation of micro irrigation, because it detects small variations in the process (Siqueira *et al.*, 2018).

Also, with regard to pulsed application with a non-compensated emitter, the Shewhart graphs and the EWMA make more visible the amplitude of values in a set of 25 collected data. And, in this aspect, applications at longer pulse times are better qualified with respect to application uniformity because they present smaller amplitudes.

In the evaluation of the treatments involving the auto-compensated emitter with statistical process control, the caveat in the evaluation was also necessary, since the data set of each treatment also presented non-uniformity and self-correlation. Figures 9 and 10 show the

Shewhart control chart and the EWMA for the treatments with self-pumping emitters.

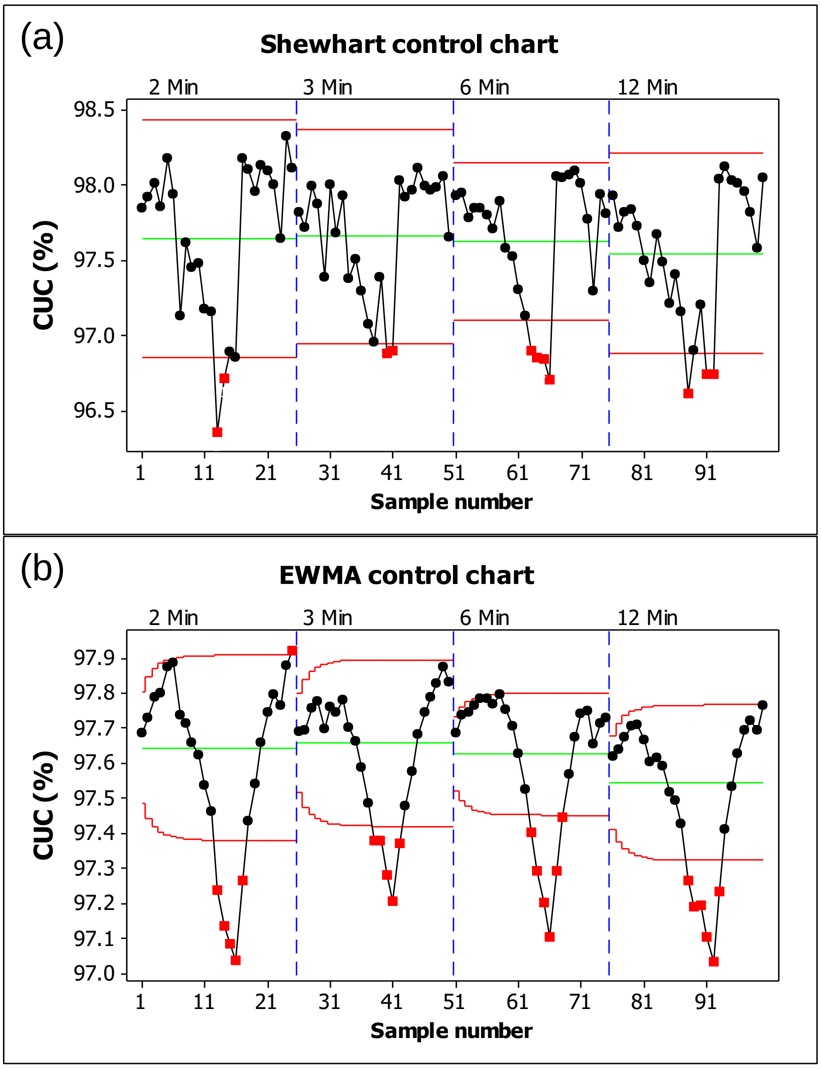


Figure 9. (a) Shewhart control chart and (b) EWMA control chart for CUC values (auto-compensated emitter).

The first behavior visible in all graphs, whether for CUC or DUC, and regardless of the pulse time is that the uniformity assumed two averages during the set of 25 collections, one of 97% and the other of 93% immediately compromising the instability of the process. This behavior can be justified by the replacement of one of the 16 drippers collected, which around the eighth collection started to reduce its flow drastically. From the tenth to the seventeenth collection this same dripper was replaced twice, since the flow rate remained low.

The emitter change was made in order not to compromise the statistic that considers the flow rate of the blocked emitter to be similar to the flow rate of the closest emitters, which proved not to be true. This pattern of variation in uniformity, after adjustments to the system, is noticeable in statistical process control techniques and agrees with the work of Silva *et al.*, (2015) who, after evaluating a auto-compensated emitter under different years of use claimed that under flow variation, due to the peculiarities and specific problems of each period, system maintenance contributes to the dripper flow rate of the system, but as a whole, remains within standards. Souza *et al.* (2006) also emphasizes that in systems with auto-compensated emitters, maintenance is necessary because, apart from the presence of clogged drippers, when the rubber membrane of the drippers' self-compensating mechanism is broken, air bubbles and mineral and organic deposits may form at the end of the lateral lines.

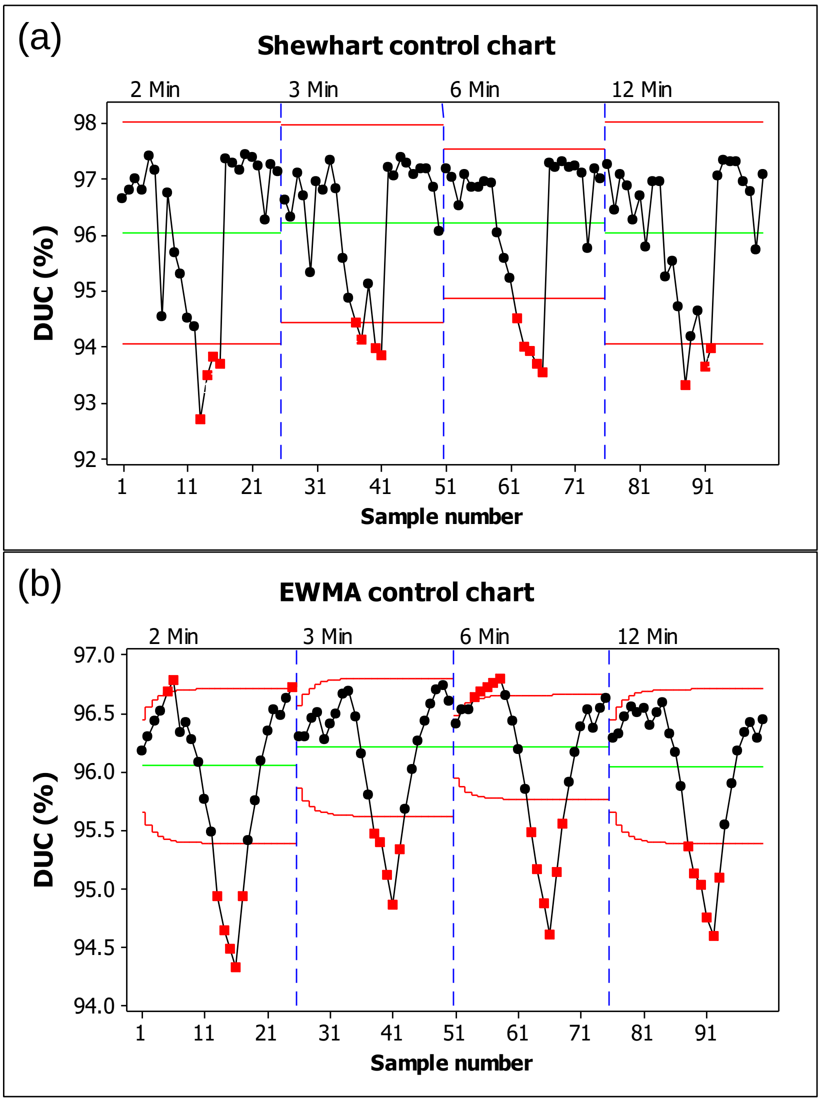


Figure 10. (a) Shewhart control chart and (b) EWMA control chart for CUD values (auto-compensated emitter).

As the mean change drastically compromises the evaluation of the control charts, other behaviors have become difficult to be noticed. However, it is worth noting that as with the non-compensated emitter, the EWMA graphs were more judicious than the Shewhart graphs. As can be seen in Figure 9a, for the 2-minute treatment, and in Figure 10a for the 2- and 6-minute treatments, there were 7 consecutive points above the mean line.

Also, regarding the pulsed application with a auto-compensated emitter, the Shewhart graphs and the EWMA make more visible the range of values in a set of 25 collected data. Moreover, any pulse time is qualified with respect to application uniformity.

The statistical control ratings showed that for all pulse times and both dripper models, there is behavior which somewhat depreciates the treatment in question. Although the CUC and DUC ratings for all treatments exceeded 90%, the graphs revealed a lack of statistical control.

Such lack of control, however, should be understood as a metric to differentiate the treatments and as far as possible assess whether their application is appropriate. In this sense, the eight treatments in this research revealed that with the use of a non-compensated emitter all pulse times are qualified for a low-level irrigation system and with lines up to 20 meters long; however, opting for larger pulses brings the advantage of achieving higher uniformity and lower variability.

Regarding the use of the auto-compensated emitter in the same low-level configuration, all pulse times are equally indicated; however, the control charts showed that care should be taken with the change of the applied blade when the system undergoes maintenance, since the replaced emitters take on new flow rates at the risk of this uniformity dropping drastically.

This approach to statistical process control techniques, where one treatment is classified as better than the other by the number of out-of-control points, has already been used by other authors. Lopes *et al.* (2021) for example, when evaluating the uniformity of a drip fertigation system with liquid peat at different inclinations reached the conclusion that liquid peat presents excellent uniformity (>90%) when used for drip irrigation systems. However, even with instability in the process, Lopes points out that the low-level application was the most uniform, followed by the upslope and downslope treatments, respectively.

In this sense, even having uncontrolled points, all the treatments tested are qualified for drip irrigation. From this perspective, it is recommended that a non-compensated emitter with different pulse times be used, with a minimum indication of up to 2 minutes, for level drip irrigation systems with lateral lines up to 20 meters long.

4. CONCLUSIONS

The DUC was more accurate and more sensitive than the CUC in the evaluation of application uniformity.

The decrease in pulse time causes a decrease in flow rate and uniformity in drip irrigation systems with emitters without anti-entrainment systems. However, this decrease is subtle, to the point that uniformity presents an excellent performance (>95%) for all pulses tested.

The use of drippers with an anti-drain system stabilizes the flow and uniformity independent of the applied pulse time. And also provides excellent performance with uniformities above 92%

Using the Shewhart control charts and the EWMA control chart was effective in monitoring the uniformity of the pulsed drip irrigation system. The Shewhart control chart was more robust, while the EWMA control chart was more sensitive, as it indicated trends and deviations not shown by the Shewhart control chart.

In the treatments with the non-compensated emitter, the statistical process control emphasized that under shorter pulse times the application instability increases. As for the auto-compensated emitters, the SPC highlighted the concern with application uniformity after maintenance processes.

In conclusion, in a pulsed drip irrigation for low-level application and with lines up to 20 meters it is recommended that drippers without an auto-compensated system be used, since they are cheaper. Further, the drippers should be used under pulse times up to the minimum of 2 minutes.

5. ACKNOWLEDGMENTS

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