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# Flow rate changes of drippers with dilutions of treated water produced by oil exploration in the Brazilian semiarid region*

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## Abstract

The liquid residue called "produced water" from the exploitation of oil in the ground and sea is generated in large volumes and has significant polluting potential. In the Brazilian semiarid region, this liquid can be applied to the agricultural lands, if properly treated and applied to the soil by dripping. It is an alternative that can mitigate water scarcity and impacts on the environment. However, the vulnerability of drippers to clogging is a problem and can be mitigated with the dilution technique. The flow rate changes of drippers for the application of dilutions of produced water treated (PW) with underground water (UW) was analyzed. The experiment was conducted in a completely randomized split-split-plot design with three replications. Plots consisted of treatments (D1: 100% of UW, D2: 90% of UW and 10% PW, D3: 80% of UW and 20% of PW, D4: 70% of UW and 30% of PW and D5: 60% of UW and 40% of PW). The split-plots consisted of types of drippers (G1: 1.6 L $h^{-1}$, G2: - 1.6 L $h^{-1}$, G3: 1.7 L $h^{-1}$) and split-split-plots consisted of evaluation times (0, 40, 80, 120 and 160 h). Flow rate (D) and flow rate coefficient of variation (FCV) were taken every 40 hours untill 160 h. The results showed that the G3 emitter was the most resistant to clogging. The dilutions D2 and D3 provided the lowest losses in hydraulic performance in the drip units. The highest rates of clogging occurred in the G2 emitter operating in the D5 dilution.

**Keywords:** Reuse, petroleum, emitters, clogging, dilution.

**Abbreviations:** PW_Produced water; UW_Underground water; F_Flow rate; FCV_Flow rate coefficient of variation; EC_Electric conductivity; SS_Suspense solids; DS_Dissolved solids; TDR_Totally randomized design.

## Introduction

The intensification of water scarcity is a problem that is being faced worldwide (Bichai et al., 2012). Brazil has a large amount of fresh water, but most of the reserves are concentrated in the Amazon region, while other regions bordering the Atlantic Ocean, especially the Northeast, have low water availability (Bressiani et al., 2015).

The causes of water scarcity are a combination of several factors such as inefficient water distribution, no emergency plan or basic structure to cope with rainy periods or to use them more efficiently, low levels of treatment and use of wastewater, degradation environmental resources, climate change, among others (Urbano et al., 2017). The Brazilian northeastern region features sedimentary basins with hundreds of oil fields, with a yearly output of approximately 44 million petroleum barrels. The Potiguar Basin is extended to the states of Rio Grande do Norte and Ceará, whose land section may be classified as mature due to its advanced exploitation condition (Anp, 2018).

Similar to many other exploration and production activities, the oil industry produces large quantities of waste and effluents. The largest volume of effluent generated in this type of activity is the "produced water" (PW), which is a mixture of naturally formed water (in greater quantity) existing below or inside the oil and gas reservoir, of re-injected water and chemicals used during the drilling, stimulation, production and oil-water separation processes (Santos et al., 2014; Drioli et al., 2015).

The volume of water produced generally increases with the age of the reservoir and, in certain cases, can reach up to 98% of the total volume of fluid (Alzahrani and Mohammad, 2014). Oil/water ratio of the 1: 3 is generally known for most oil wells (Munirasu et al., 2016).

Studies on wastewater from oil fields and its application in the soil-plant system are being developed (Burkhardt et al., 2015; Sousa et al., 2016). Actually, it may be an excellent alternative for semi-arid lands. However, its chemical composition should be analyzed since the produced water has high rates of organic and mineral contents and heavy metals, as a rule (Al-Haleem et al., 2010; Igunnu and Chen, 2014), which may negatively affect the soil and the environment as a whole.

The drip irrigation system is an important technological alternative for the efficient use of water resources in semiarid environments. It saves water and electricity, increases crop yields and minimizes losses due to evaporation, percolation and runoff, when well designed and managed, (Kilic, 2020) and risks of microbiological contamination of agricultural products (Batista et al., 2017).

The susceptibility to the clogging of emitters is a bottleneck that restricts the application and popularization of drip irrigation with wastewater. It is also strongly related to the formation of biofilms resulting from the interaction between physical, chemical and biological agents (Fernandes et al., 2014; Mesquita et al., 2016; Cunha et al., 2017; Silva et al., 2019).

Biofouling formed on the emitter's internal devices is the main cause for clogging. It actually affects hydraulic performance indexes and the efficiency of effluent application by the drip irrigation system (Song et al., 2017). Biofouling and fouling are two leading issues in drip irrigation emitters (Xiao et al., 2020). The narrow section and labyrinth geometry of the dripper channel result to the development of a heterogeneous flow rate behaviour within the vortex zones, which enhances the fouling mechanisms (Lequette et al., 2020).

Fouling is the accumulation of unwanted material on surfaces that can be divided into four categories: (1) particle fouling by sedimentation of particles and macro-molecules; (2) organic fouling with the sedimentation of organic materials; (3) chemical precipitate due the precipitation of low-solubility salts; and (4) biological fouling (Biofouling) occuring by adherence\detachment of microorganisms to the inner surfaces of pipes and drippers comprising the irrigation system and the development biofilms (Katz et al., 2014).

Two important impacts are usually occurred from the clogging of drip irrigation system emitters. They are changes in the design flow rate and the increase in the flow variation coefficient (Fernandes et al., 2014; Mesquita et al., 2016; Cunha et al., 2017), which directly interfere with water distribution uniformity. Through a simulation study, López-Mata et al. (2010) proved that the increase in the uniformity of water distribution results in productivity increase of the corn crop.

A number of factors on the effects of this residue on the hydraulic performance of drip irrigation systems such as the periods of water scarcity in the northeastern semiarid, the large volume of water produced generated from oil exploration in the region and the lack of information in Brazil and in the world have made the development of this research necessary and important.

Current assay investigates the flow rate changes of non-self-compensating drippers in the application of dilutions of treated water produced by oil exploration in the Brazilian semiarid region.

## Results and Discussion

### *Flow rate (F) behavior of non-self-compensating drippers applied dilutions of treated water produced by oil exploration*

Figure 1 shows the flow rates (F) of the drip units equipped with the three types of non-self-compensating emitters operating with dilutions of treated produced water for 160 h. There was an increase in the levels of clogging and emitters flow rate change in dilutions with greater proportions of treated produced water in relation to groundwater in contrast to the results presented by Batista et al. (2014), where the application of greater proportions of groundwater in relation to the swine effluent potentiated the clogging of emitters in the drip units that operated for 160 h. This fact is attributed to the physical-chemical and microbiological composition of the swine effluent, which presents a risk of clogging emitters by microbiological agents, greater than that of treated produced water.

We noticed in the G1 emitter, that the dilutions influenced the flow rate oscillations over 160 h (Figure 1A). This is probably due to the agents that cause clogging (Table 5) and movement of the lateral lines at the time of the evaluations, which enabled the expenditure of fragments of the bioincrustration inside the emitters and the lateral lines.

In the D1 and D4 dilutions, there was only an increase in the flow rate after the initial time of 0 h, with a maximum flow increase of 7.78 and 7.65%, respectively, both in 40 h time. After the initial time of 0 h, the dilutions D2 and D5 provided an increase in the flow rate in the 40 and 80 h times and a reduction in the flow rate in the 120 and 160 h times. We noted that the maximum flow rate was reached at 80 h in the values of 2.04 and 1.58%, while the maximum flow rate reductions were 1.51% at 120 h and 14.31% at 160 h for D2 and D5, respectively. In the D3 dilution, there was only a reduction in the flow rate after the initial time of 0 h, with the maximum flow rate reduction in the value of 5.41% at 120 h. These results differ from those found by Cunha et al. (2017), where the same emitter G1 applied a dilution of 33% of dairy effluent in 67% of water supply for 200 h. There was only a decrease in the flow rate, when the flow rate of the initial time is compared to the others. We noted that the maximum flow rate reduction occurred at 160 h (10.49%). Fernandes et al. (2014) studied the cashew nut effluent and reported a decrease in the flow rate of non-self-compensating emitter of 1.65 L $h^{-1}$ over time, where the maximum flow rate reduction was 42% at 160 h. In the work of Marque et al. (2016) with a 50% dilution of dairy effluent in 50% of water supply, the same emitter G1 showed a reduction and an increase in flow over the 160 h of operation. However, the maximum flow reduction occurred at 160 h (7.55%).

In the G2 emitter, greater fluctuations in flow rates were noted over time in relation to the G1 and G3 emitters. In addition, there was greater interference from the dilutions of treated water produced in the process of clogging the emitters and, consequently, in the flow rate modification (Figure 1B).

Dilutions D1, D4 and D5 caused both an increase and a reduction in flow rate over time. In D1, there was an increase in flow rate, after the initial time of 0 h, reaching the maximum flow rate increase at 80 h (3.67%); while the flow rate decreased after 120 h, reaching the maximum reduction at 160 h (2.66%).

D4 and D5 had the maximum flow rate increases at 40 h (3.69 and 3.00%). After 80 h, there was a decrease in flow rate, reaching the maximum reduction at 160 h (8.40 and 31.33%). The D2 dilution only provided an increase in flow rate over time, with the maximum increase at 80 h (5.31%). In the D3 dilution, there was only a reduction in flow rate, after the initial time (0 h), presenting a maximum flow rate reduction at 160 h (8.93%). Cunha et al. (2017) only reported a reduction in the flow rate of the same G2 emitter by applying a dilution of 33% of dairy effluent in 67% of water supply, when establishing a comparison between the initial flow rate and that of other times, with maximum flow rate reduction at 80 h (17.50%). The work developed by Marques et al. (2016) with the G2 emitter applied a 50% dilution of dairy effluent in 50% water supply for 200 h. They showed a decrease in flow rate, when compared the initial time with the others, with maximum reduction at 120 h (20.63%).

there was also a change in flow rate in the G3 emitter over time, mainly in dilutions with greater proportions of treated produced water in relation to groundwater (Figure 1C). In dilutions D1, D3, D4 and D5, there was both an increase and a reduction in flow rate, while in D2 there was only a reduction in flow rate over time. In D1 and D5, there was a maximum increase in flow at 40 h (6.35 and 0.03%), while it decreased after 80 h, showing a maximum reduction at 160 h (3.78 and 11.73%). The D2 dilution provided a decrease in flow rate, after the initial time of 0 h, with maximum flow rate reduction at 160 h (4.31%). In the D3 dilution, there was a maximum increase in flow rate at 40 h (0.28%), while after 80 h the flow rate decreased and reached its maximum reduction at 120 h (8.01%). After the initial time (0 h), the D4 dilution showed an increase in the flow rate, with the maximum increase at 80 h (1.32%), while after 120 h the flow rate was decreased and reached the maximum reduction at 160 h (11, 00%). Different results were presented by Marques et al. (2016) and Cunha et al. (2017) who used the same G3 emitter for dilution of 50% of dairy effluent with 50% of water supply and 33% of dairy effluent with 67% of water supply for 200 h, respectively. They showed a decrease in flow rate over time, when comparing the flow rate in the initial time (0 h) with others, with a maximum flow rate reduction at 120 h, of 17.75 and 26.19%, respectively.

### *Flow rate coefficient of variation (FCV) behavior of non-self-compensating drippers applied dilutions of treated water produced by oil exploration*

Figure 2 shows the flow rate variation coefficient (FCV) values of the drip units equipped with three types of non-self-compensating emitters applying dilutions of water produced during 160 h. The FCV is a hydraulic performance indicator that detects the obstruction of emitters when its value increases over the time of operation and its classification changes from good (FCV ≤ 10%) to reasonable (10%> FCV ≤ 20%) or unacceptable (FCV > 20%) (Asabe, 2008; Costa et al., 2019). It was also found that D5 was the treatment that most influenced the increase in FCV, and consequently, the obstruction of the emitters over the operation time of the irrigation units. This fact is probably due to the greater hardness of the effluent in D5 (Table 5), which along with the pH > 7.0, contributed the reduction of calcium solubility and the formation of calcium carbonate precipitates that lodged inside the labyrinths of emitters (Cunha et al., 2020).

In the drip units with emitter G1 (Figure 2A) we noticed that the treatments D1 to D4 presented smaller oscillations in the values of FCV throughout the experimental period. However, D5 presented a more significant increase of the FCV after 120 h of operation. The FCV values of treatments D1 to D4, were less than 10% over the 160 h of operation, which was classified as good Asabe (2008). Cunha et al. (2017) tested the non-self-compensating type of emitter for 200 h using a dilution of 33% of dairy effluents plus 67% of groundwater for 200 h as circulating fluid. They found that the FCV was less than 10% throughout the experimental period. In the D5 treatment, the FCV values were classified as good (FCV ≤ 10%) at the 0, 40 and 80 h operating times, reasonable (10% < FCV ≤ 20%) at the 120 h operating time and unacceptable (FCV > 20%) in the 160 h operating time, according to the Asabe classification (2008).

Figure 2B shows that the greatest oscillations of FCV was occurred in the drip units equipped with the G2 emitter when the G1 and G3 units were compared. The G2 emitter was the most susceptible to clogging among the three emitters tested, even having the shortest labyrinth length of 13 mm (Table 4). Silva et al. (2013) indicated that the non-self-compensating emitter of 1.65 L $h^{-1}$ with the longest labyrinth length of 58 mm, was the most susceptible to obstruction when applying effluent from the cashew nut processing, at the service pressure of 70 kPa for 160 h. Classification of FCV values of Asabe (2008) explains that (a) D1 provided good values (FCV ≤ 10%) from 0 to 120 h, while at 160 h there was a change to reasonable (10% < FCV ≤ 20%); (b) D2 favored good values (FCV ≤ 10%) from 0 to 160 h; (c) D3 caused good values (FCV ≤ 10%) at 0, 40 and 120 h, however reasonable values (10% < FCV ≤ 20%) at 80 and 160 h; (d) D4 allowed good values (FCV ≤ 10%) at 0, 40 and 80 h, reasonable value (10% < FCV ≤ 20%) at 120 h and unacceptable (FCV ≥ 20%) at 160 h; and e) D5 resulted in good values at 0 and 40 h (FCV ≤ 10%), reasonable (10% < FCV ≤ 20%) at 80 h and unacceptable (FCV ≥ 20%) at 120 and 160 h. Cunha et al. (2017) used the same G2 emitter from the present study was tested. In this study, the G2 emitter applied a dilution of 33% of dairy effluent plus 67% of groundwater and it was noted, throughout the 200 h of operation, that the values of FCV were all classified as good (FCV ≤ 10%). This corroborates the results obtained in treatment D2 of the present study, diverging from the results found in treatments D1, D3, D4 and D5. Costa et al. (2019) used a non-self-compensating emitter of 1.65 L $h^{-1}$, operating with sanitary wastewater. They revealed that after 400 h of application of the effluent, the FCV classification proposed by Asabe (2008) went from good to unacceptable, corroborating with the results of treatments D4 and D5 of the present study and diverging from the results found for treatments D1, D2 and D3 of the present study.

Regarding the drip units equipped with the G3 emitter, there was a greater increase in the FCV values in the D4 and D5 treatments at 160 h, considering that in these dilutions the highest mean hardness values occurred (Table 5), an attribute that contributes to the clogging chemical of emitters by precipitates of calcium carbonate (Cunha et al., 2020). We verified in treatments D1 to D3 that the FCV values were classified as good (≤ 10%), while in D4 and D5 the FCV values were also considered good (≤ 10%) until 120 h and reasonable (10% < CVQ ≤ 20%) at 160 h of operation, throughout the experimental period, according to the classification proposed by Asabe (2008). These results do not corroborate with those presented by Batista et al. (2016). They reported that after 160 h of operation, the FCV values were higher than 20% and received the unacceptable classification (Asabe, 2008) on their study with drip units, equipped with non-self-compensating emitters of 1.70 and 2.00 L $h^{-1}$, subjected to service pressures of 75, 145, 215 and 285 kPa and which applied swine effluent.

### *Analysis of variance of flow rate (F) data and flow rate variation coefficient (FCV)*

Table 1 presents a summary of the analysis of variance of the flow (F) and flow rate variation coefficient (FCV) variables in the subdivided plot scheme. Analyzing the F and FCV variables showed that the triple dilution of effluent (D) x type of drippers (G) x evaluation time (T) interaction was significant at 1% probability by the F test and the coefficients of variation of the subsubplots (CVsubsubplots) were 3.36 and 54.77%, respectively. Silva et al. (2019) studied drip units in a split-split-plot scheme by applying sanitary wastewater for 400 h. They showed a significant triple interaction at 1% probability by the F test, but with higher CV for subsubplots (8.63%). Batista et al. (2018) studied the FCV variables on dripper units in a split-split-plot scheme operating with swine effluent proportions plus well water for 160 h. They reported a significant triple interaction at 1% probability of F test, while in the present study the value of CV subsubplots was smaller (32.00%).

### *Analysis of regression of flow rate (F) data*

Table 2 shows the regression equations for the flow rate variable (F) as a function of the operating time (T) of the dripper units operating with the three non-self-compensating emitters (G1, G2 and G3) and the five treatments (D1, D2, D3, D4 and D5). In the drip units equipped with the G1 emitter, the square root regression model was the one that best fitted the F and T data for treatments D1, D4 and D5, while the mean was the best representation in D2 and D3. Marques et al. (2016) applied a drip unit equipped with the same G1 emitter, by applying a 50% dilution of dairy effluent plus 50% supply water for 200 h. The average was the best representation for the F and T data, corroborating with the results from D2 and D3. The positive and negative coefficients of the square root regression equations represent the increase and decrease in flow rate over the operating time, respectively. We also noticed that the coefficients of the regression equation of D5 (0.0337 and 0.00406) were higher than those obtained in D1 and D4, thus indicating a greater susceptibility to clogging of G1 operating only with translated produced water (D5), where the risks of obstruction with chemical precipitates are greater due to the hardness (Table 5), especially when the pH of the fluid is greater than 7.0 (Cunha et al., 2020). These results differ from those found by Batista et al. (2014) with a drip unit, equipped with a non-self-compensating emitter of 1.70 L $h^{-1}$, applying a proportion of 25% pig effluent plus 75% groundwater for 160 h, where the angular coefficient of the linear model, obtained for F and T data were lower (0.000789). In the drip units that used the G2 emitter, the relationship between F and T was better adjusted in treatments D1 and D2 by the quadratic regression model, in D3 and D4 by the mean and in D4 by the linear regression model. These results do not corroborate with those found by Marques et al. (2016) who adjusted the square root model to the F and T data for the same type of emitter by applying a 50% dilution of dairy effluent plus 50% supply water for 200 h. Applying the first derivative to the quadratic equations of D1 and D2 and equaling zero (0), the dependent variable F (dF / dT = 0) obtained the maximum points of 66 and 81 h (T = -b / 2a), respectively. The coefficient of the linear regression equation also called the angular coefficient of the line (0.00287) expressed at the G2 emitter clogging rate, over the 160 h operating time. This result was inferior to that obtained by Fernandes et al. (2014) in their study with a drip unit, equipped with a non-self-compensating emitter of 1.65 $Lh^{-1}$, applying effluent from cashew nut processing for 160 h, where the clogging rate was 0.00308. On the other hand, in drip units with G3 emitter the best representation of F data as a function of T was the average in treatments D1, D3 and D4 and the linear regression model in D2 and D5. These results differ from those presented by Marques et al. (2016), where the quadratic model was the one that best fitted the F and T data, for the same type of emitter operating with dilution of dairy effluent for 200 h. The angular coefficients of D2 and D5 were 0.000483 and 0.00120, respectively, indicating a higher rate of clogging in D5. These results differ from those found by Batista et al. (2011), where the slope coefficients were 0.0024, 0.00085 and 0.0024 for drip units, equipped with a 1.70 $Lh^{-1}$ non-compensating emitter, which applied preliminary, secondary and tertiary sewage for 500 h, respectively. This indicated that the type of clogging rate varies with the quality of wastewater. It should be noted that all adjusted regression models had a determination coefficient ($R^2$) greater than or equal to 80%. The higher the $R^2$, the better the model and the smaller the error, and models with $R^2$ values greater than 80.0% are more reliable for predictive purposes (Olmez, 2009).

### *Regression of flow rate variation coefficient (FCV)*

Table 3 shows the regression equations for the variable flow rate variation coefficient (FCV) as a function of the operating time (T) of the drip units operating with the three non-self-compensating emitters (G1, G2 and G3) and the five treatments (D1, D2, D3, D4 and D5). Analysis of the drip units equipped with the G1 emitter showed that the linear regression model best fitted the FCV and T data for treatments D1 and D5, while the mean was the most adequate representation in D2, D3 and D4. The linear model of D1 represented a reduction in FCV, along with T, while in D5 the angular coefficient was 0.120 and the FCV increased with the T, indicating a higher rate of clogging of the emitters, compared to other treatments. Silva et al. (2016) worked with drip units equipped with a non-self-compensating emitter of 1.65 $Lh^{-1}$, while they applied cashew nut effluent for 160 days. They found that for the service pressure of 70 kPa the linear model was the best adjusted to FCV and T data, having a higher clogging rate (0.160). In the drip units equipped with the G2 emitter, the average represented the ratio between FCV and T in the treatments D1, D2 and D3, while the linear model was the one with the best fit to D4 and D5. Comparing the angular coefficients of the linear equations of D4 (0.111) and D5 (0.282), we noticed that the clogging rate is higher in the D5 treatment. Batista et al. (2016), applied swine effluent with drip units for 160 and found that the linear model was the best to represent the ratio between FCV and T in a 2.00 $Lh^{-1}$ non-self-compensating emitter, while subjected to a service pressure of 285 kPa with an angular coefficient of 0.116. In the drip units with emitter G3, the mean was the best representation of the

**Table 1.** Summary of the analysis of variance from flow rate (F) and flow variation coefficient (FCV) variables in split-split-plot scheme.

| Variation source | Degrees of freedom | Mean square | |
|---|---|---|---|
| | | F | FCV |
| Dilution of effluent (D) | 4 | $0.21^{**}$ | $508.02^{**}$ |
| Residue (a) | 8 | 0.001 | 31.7 |
| Type of drippers (G) | 2 | $1.81^{**}$ | $790.12^{**}$ |
| D x G | 8 | $0.027^{**}$ | $146.51^{**}$ |
| Residue (b) | 20 | 0.003 | 40.67 |
| Evaluation time (T) | 4 | $0.12^{**}$ | $364.60^{**}$ |
| D x T | 16 | $0.023^{**}$ | $162.37^{**}$ |
| G x T | 8 | $0.009^{**}$ | $106.07^{**}$ |
| D x G x T | 32 | $0.005^{**}$ | $39.47^{**}$ |
| Residue (c) | 122 | 0.002 | 20.98 |
| General means | | 1.46 | 8.36 |
| $CV_{plot}$ (%) | | 2.3 | 67.32 |
| $CV_{subplot}$ (%) | | 3.72 | 76.25 |
| $CV_{subsubplot}$ (%) | | 3.36 | 54.77 |

Note: ** Significant at 1% probability by the F test. CV - Coefficient of variation.

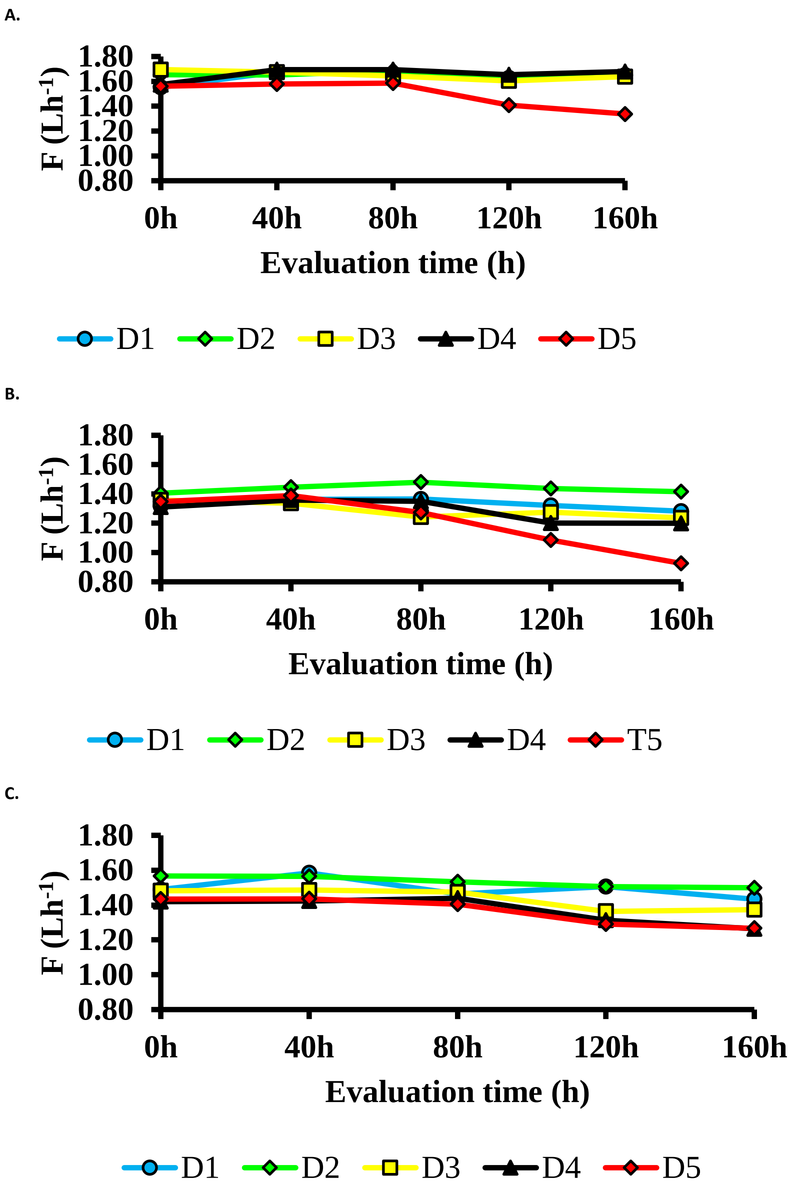

**Fig 1.** Flow rate (F) graphs according to operation times in drip units with emitters G1 (A), G2 (B) and G3 (C), with dilutions of treated water produced by oil exploration.

**Table 2.** Regression equations adjusted to flow rate (F) variable according to operation times (T) of drip units for three types of emitters (G1, G2 and G3) and five treatments (D1, D2, D3, D4 and D5) evaluated.

| Dripper | Treatment | Regression equation | $R^2$ |
|---|---|---|---|
| G1 | D1 | $\hat{F} = 1.556 + 0.0266^{*}T^{0,5} - 0.00162^{0}T$ | 0.88 |
| | D2 | $\hat{F} = \bar{F} = 1.652$ | - |
| | D3 | $\hat{F} = \bar{F} = 1.651$ | - |
| | D4 | $\hat{F} = 1.576 + 0.0275^{*}T^{0,5} - 0.00163^{0}T$ | 0.90 |
| | D5 | $\hat{F} = 1.577 + 0.0337^{0}T^{0,5} - 0.00406^{*}T$ | 0.91 |
| G2 | D1 | $\hat{F} = 1.321 + 0.00128^{*}T - 0.00000973^{*}T^{2}$ | 0.95 |
| | D2 | $\hat{F} = 1.406 + 0.00147^{*}T - 0.00000902^{*}T^{2}$ | 0.86 |
| | D3 | $\hat{F} = \bar{F} = 1.290$ | - |
| | D4 | $\hat{F} = \bar{F} = 1.283$ | - |
| | D5 | $\hat{F} = 1.434 - 0.00287^{**}T$ | 0.87 |
| G3 | D1 | $\hat{F} = \bar{F} = 1.495$ | - |
| | D2 | $\hat{F} = 1.573 - 0.000483^{**}T$ | 0.94 |
| | D3 | $\hat{F} = \bar{F} = 1.436$ | - |
| | D4 | $\hat{F} = \bar{F} = 1.372$ | - |
| | D5 | $\hat{F} = 1.463 - 0.00120^{*}T$ | 0.87 |

$^{**}$, $^{*}$ and $^{0}$ significant at 1, 5 and 10% of probability by test t, respectively.

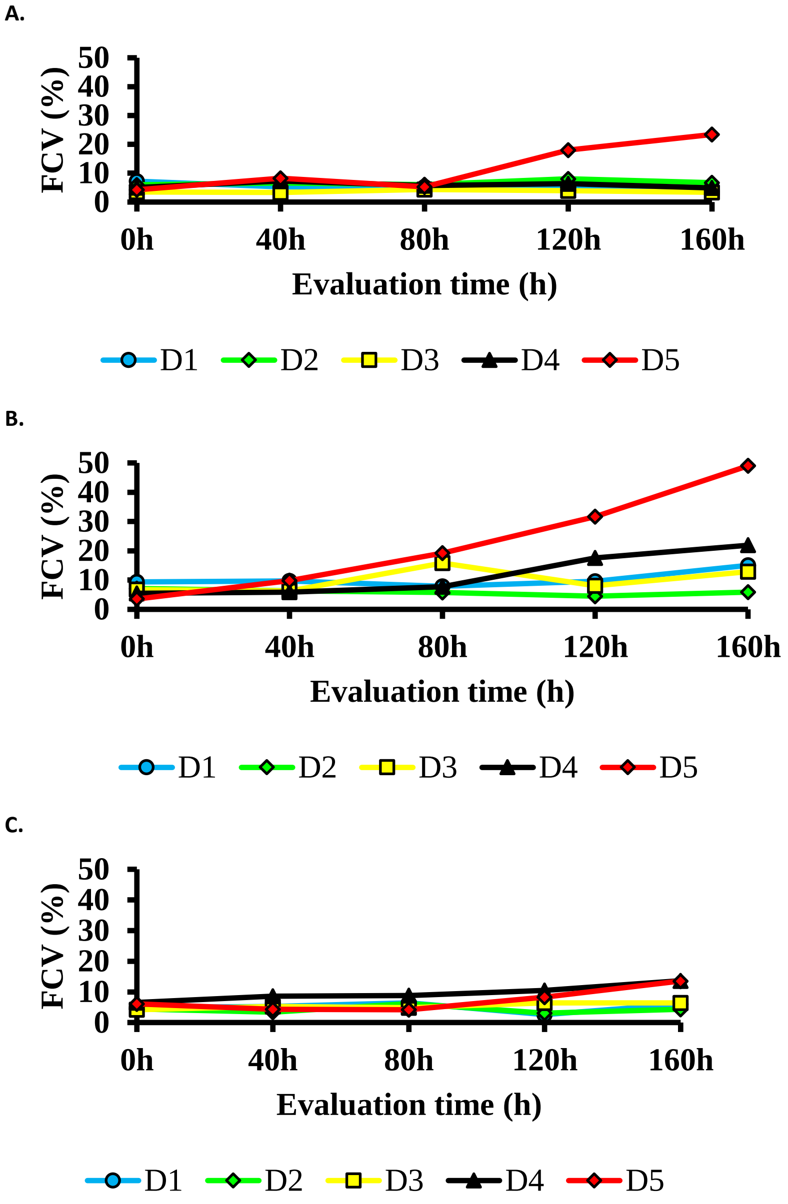

**Fig 2.** Flow coefficient of variation (FCV) graphs according to operation time in drip units with emitters G1 (A), G2 (B) and G3 (C), applying dilutions of treated water produced by oil exploration.

**Table 3.** Regression equations adjusted to flow variation coefficient (FCV) variable according to operation time (T) of drip units for three types of drippers (G1, G2 and G3) and five treatments (D1, D2, D3, D4 and D5) analyzed.

| Dripper | Treatment | Regression equation | $R^2$ |
|---|---|---|---|
| **G1** | D1 | $\widehat{\mathrm{FCV}} = 6.807 - 0.01952^{*}\mathrm{T}$ | 0.87 |
| | D2 | $\widehat{\mathrm{FCV}} = \overline{\mathrm{FCV}} = 6.672$ | - |
| | D3 | $\widehat{\mathrm{FCV}} = \overline{\mathrm{FCV}} = 3.683$ | - |
| | D4 | $\widehat{\mathrm{FCV}} = \overline{\mathrm{FCV}} = 5.961$ | - |
| | D5 | $\widehat{\mathrm{FCV}} = 2.200 + 0.120^{*}\mathrm{T}$ | 0.81 |
| **G2** | D1 | $\widehat{\mathrm{FCV}} = \overline{\mathrm{FCV}} = 10.324$ | - |
| | D2 | $\widehat{\mathrm{FCV}} = \overline{\mathrm{FCV}} = 5.914$ | - |
| | D3 | $\widehat{\mathrm{FCV}} = \overline{\mathrm{FCV}} = 9.968$ | - |
| | D4 | $\widehat{\mathrm{FCV}} = 2.796 + 0.111^{**}\mathrm{T}$ | 0.88 |
| | D5 | $\widehat{\mathrm{FCV}} = 0.0747 + 0.282^{**}\mathrm{T}$ | 0.96 |
| **G3** | D1 | $\widehat{\mathrm{FCV}} = \overline{\mathrm{FCV}} = 4.987$ | - |
| | D2 | $\widehat{\mathrm{FCV}} = \overline{\mathrm{FCV}} = 4.267$ | - |
| | D3 | $\widehat{\mathrm{FCV}} = 4.281 + 0.0140^{*}\mathrm{T}$ | 0.83 |
| | D4 | $\widehat{\mathrm{FCV}} = 6.401 + 0.0401^{**}\mathrm{T}$ | 0.92 |
| | D5 | $\widehat{\mathrm{FCV}} = 6.105 - 0.0835^{*}\mathrm{T} + 0.000817^{**}\mathrm{T}$ | 0.99 |

$^{**}$, $^{*}$ and $^{0}$ significant at 1, 5 and 10% of probability by test t, respectively.

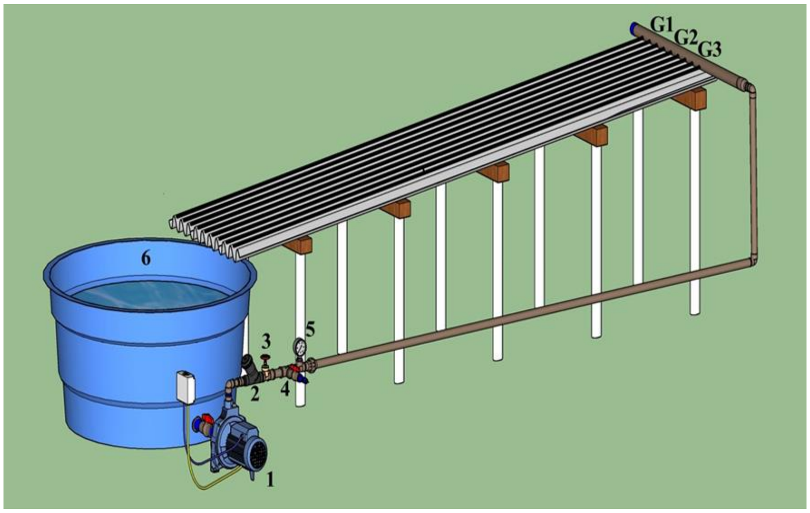

**Fig 3.** Bench test comprising of centrifuge pump (1), screen filter (2), valve (3), collection site for effluent samples (4), manometer (5), reservoir for the storage of diluted treated produced water (6) and non-self-compensating drippers (G1, G2 and G3).

**Table 4.** Characteristics of non-self-compensating drippers used in the assays: nominal flow rate (F), filtration area (FA), length of labyrinth (LL), operating pressure range (OPR) and spacing between emitters (SE) adapted from Vale et al. (2020).

| Drippers | F (L $h^{-1}$) | FA ($mm^2$) | LL (mm) | OPR (kPa) | SE (m) |
|---|---|---|---|---|---|
| G1 | 1.60 | 34.0 | 23 | 60 - 100 | 0.30 |
| G2 | 1.60 | 17.0 | 13 | 65 -100 | 0.30 |
| G3 | 1.70 | 6.0 | 44 | 50 - 300 | 0.20 |

**Table 5.** Means and standard deviations of the physical and chemical attributes of dilutions of treated water produced by oil exploration (D) adapted from Vale et al. (2020).

| Attributes | Treatments | | | | |
|---|---|---|---|---|---|
| | D1 | D2 | D3 | D4 | D5 |
| pH | 8.70±0.27 | 8.57±0.20 | 8.61±0.23 | 8.47±0.16 | 8.60±0.05 |
| EC | 0.72±0.08 | 0.75±0.16 | 0.78±0.12 | 0.72±0.06 | 0.63±0.07 |
| $Ca^{2+}$ | 0.50±0.27 | 0.68±0.30 | 0.86±0.45 | 1.07±0.55 | 1.05±0.94 |
| $Mg^{2+}$ | 0.38±0.13 | 0.51±0.24 | 0.74±0.25 | 0.65±0.51 | 1.00±0.61 |
| $CO_3^{2-}$ | 1.60±0.44 | 1.20±0.46 | 1.20±0.59 | 1.40±0.27 | 1.40±0.30 |
| $HCO_3^-$ | 3.00±0.11 | 3.30±0.32 | 3.40±0.38 | 3.40±0.22 | 3.40±0.29 |
| Hardness | 45,50±8,39 | 69,50±8,44 | 84,50±10,94 | 98,00±7,95 | 108±6,58 |
| TSS | 10±6 | 10±5 | 8±2 | 12±6 | 8±5 |
| TDS | 298±122 | 373±97 | 379±75 | 319±129 | 319±129 |

EC - Electric conductivity, in dS $m^{-1}$; $Ca^{2+}$ - Calcium, in $mmol_c$ $L^{-1}$; $Mg^{2+}$ - Magnesium, in $mmol_c$ $L^{-1}$; TSS - Total suspended solids, in mg $L^{-1}$, TDS - Total dissolved solids, in mg $L^{-1}$, $CO_3^{2-}$ - Carbonate, in $mmol_c$ $L^{-1}$ and $HCO_3$ – Bicarbonate, in $mmol_c$ $L^{-1}$.

data of FCV and T in treatments D1 and D2, while the linear and quadratic models were best fit for treatments D3 and D4 and treatment D5, respectively. These results differ from Costa et al. (2019), where the square root model was the one that best fit the FCV and T data of a 1.65 $Lh^{-1}$ in non-self-compensating emitter operating with sanitary wastewater for 400 h. Table 3 also shows that the adjusted regression models presented a coefficient of determination ($R^2$) greater than or equal to 80%, which is more reliable for predictive purposes according to Olmez (2009).

## Materials and methods

### *Experimental set-up*

Current assay was performed at the experimental unit of the Laboratory of Rural Constructions and Environment of the Department of Engineering and Environmental Sciences (DECAM) of the Engineering Center (CE), on the Eastern Campus of the Universidade Federal Rural do Semi-Árido (UFERSA) in Mossoró, RN, Brazil, at 5°12’13.14” S and 37°19’26.93” W, between 26th August and 5th October 2018.

Five 8.00 $m^2$ (1.00 m wide by 8.00 m long) test benches were prepared, with a wooden basis to hold the undulated fiber-cement tiles. Tiles were set at a 2.5% slide for the recirculation of the effluent. A 0.31 $m^2$ reservoir was placed at the lower part of each bench. The device was locked to a drip irrigation system composed of a 0.50 hp motor pump, a filter screen with 130 µm pores, valve, a site for collecting effluent samples, a glycerin analogic manometer (0 - 400 kPa), a main line measuring 32 mm, a derived line measuring 50 mm and nine 8.00 m lateral lines.

The drip irrigation system was divided into three dripper units distributed at random on the bench test. Each dripper unit comprised of three lateral lines measuring 8.00m acquired from a sole drip manufacturer. Sixteen drippers, at an equal distance from each other, were selected in each lateral line to assess distribution uniformity of the effluent. Fig. 3 shows the bench test.

The three-labyrinth-type and non-self-compensating drippers were chosen for their lowest clogging rates, highly commercialized in Brazil as shown in Table 4 (adapted from Vale et al., 2020).

Produced water was retrieved from a petroleum-producing company on the Potiguar Basin, close to Jucuri RN Brazil, rural area in the municipality of Mossoró, Brazil. After collection, the water underwent treatment with organic polymer AGEFLOC DW-3753 on the site of the assay. Underground water for dilution derived from a tubular well administered by the Water and Sewage Company of Rio Grande do Norte (CAERN).

### *Conducting the experiment*

Water was diluted with scale pails and stored in reservoirs at the end of each test bench, according to each treatment. The following treatments were assessed: D1 - 100% of UW (underground water), control; D2 - 90% of UW and 10% PW (treated produced water); D3 - 80% of UW and 20% of PW; D4 - 70% of UW and 30% of PW; and D5 - 60% of UW and 40% of PW. Drip units from each bench test ran at an average of four hours a day until deadline at 160 h, for the potential formation of incrustation in the drippers and in the lateral lines. Five evaluations on the effluent´s distribution uniformity was taken during this period, at an interval of 40 h each, specifically at times 0, 40, 80, 120 and 160 h.

Flow rate of 16 drippers selected by lateral line (totaling 48 emitters per drip) was evaluated by collecting the applied effluent volume by the dripper during the time of three minutes. Drip flow rate was determined by equation 1:

$$\mathrm{F} = \frac{\mathrm{V}}{1000.\mathrm{t}}.60 \qquad (1)$$

Where, F is the dripper´s flow rate, in L $h^{-1}$; V is the volume of the collected effluent, in mL; t is the effluent collection time, in min.

The flow rate coefficient of variation (FCV) was calculated by flow rate data of each lateral line, according to equation 2:

$$\mathrm{FCV} = 100.\frac{\sqrt{\frac{\sum_{i=1}^{n}(q_i - q_a)^2}{n_e - 1}}}{q_a} \qquad (2)$$

Where, FCV is flow rate coefficient of variation, in %; $q_i$ is the flow rate of each dripper, in L $h^{-1}$; $q_a$ - is the average flow rate of drippers, in L $h^{-1}$; $n_e$ is the number of evaluated drippers.

The ASAE EP 405 standard proposes the following classification for FCV values: less than 10%, good; between 10 and 20%, reasonable; and greater than 20%, unacceptable (Asabe, 2008).

Dilution samples for each treatment were collected by the end of each evaluation for physical and chemical analyses as shown in Table 5 adapted from Vale et al. (2020). Samples were sent to the Laboratory of Soil, Water and Plant Analyses (LASAP) of UFERSA: pH was determined by pH-meter; electric conductivity (EC) was determined by conductivity-meter; calcium ($Ca^{2+}$) and magnesium ($Mg^{2+}$) were determined by titrimetric method. The levels of carbonate ($CO_3^{2-}$) and bicarbonate ($HCO_3^-$) were obtained by the titrimetric method, while the hardness was obtained by adding the contents of the multivalent cations $Ca^{2+}$ and $Mg^{2+}$. Concentrations of total suspended solids (TSS) and total solids (TS) were calculated by the gravimetry and concentrations of total dissolved solids (TDS) were assessed by the difference between TS and TSS concentrations. The analyzes followed the recommendations of the Standard Methods for the Examination of Water and Wastewater (Baird et al., 2017).

## Statistical analysis

The experiment was set up in a completely randomized design in a split-split-plot scheme with three repetitions. Having the dilutions of treated water produced by oil exploration (D1, D2, D3, D4 and D5) in the plots, the types of non-self-compensating drippers (G1 - 1.6 L $h^{-1}$, G2 - 1.6 L $h^{-1}$ and G3 - 1.7 L $h^{-1}$) in the subplots and evaluations time in the subsubplots (0, 40, 80, 120 and 160 h).

Data on the F and FCV underwent analysis of variance by F test ($p \leq 0.01$). Averages were compared by Tukey´s test ($p \leq 0.05$). The regression models were selected based on the value of the coefficient of determination ($R^2 \geq 80\%$) according to Olmez (2009) and the significance of the coefficients of the regression equation using the "t" test ($p \leq 0.10$).

## Conclusion

The G3 emitter was the most resistant to clogging by chemical agents, presenting smaller oscillations over the operating time of hydraulic indicators flow rate and flow rate variation coefficient. The dilutions D2 (90% of groundwater plus 10% of treated produced water) and D3 (80% of groundwater plus 20% of treated produced water) provided the lowest losses in hydraulic performance in the drip units.

The highest rates of clogging was occurred in the G2 emitter operating in the D5 dilution (60% of groundwater plus 40% of treated produced water).

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