Effect of a friction-reducing additive on the drip irrigation uniformity with sugarcane vinasse

Efecto de un aditivo reductor de fricción sobre la uniformidad del riego por goteo con vinaza de caña de azúcar

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ABSTRACT

Fertigation using vinasse, a high nutrient residue, is a viable form of complementary soil nutrition. However, it represents a dangerous risk of contamination if not properly disposed of. The objective of this study was to evaluate the irrigation and fertigation uniformity using vinasse in a drip irrigation system with and without the addition of polyacrylamide (friction-reducing polymer) applied at a concentration of 0.01 kg m^{-3} (10 mg L^{-1}). The tests consisted of collecting flow from 16 drippers in the system. Four were selected from each of the four lateral lines (first emitter, those located at 1/3 and 2/3 of the length, and the last one). Uniformity was obtained by the coefficient of distribution uniformity (CDU), Christiansen's uniformity coefficient (CUC), the total coefficient of variation (CVt), and the statistical uniformity coefficient (SUC). The CUC values after the addition of the polymer were 2.33% and 2.1% higher for water and vinasse, respectively. For the CDU, the addition of the polymer resulted in values of 6.07% and 5.3% higher for water and vinasse, respectively, and the SUC resulted in values of 3.99% and 3.83% for water and vinasse, respectively. We concluded that vinasse showed a lower average uniformity compared to water. However, when the friction-reducing agent was added, an increase was observed in the average uniformity in the drip irrigation system.

Key words: fertigation, polyacrylamide, application uniformity, irrigation evaluation.

RESUMEN

La fertirrigación con vinaza, un residuo rico en nutrientes, es una forma viable de nutrición complementaria del suelo. Sin embargo, representa un riesgo peligroso de contaminación si no se elimina correctamente. El objetivo de este estudio fue evaluar la uniformidad del riego y fertirrigación mediante el uso de vinaza en un sistema de riego por goteo con y sin la adición de poliacrilamida (polímero reductor de fricción) aplicada a una concentración de 0.01 kg m^{-3} (10 mg L^{-1}). Los ensayos consistieron en recolectar el flujo de 16 goteros en el sistema. Se seleccionaron cuatro de cada una de las cuatro líneas laterales (primer emisor, los ubicados a 1/3 y 2/3 de la longitud, y el último). La uniformidad se obtuvo mediante el coeficiente de uniformidad de distribución (CUD), el coeficiente de uniformidad de Christiansen (CUC), el coeficiente de variación total (CVt) y el coeficiente de uniformidad estadística (CUE). Los valores de CUC después de la adición del polímero fueron un 2.33% y un 2.1% más altos para el agua y la vinaza, respectivamente. Para el CUD, la adición del polímero resultó en valores de 6.07% y 5.3% más altos para agua y vinaza, respectivamente, y el CUE resultó en valores de 3.99% y 3.83% para agua y vinaza, respectivamente. Se concluyó que la vinaza presentó una uniformidad promedio menor en comparación con el agua. Sin embargo, cuando se agregó el agente reductor de fricción, hubo un aumento en la uniformidad promedio en el sistema de riego por goteo.

Palabras clave: fertirrigación, poliacrilamida, uniformidad de aplicación, evaluación del riego.

Introduction

There was a great production incentive in the sugar and alcohol industry in Brazil with the creation of PROÁLCOOL (National Ethanol Program), increasing pollution from refineries (Christofoletti *et al.*, 2013). In Brazil, ethanol is used as fuel in the form of hydrated ethanol (mixture of alcohol and water) and is also added to gasoline as anhydrous ethanol (Milanez *et al.*, 2008). With the rise in the utilization of biofuel vehicles, the cultivation of sugarcane has also grown in recent years. Brazil is the largest producer of sugarcane in the world with a forecast of 665.1 million t to be harvested for the 2020-2021 season. However, given the current scenario of the Covid-19 pandemic, there was a reduction in production compared to the previous harvest (7.9%), although production of 32.9 billion L of ethanol is still expected (CONAB, 2020).

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The introduction of ethanol to the market as a biofuel and a sustainable alternative to replace non-renewable fossil fuels (EPE, 2017) has drawn attention to research in the agricultural area. However, the generation of effluents such as vinasse, is an inevitable consequence (Macedo, 2007). Freire and Cortez (2000) state that vinasse is the main residue of the distillation process in the sugar and ethanol industry as a result of the fermentation process. For each liter of ethanol produced, 10 L of vinasse are generated, thus creating a massive amount of this residue. Studies of vinasse show a great nutritional potential due to its composition (Barros *et al*., 2010), with benefits such as increased K^+ and Mg^{+2} content in soils (Silva *et al*., 2019). Additionally, this subproduct may be applied in crops through fertigation (Silva *et al*., 2007). Using vinasse with the correct management benefits soil fertility and crop development (Chitolina & Harder, 2020).

The Sugarcane Technology Center (CTC), located in Piracicaba, SP, Brazil, carried out studies on the characterization of vinasse. The first study was performed in 1995, with 64 samples in 28 plants in the State of São Paulo, and the second was carried out in 2007. Table 1 shows the variation in the characterization of the composition of sugar cane vinasse.

TABLE 1. Sugarcane vinasse characterization.

Description	Values
CaO (mg L^{-1})	71 - 2614.7
BOD (mg L^{-1})	5,879 - 75,330
COD (mg L^{-1})	9,200 - 97,400
Fe (mg L^{-1})	2 - 200
P (mg L^{-1})	<10 - 188
Glycerol (% v/v)	0.26 - 2.50
MgO (mg L^{-1})	97 - 1,112.9
Mn (mg L^{-1})	1 - 12
N (mg L^{-1})	81.2 - 1,214.6
Ammoniacal N (mg L^{-1})	0.4 - 220.0
pH	3.5 - 4.9
K (mg L^{-1})	814 - 7,611.5
Sulfate (mg L^{-1})	92.3 - 3,363.5
Sulfite (mg L^{-1})	5 - 153
Zn (mg L^{-1})	<0.5 - 4.6
T (°C)	65 - 110.5
Cu (mg L^{-1})	<0.2 - 3.2
Al (mg L^{-1})	<5.0 - 120.0

BOD - biochemical oxygen demand; COD - chemical oxygen demand. Adapted from Elia Neto and Nakahondo (1995) and Elia Neto and Zotelli (2008).

The composition, organic matter concentration and chemical composition of vinasse may vary according to the mode of product preparation, the fermentation method, the type of material used for fermentation, among other parameters (Robertiello, 1982). Freire and Cortez (2000) support this statement due to the great variability in the chemical composition of vinasse, as it contains large amounts of organic matter and potassium, calcium, and sulfate, low levels of nitrogen, phosphorus, and magnesium, and low concentrations of micronutrients.

Although the use of vinasse as a fertilizer may provide several benefits, attention should be paid to the problems that its application may cause. Several authors cite vinasse as a pollutant (Christofoletti *et al*., 2013), and its composition is considered a factor of importance that may cause changes in the aquatic flora and fauna of rivers and lakes. Additionally, large quantities of this residue may affect soil properties (physical, biological, and chemical). Applying vinasse in an uncontrolled manner may cause profound changes in soil properties, from salinization and changes in the nutritional balance to ion leaching into groundwater (Ribeiro *et al.,* 2010). The basic rate of water infiltration in the soil may show a reduction of up to 40% in soils with the uncontrolled application of vinasse (Dalri *et al*., 2010). Thus, the Environmental Company of the State of São Paulo (CETESB), in its standard P4.231 (CETESB, 2006), indicates the recommended values for the application of vinasse in the soil to prevent modifications resulting from the excessive use of the product.

Unfortunately, fertigation used in plants is not always treated in an appropriate and technical way, considering the quantity, quality and time required for each irrigation. Sprinkler irrigation using a self-propelled system with hydraulic cannon is a common method used with vinasse; nevertheless, its application uniformity is low (Bebé *et al*., 2009). Drip systems are a more efficient alternative since they irrigate only a part of the soil surface, directly in the root region and with low amounts of water. Thus, these systems have a low flow with high frequency, keeping the soil always close to field capacity (Bernardo *et al*., 2006).

Fertigation using vinasse requires an adequate dimensioning of the irrigation system that transports fluids to the crops. Hydraulic parameters must be considered, such as pressure drops in pipes and channels due to the way this subproduct is applied (Justi *et al*., 2012). These hydraulic factors affect not only the efficiency of the system but also the fixed and variable costs, like piping and electricity. The economic aspect of vinasse application may not be advantageous when inadequately measured, showing the importance of studies related to head loss.

Scientists have tried to find possible ways to reduce the friction factor inside the ducts. In 1948, the British chemist B.A. Toms demonstrated a diluted polymer solution that changed the flow pressure without changing the flow (Virk *et al.*, 1967; Bizotto *et al.*, 2011). Researchers started using these polymers in the 80's, creating new possibilities for study. According to Bizotto and Sabadini (2008), the application of polymers prevents the formation of swirls and reduces the loss of kinetic energy in the flow, with both resulting in reduced friction. The use in drip irrigation may or may not affect the uniformity of application in the drip system with irrigation and fertigation with vinasse. This study aimed to evaluate the influence of polyacrylamide as a friction-reducing additive on drip irrigation and fertigation using water and sugarcane vinasse.

Materials and methods

The experimental setup of the drip irrigation system consisted of a recycling system of water and vinasse with a canvas adapted for collecting liquids. The system was placed in a wooden structure with dimensions of 5.00 m length x 1.08 m width x 1.55 m height at the Advanced Campus Jandaia do Sul, Federal University of Parana - UFPR (Brazil).

The dripper tube (model Manari, Petroisa®, Avare, SP, Brazil) was non-compensating, with nominal flow of 1.5 L/h, a 0.1 m gap between drippers and 98.1 kPa of service pressure. The irrigation system consisted of four dripper tubes of 4.60 m long for a total of 46 emitters per line.

The system layout was arranged so that the pipes could be coupled to a pump set (model QB60, GAMMA®, Quatro Barras, PR, Brazil), with a maximum flow of 36 L/min (6×10^{-4} m^3/s) and output suppression of 313.6 kPa, connected to a 200 L reservoir. The suction tube diameter was 2.54 cm (1 inch) in PVC, with 2.54 cm (1 inch) filter coupled to a 2.54 cm ball valve (1 inch) located at the outlet reservoir that is responsible for controlling the flow and pressure of the system. The system was monitored using a Bourdon pressure gauge maintained at 98.1 kPa.

The tests used two fluids, water and sugar cane vinasse with and without the friction-reducing polymer and the addition of polyacrylamide (FLONEX 9051 SI, SNF, Brazil) at a concentration of 0.01 kg m^{-3} (10 mg L^{-1}). This material is

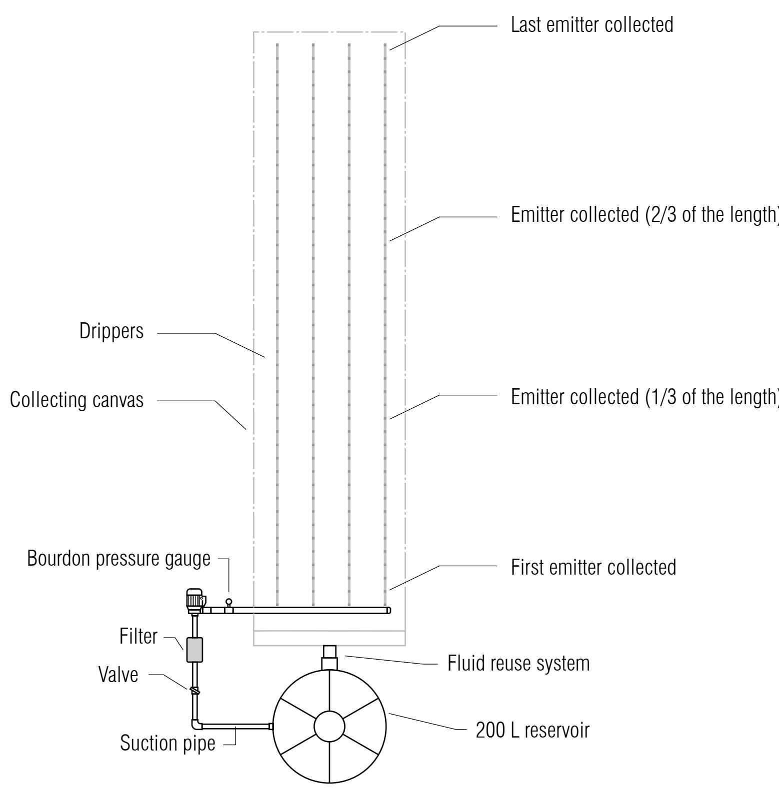

FIGURE 1. System layout assembled for the tests.

presented in the form of a light powder with color ranging from white to slightly pink, an apparent specific mass of 0.80 g cm^{-3}, viscosity of 500 cP at a concentration of 5 g L^{-1}, 200 cP at 2.5 g L^{-1}, and 80 cP at 1.0 g L^{-1}, and 90% purity. The experiment layout is shown in Figure 1.

Drip flow rates were collected using the methodology proposed by Keller and Karmeli (1975), in which the flow rates of the 16 drippers within the irrigation system are determined by selecting four drippers from four lateral lines (first emitter of the lateral line, those located at 1/3 and 2/3 of the length, in addition to the last lateral dripper).

Flow collecting was performed manually through the volume of each selected dripper after 4 min. A total of 200 irrigation cycles was carried out divided into water, vinasse, and both fluids with the addition of polyacrylamide. Each irrigation cycle had 16 flow samples for a total of 3200 samples. The statistical coefficients used for the evaluation of uniformity (Keller & Karmeli, 1975) were determined according to Equations 1-4.

$$CDU = \frac{qn}{qm} \times 100 \quad (1)$$

where CDU is the coefficient of distribution uniformity (%), qn is the average flow 25% lower from emitters (L/h), and qm is the average flow rates of emitters (L/h) resulting in a value directly proportional to the uniformity of the system (Keller & Karmeli, 1974). The classification proposed by ASAE (1996) was used, in which CDU is "excellent" when higher than 90%, "good" when between 75-90%, "regular" when between 62-75%, "poor" when between 50-62%, and "unacceptable" when the value is below 50%.

$$CUC = \left[1 - \frac{\sum_{(i=1)}^{n} \left| X_i - \overline{X} \right|}{n \times \overline{X}}\right] \times 100 \quad (2)$$

where CUC represents the Christiansen's uniformity coefficient (%), X_i is the volume obtained in order collector i (L), $\overline{X}$ is the average volumes obtained from the collectors (L), and n is the number of collectors. For the CUC, values above 90% are considered "excellent", between 80-90% are considered "good", between 70-80% are considered "regular", between 70-60% are considered "poor", and below 60% are considered "unacceptable" (Bernardo *et al.*, 2006).

$$CVt = \frac{SD}{qm} \quad (3)$$

where CVt is the total coefficient of variation (dimensionless), SD is the standard deviation of flows (L/h), and qm is the average flow (L/h). This coefficient of variation is used to calculate the statistical uniformity coefficient (SUC) by Equation 4. Table 2 shows the classification for this coefficient.

$$SUC = 100 \times (1 - CVt) \quad (4)$$

TABLE 2. Classification for the statistical uniformity coefficient (SUC).

Classification	SUC (%)
Excellent	>90
Good	80-90
Regular	70-80
Poor	60-70
Unacceptable	<60

Adapted from Favetta and Botrel (2001).

Results and discussion

The descriptive statistics considered the mean, mean standard error, standard deviation, minimum, first quartile, median, third quartile and maximum values for the CUC, CDU and SUC calculated for the evaluated variables liquid (water and vinasse) and polyacrylamide (with or without friction-reducing agent) (Tabs. 3-5). When the polyacrylamide was added, the CUC increased by 2.33% for water and 2.1% for vinasse. In relation to the CDU, for water the increase was 6.07% and for vinasse it was 5.3%. As for the SUC, there was an increase of 3.99% for the analysis with water and 3.83% for vinasse.

TABLE 3. Descriptive statistics of the Christiansen's uniformity coefficient (CUC) for liquid and polymer.

	CUC (%)			
	Water	Water*	Vinasse	Vinasse*
Average	89.28	91.41	87.62	89.46
Standard deviation	1.70	0.51	3.10	1.71
Variance	2.90	0.26	9.58	2.92
Minimum	85.15	90.23	76.49	84.66
1st Quartile	88.03	91.11	85.52	88.86
Median	89.83	91.47	87.73	89.80
3rd Quartile	90.70	91.79	90.14	90.71
Maximum	91.66	92.44	94.18	91.99
Amplitude	6.51	2.21	17.69	7.33

* Liquid with added friction-reducing agent (polyacrylamide).

The results for the CUC were classified as "excellent" for the flow of water with polyacrylamide, and "good" for the other variables. Considering the ideal values in the literature, only water with polyacrylamide obtained the expected results. For the CDU and SUC values, the results were more sensitive. For SUC, all results were within what was classified as "good" and "very good"; water with polyacrylamide came close to "excellent" (over 90%) (ASAE, 1996; Favetta & Botrel, 2001).

TABLE 4. Descriptive statistics of the coefficient of distribution uniformity (CDU) for liquid and polymer.

	CDU (%)			
	Water	**Water***	**Vinasse**	**Vinasse***
Average	81.22	86.15	77.67	81.79
Standard deviation	4.16	1.15	6.52	3.87
Variance	17.29	1.33	42.44	15.00
Minimum	70.72	82.89	54.87	69.63
1st Quartile	78.45	85.34	72.85	81.03
Median	81.95	86.29	77.48	83.28
3rd Quartile	84.77	86.95	83.28	84.43
Maximum	86.51	88.10	90.07	86.16
Amplitude	15.79	5.21	35.2	16.53

* Liquid with added friction-reducing agent (polyacrylamide).

TABLE 5. Descriptive statistics of the statistical uniformity coefficient (SUC) for liquid and polymer.

	SUC (%)			
	Water	**Water***	**Vinasse**	**Vinasse***
Average	85.85	89.28	83.16	86.35
Standard deviation	3.21	0.59	4.98	2.99
Variance	10.30	0.35	24.82	8.94
Minimum	76.71	87.61	69.27	78.06
1st Quartile	84.01	88.95	79.70	86.10
Median	86.82	89.41	83.67	87.46
3rd Quartile	88.68	89.76	87.91	88.22
Maximum	89.52	90.22	92.70	89.39
Amplitude	12.81	2.61	23.43	11.33

* Liquid with added friction-reducing agent (polyacrylamide).

Since the drip system tended to clog, external and internal agents affected the general uniformity, causing changes in tests 13 and 26. Vinasse has a high content of organic matter and particles in suspension that caused the clogging of the emitters and filter (Fig. 2), especially in tests using vinasse without polyacrylamide. The system suffered blockages, verified by signs of change in the pump pressure, suction and visually perceptible obstruction of the emitters. The cleaning procedure consisted of removing all the vinasse from the system to wash it with water, making it recirculate within the tubes. Additionally, the emitters were unblocked and the filter was cleaned. When the CDU showed low values, some factors directly affected the results, such as quality control in the manufacturing processes, handling failure, physical changes in components, and aging and clogging of emitters (Merriam & Keller, 1978), which was observed in this experiment, as the drippers clogged (Fig. 2).

Cunha *et al.* (2006) observed the same clogging problem with wastewater from the pulping of filtered coffee fruits that was found with fertigation using vinasse. The CUC started with a value of 95.96% and, after 144 h, a reduction of 76% was observed. In the case of CDU, the reduction was 100%, going from an initially "excellent" result to "unacceptable" at the end of the period.

FIGURE 2. Screen filter clogged with particles from vinasse.

The clogging of emitters has several possible causes, such as the quality of water or drained fluid (Nakayama & Bucks, 1991). This was confirmed in this experiment by the rapid clogging by particles of vinasse duo to its high load of organic matter (Fig. 2). Zhou *et al.* (2017) stated that the clogging of emitters by the presence of organic material and microorganisms is one of the barriers to the development of drip irrigation, especially when using wastewater. Even with this issue, the results confirmed what was stated in theory. It is possible to notice that the addition of polyacrylamide caused the uniformity to increase, in both water and vinasse. The addition of the polymer to vinasse caused uniformity to reach higher values than those observed in water without the addition of this polymer. In controlled experiments, Oliveira and Villas Bôas (2008) and Silva and Silva (2005) obtained higher uniformities for the application of dripping water, maintaining 97.70% for CUC and 76% for micro sprinkling.

Figures 3-5 show the comparison between the addition or not of polyacrylamide to both liquids (water and vinasse) for CUC, CDU, and SUC, respectively. Figures 3A, 4A and 5A show the uniformities for pure water and water

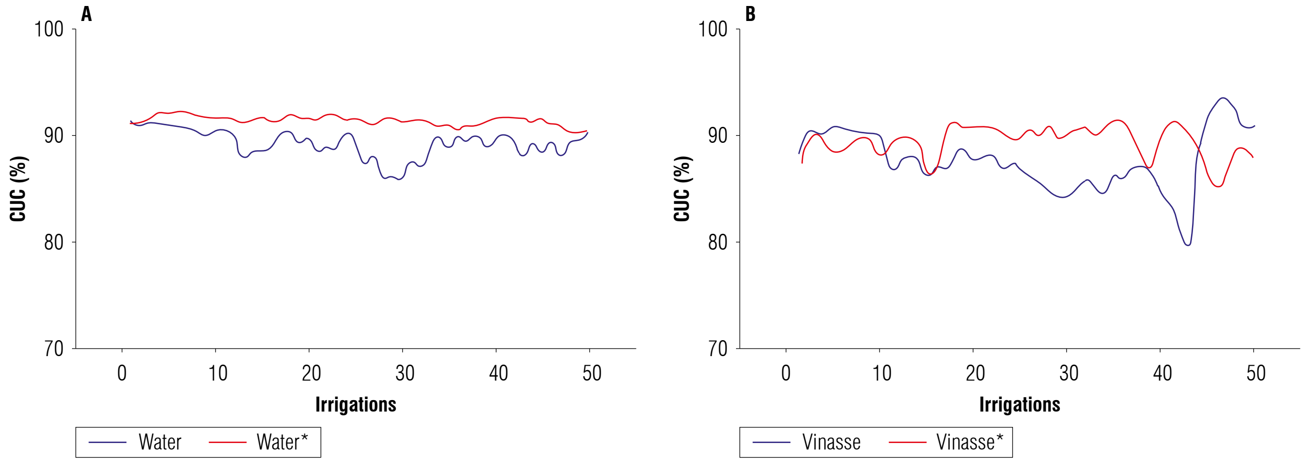

FIGURE 3. Comparison of the Christiansen's uniformity coefficient (CUC) with addition and without addition of polyacrylamide in A) water and B) vinasse. *Liquid with added friction-reducing agent (polyacrylamide).

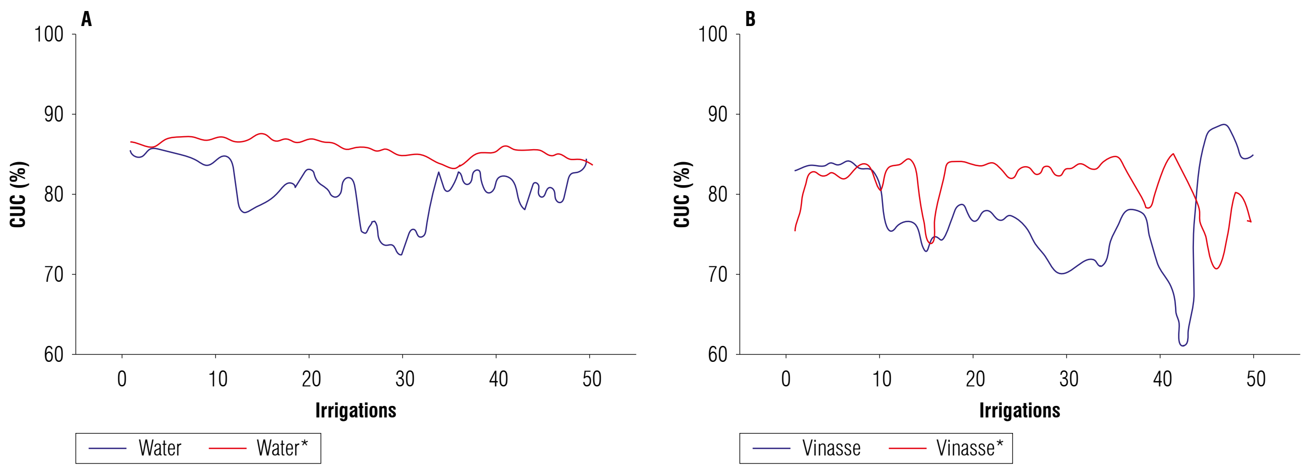

FIGURE 4. Comparison of the coefficient of distribution uniformity (CDU) with addition and without addition of polyacrylamide in A) water and B) vinasse. *Liquid with added friction-reducing agent (polyacrylamide).

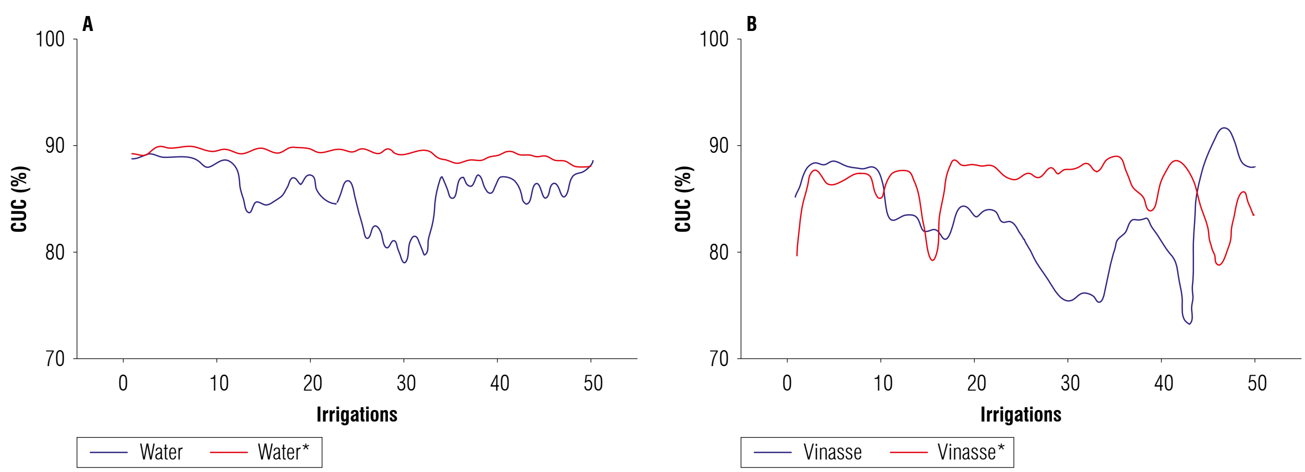

FIGURE 5. Comparison of the statistical uniformity coefficient (SUC) with addition and without addition of polyacrylamide in A) water and B) vinasse. *Liquid with added friction-reducing agent (polyacrylamide).

with polyacrylamide, while Figures 3B, 4B and 5B show the uniformity of vinasse with and without the addition of polyacrylamide.

In all cases listed above, the addition of the polymer caused an increase in uniformity, optimizing the system. The positive results of the polymer are similar to those obtained by Justi *et al.* (2017) when comparing the effect of polyacrylamide in tests with a variation of flow and diameters 2.54 cm, 1.905 cm, and 1.27 cm (1, ¾, and ½ inches) using water and vinasse in polyethylene pipes. In that study, the authors obtained an increase in flow values only with the addition of the polymer. Al-Yaari *et al.* (2009), when studying the reduction of friction in the flow of oil and water, found friction reductions of up to 65%, positively confirming that the use of friction-reducing polymer in pipes may also affect irrigation uniformity. Even for CDU that is an extremely sensitive coefficient (Merriam & Keller, 1978), an increase of up to 5% in the uniformity average was verified, emphasizing the role of the friction-reducing agent within the system.

The uniformity of vinasse is, in general, less than ideal; however, the conditions become more advantageous with the addition of polyacrylamide since uniformity is increased, reducing operating costs. This justifies the use of vinasse from a technical perspective.

Conclusions

The evaluation of irrigation systems is of paramount importance due to the necessity for saving resources and preserving the environment through the sustainable use of liquids of lesser quality than water, such as vinasse that may be used as a biofertilizer. Based on the results obtained in the present study, the average of uniformity coefficients analyzed (CUC, CDU and SUC) of water were 1.89%, 4.57% and 3.23%, higher than those found in fertigation with vinasse without the polymer, as expected due to the characteristics of the fluids. However, the uniformity coefficients were higher both in water and in vinasse when adding polyacrylamide.

The results for vinasse with the addition of the polymer exceeded by 0.2%, 0.7%, and 0.58% the values of polymer-free water for CUC, CDU and SUC, showing the efficiency and positive influence of the addition of the polymer in the evaluation of fertigation with vinasse.

For further studies, we suggest evaluating the flocculating effect of polyacrylamide on sugar cane vinasse in different dilutions and how the polymer may have an impact on physicochemical characterization and irrigation.

Conflict of interest statement

The authors declare that there is no conflict of interest regarding the publication of this article.

Author's contributions

ALJ designed the experiments and reviewed the translation. LGM carried out the field experiments and wrote the article. Both authors contributed to the data analysis and reviewed the manuscript.

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