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Full Length Research Paper

Biofouling and performance of labyrinth-type emitters in drip irrigation with treated domestic sewage

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The use of wastewater in irrigated agriculture is an alternative to the lack of water resources of higher quality and allows obtaining, besides the reuse, environmental improvements. In the application of wastewaters, such as treated domestic sewage, localized drip systems are affected by the decrease in application of uniformity and discharge rate of the emitters, due to clogging. In this context, this study aimed to characterize the material of the biofouling and evaluate its effects on the hydraulic performance of emitters utilized in drip irrigation with wastewater from treated domestic sewage. The experiment was carried out on a bench at the field, in the Brazilian semi-arid region, in the state of Paraíba, Brazil, and consisted of the application of wastewater and public-supply water using three models of labyrinth-type emitters. The hydraulic performance of the emitters was monitored through the variation in discharge rate and coefficient of uniformity along 1188 h of operation. X-ray spectroscopy analysis was performed to characterize the chemical composition of the material that caused biofouling. The chemical elements identified in the characterization of the biofouling material were sodium, magnesium, aluminum, silicon, chlorine, calcium, iron, carbon and oxygen; the latter two were found in higher amounts. In addition, the presence of fluorine was also detected. Biofouling caused linear and quadratic reduction in the discharge rate of the emitters over the time of operation. Both wastewater and the hydraulic characteristics of the labyrinth contributed to clogging of the emitters.

Key words: Biofilm, X-ray spectroscopy, uniformity coefficient, wastewater, emitter clogging.

INTRODUCTION

One of the reasons for the utilization of wastewaters in irrigated agriculture is the scarcity of water in some regions. According to Cirelli et al. (2009), the use of wastewater, with or without treatment, is in increase in arid and semi-arid regions; it is a valuable resource, but the environmental effects of its use in irrigation need to be studied. Besides the environmental effects, the consequences on the irrigation systems may lead to loss of efficiency and reduction of useful life of the equipment and materials.

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For the application of wastewaters, such as treated domestic sewage, in irrigated agriculture, the adequate choice, due to the contamination, is drip irrigation (Tripathi et al., 2014). With regards to the form of application with higher efficiency and lower water volumes, however, one of the problems of this application of wastewaters is the clogging of the emitters.

Water quality is directly associated with the clogging process. Nakayama et al. (2006) classified some physicochemical parameters for the risk of clogging. These parameters are fundamental for the control of the quality of the water applied through the system in order to prevent problems related to the wear and clogging of the emitters.

Emitter clogging by the use of domestic sewage, according to Batista et al. (2010), the problem is the biofilm, a result of the interaction between colonies of bacteria and fungi, causing partial or total clogging of the emitters, leading to decrease in distribution uniformity. For Oliver et al. (2014), the fouling biomass in the emitters is a compound of microbial secretions and particles in suspension.

Irrigation using wastewaters with high bacterial load promotes the formation of biofilm in the piping. For Beech et al. (2005), the produced extracellular polymeric substances (EPS) comprehend different macromolecules, interfere with the initial cellular adherence on the surface of the material and form the matrix of the biofilm.

Besides the quality characteristics of the applied water, various factors influence the clogging process, for instance, irrigation frequency (Zhou et al., 2015), flow speed (Li et al., 2012) and the depth of the pathway in the emitter (Zhou et al., 2014).

In labyrinth-type emitter, the channels that form the flow path to dissipate energy and standardize the output discharge rate are prone to clogging, due to regions with low flow speed where small particles accumulate. Li et al. (2008) recommend the elimination of these low-speed regions to improve the anti-clogging capacity.

For biofouling of piping systems used in irrigation, the energy-dispersive X-ray spectroscopy in electronic microscopy analysis allows the identification of the clogging material caused by inadequate quantity of water.

In this context, the effects of biofouling on the performance of systems subjected to operation with wastewater from treated domestic sewage and clean water from the public supply system were monitored in a Brazilian semi-arid region, with subsequent chemical characterization through X-ray spectroscopy analysis, in the labyrinth channels of the emitters.

MATERIALS AND METHODS

Conduction of the experiment

The experiment of emitter clogging was carried out at the headquarters of the National Institute of the Semi-Arid Region (INSA), located in the municipality of Campina Grande, in the state of Paraíba, Brazil, at the geographic coordinates of 7° 16’ 20’’ S and 35° 56’ 29’’ W, and altitude of 550 m. The local climatic conditions along the experimental period were dry, that is, there were no rainfalls. Köppen’s classification classifies the climate of the region as *As*, with rains in the autumn and dry periods in the rest of the year. The electronic microscopy with analysis through X-ray spectroscopy was performed in the same municipality, at the laboratory of Materials Engineering of the Federal University of Campina Grande.

The freshwater (FW) used in the experiment was provided by the Company of Water and Sewerage of the Paraíba State (CAGEPA) to the INSA. The wastewater (WW) comes from the anaerobic sewage treatment station, composed of septic tank and filter formed by a bed of crushed stone contained in a rectangular tank. The sewage supplying the station comes from disposals of the research institute.

Three models of labyrinth-type, non-pressure compensating emitters were used in the experiment. The non-pressure compensating emitters have higher potential for the formation of biofilm; another reason for the choice is the wide use of these emitters in the area encompassed by the Brazilian semi-arid region, where they are subjected to varied water quality, with big clogging potential.

The selected emitters were: Netafim® Streamline 16080, referred to as E1, with discharge rate of 1.6 L h^{-1} at pressure of 100.0 kPa, arranged in the lateral line at spacing of 0.3 m; Naandanjain® Taldrip, referred to as E2, with discharge rate of 1.7 L h^{-1} at pressure of 100.0 kPa, spaced by 0.2 m; and Netafim® Tiran 16010, referred to as E3, with discharge rate of 2.0 L h^{-1} at pressure of 100.0 kPa and spacing of 0.4 m.

In order to have the interference of the climate on the clogging of the emitters, an experimental bench (10 x 2 x 1.5 m, L x W x H) was mounted at the field, without climate protection, the experiment were carried out in the summer, with no rain and high temperature; at the end, gutters channeled the waters to the individual storage systems at a lower level.

The experiment had one lateral line for each emitter and type of water, totaling six lateral lines; they were suspended at 0.3 m from the bench to facilitate the determination of the discharge rates of the emitters through a simultaneous collection mechanism with expanded polystyrene plates and collecting cups.

The types of water (wastewater and freshwater) had individual systems, which contained: controller with 120-mesh disc filter (IRRITEC® - Model FLD), opening and closing valves, hydrometer (LAO® - Model UJB1) with nominal discharge rate of 1.5 m^3 h^{-1}, glycerin-filled Bourdon-type manometer (GE®) with resolution of 0.1 kg cm^{-2} and direct-action pressure controllers (BERMAD® - Model 0075 PRVy).

The inlet pressure was regulated at 100.0 kPa, within the ranges of use described in the catalogues of the manufacturers of the three emitter models. Figure 1 shows the layout of the bench, controller, pumping system and storage systems of the waters.

The length of 10.0 m of the lateral line was necessary to obtain the minimum of emitters tested for the model with highest spacing, according to the Brazilian technical norm ABNT/NBR ISO 9261:2006 for tests with emitters.

The hydraulic performance of the system was monitored through an initial evaluation with the new emitters and, later, every 36 h of operation; the operation time was 12 h per day, controlled by an automatic system.

Evaluations were performed with the collection of water for 4 min using collecting cups in each emitter, simultaneously. Twenty-five emitters (replicates) were randomly selected for each type of water and model of emitter; then, using a graduated cylinder, the volume was determined and transformed to discharge rate (L h^{-1}).

The operation limit of the system was a value higher than 1000 h, time necessary for a probable clogging of the drippers, according to

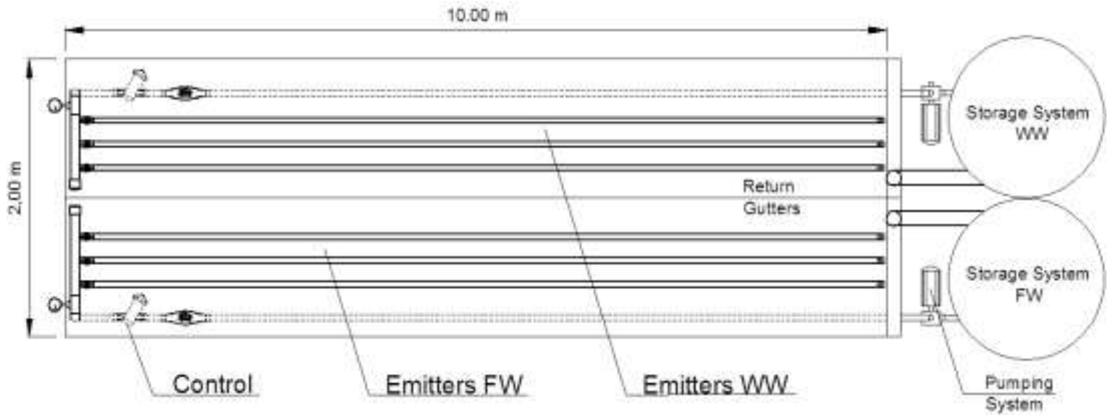

Figure 1. Layout of the individual systems for wastewater and freshwater with the return gutters and storage systems.

Liu and Huang (2009). At the end of the experiment, thirty-three evaluations were obtained, in a total of 1188 h of operation.

Hydraulic performance monitoring

With the data of discharge rate of the initial and subsequent evaluations, the variation of the discharge rate (Dra) and the coefficient of uniformity (CU), also used by Zhou et al. (2013), were calculated using Equations 1 and 2.

$$Dra = 100\left(\frac{\sum_{i=1}^{n} q_i}{nq_{new}}\right) \quad (1)$$

Where: Dra, variation of discharge rate, %; q_i, discharge rate of the tested emitter, L h^{-1}; q_{new}, discharge rate of the new emitter, L h^{-1}; and n, number of tested emitters.

$$CU = 100\left(1 - \frac{\sum_{i=n}^{n}\left|q_i - \bar{q}\right|}{n\bar{q}}\right) \quad (2)$$

Where: CU, Coefficient of uniformity, %; and $\bar{q}$ = mean discharge rate of the emitters, L h^{-1}.

Physicochemical and microbiological analyses of the waters

At the beginning of the experiment, the wastewater and freshwater were subjected to physicochemical and microbiological characterization. The analyses were carried out by the Reference Laboratory in Desalination (LABDES) of the Federal University of Campina Grande (UFCG) using the defined substrate technology (Colilert) for the microbiological analysis, while the physicochemical analysis used the Standard Methods methodology. Table 1 shows the physicochemical and microbiological characteristics of both types of water.

Coliform is only microbiological parameter: indicate bacterial population, main constituent of biofilm. The other elements are at risk of clogging in drip irrigation.

Energy-dispersive X-ray spectroscopy (EDS) analysis

In order to know the chemical composition of the biofouling in the labyrinth of the emitters subjected to irrigation, energy-dispersive X-ray spectroscopy (EDS) was performed using a scanning electron microscope (SEM), one of the techniques used in the study of biofouling (Beech et al., 2005). The electronic microscope used was a Shimadzu Corporation® - Superscan SSX-550. The analysis through EDS identifies the composition of the sample, informing the qualitative or semi-quantitative characteristics. In the SEM, the beam of electrons excites the sample, which, according to the photoelectric effect, emits X rays that are characteristic of the chemical elements present.

At the end of the experiment, one emitter was removed from the middle of each lateral line for both types of water for the EDS analysis. For each emitter, one channel of the flow labyrinth was removed, totaling six samples, which were subjected to analysis in triplicate.

Statistical analysis

For the relationship between operation time and discharge rate variation, analysis of variance was performed, with later regression using the model of best fit; for the coefficient of uniformity, the Student's t-test was used for the comparison between two means. The software Minitab 16 was used for the analyses.

RESULTS AND DISCUSSION

Chemical composition of the biofouling material

Morphological and composition characteristics of the biofoulings formed inside the flow labyrinth and which promote total or partial clogging of the emitters are dependent on many factors. The characterization of these pro-clogging agents is important in order to make good decisions in relation to the application of products

Table 1. Physicochemical and microbiological characterization of the wastewater from treated domestic sewage and freshwater.

Physicochemical parameters	Results	
	Freshwater	Wastewater
Electric conductivity (mmho cm^{-1} at 25°C)	1092.0	2139.0
pH	6.6	7.6
Aluminum (mg L^{-1})	0,13	0,09
Calcium (mg L^{-1})	26.6	48.0
Sodium (mg L^{-1})	148.9	234.7
Magnesium (mg L^{-1})	35.0	37.2
Potassium (mg L^{-1})	5.3	60.6
Total iron (mg L^{-1})	0.01	0.08
Chloride (mg L^{-1})	305.3	388.7
Silica (mg L^{-1})	3.7	6.2
Total solids dissolved at 180°C (mg L^{-1})	662.4	1160.0
Microbiological parameter		
Total coliforms (CFU)	520.0	10112.0

Table 2. Energy-dispersive X-ray spectroscopy (EDS) analysis for each emitter and type of water.

Chemical elements	Freshwater			Wastewater		
	E1	E2	E3	E1	E2	E3
C (at.%)	37.9	54.8	39.9	43.5	57.5	53.2
O (at.%)	36.2	31.2	35.1	35.5	29.9	32.9
F (at.%)	-	-	-	6.1	7.0	5.4
Na (at.%)	4.0	4.7	5.0	2.9	2.6	2.4
Mg (at.%)	2.3	2.0	2.3	1.5	1.7	1.1
Al (at.%)	3.6	1.5	2.4	1.7	1.1	1.3
Si (at.%)	5.5	1.5	4.6	6.0	-	3.7
Cl (at.%)	3.3	2.8	3.1	1.2	-	-
Ca (at.%)	2.2	1.5	0.9	1.4	-	-
Fe (at.%)	5.0	-	6.5	-	-	-

at.% - atom percentage.

and processes to unclog the system.

The results of the X-ray spectroscopy analysis of the chemical elements of the biofouling samples from the emitters used with wastewater and freshwater are shown in Table 2.

The largest amounts were related to the elements carbon and oxygen; however, the EDS analysis has limitation in the detection of light elements, underestimating their amounts. The values of carbon can be attributed to the organic matter adhered to the labyrinth walls, especially in the constitution of the EPS. In the EPS, there are carbohydrates, proteins, humic substances and nucleic acids, which interfere with the properties of microbial aggregates, such as mass transfer, characteristics of surface, adsorption capacity, stability and formation of aggregates (Sheng et al., 2010). The oxygen can be attributed to the formation of carbonates, bicarbonates and hydroxides in the biofouling, such as calcium carbonate, one of the most common factors for the clogging of emitters with chemical precipitates.

The estimate of fluorine found in the wastewater samples is due to the high concentration existing in the sewage, because of the procedure of oral hygiene with dental products such as toothpastes and mouthwashes. Thus, the concentration increases in relation to the freshwater, which is also fluoridated to combat dental cavity.

The existence of fluorine in the chemical composition of the biofouling, which is not an element with risk of clogging, is justified by the high affinity, especially to di- and trivalent metals, favoring the retention of fluorine in living organisms, as in the case of the biofilm.

Besides carbon, oxygen and fluorine, the elements sodium, magnesium, aluminum, silicon, chlorine, calcium and iron were also identified. The elements that were not quantified in the analysis have low concentrations; thus, the device is not able to measure them. The analysis of the waters demonstrates the existence of the elements found through the EDS analysis; however, the deposit of these elements was different between the emitters and types of water, indicating the interference of the hydraulic characteristics of the emitter, such as discharge rate and inlet and outlet sections of the labyrinth.

In studies on fouling with treated wastewaters in localized irrigation system, Tarchitzky et al. (2013) also observed higher values for carbon and oxygen; other elements were sulfur, phosphorus, magnesium, calcium, silicon, aluminum and iron. In addition, the elements were the same in the change of water quality, but with different proportions.

According to Oliver et al. (2014), there is no single reason for the clogging of emitters with reclaimed waters; these authors also point out that the bacterial secretions are the beginning of the biofouling process and, later, are structured by particles that escape from the filtering mechanism, such as inorganic residues.

The beginning of biofilm formation and its adhesion were identified by Yan et al. (2010) in 96 h of operation, and induced the clogging of the emitters by treated wastewaters. For Shelton et al. (2013), biofilm formation is highly irregular, unpredictable and, besides all, its effect on the microbiological quality of the water is a casual process. Biofouling is a complex process with many factors and the quality of the applied water and the hydraulic characteristics of the emitter and the system stand out as determinant components in the clogging process.

The development of image microscopy and techniques of surface analysis change the perception of the impact of microorganisms on the materials in natural environments and artificial systems (Beech et al., 2005).

Hydraulic performance of the emitters

The variation in discharge rate (Dra) expresses the reduction in the discharge rate of the system affected by the biofouling inside the emitter, causing first a partial clogging, which evolves to a total clogging along the operation time. Thus, along the operation, there was a significant relationship with the variation in the discharge rate.

For Tarchitzky et al. (2013), the measurements of emitter discharge rate show the operation affected by the fouling, which is expressed by the difference between the mean rates and the nominal flow, and also by high coefficients of variation.

In the regression analysis between the independent variable, time and the discharge rate variation, linear and quadratic models showed the best fit. Figure 2 shows the regression analysis for the three models of emitters and for both types of water, besides the fitting equation and the coefficient of correlation (R^2).

In the regression analysis, the discharge rate showed a linear response as a function of the operation time for the emitter E1, in the wastewater (Figure 2a), and for E3 in the freshwater (Figure 2f); the others showed a quadratic polynomial fit. However, the emitter E2 ($R^2 = 0.50$) utilized with freshwater (Figure 2d) obtained an unsatisfactory coefficient of determination, demonstrating little relationship between the discharge rate in the emitter and the operation time.

In the study of many emitters, pressure compensating and non-pressure compensating, with treated reclaimed water, Pei et al. (2014) identified that the variation in the discharge rate of the emitter and uniformity coefficient decreased linearly in an experiment with 540 h of operation.

The coefficient of uniformity provides the application uniformity based on the variability of the discharge rates in the system and suffers interference from the process of biofouling and, as a consequence, of the clogging. The operating time also determines the reduction in discharge rate as seen by the big drop in uniformity coefficients. According to Figure 3, the freshwater showed the best coefficients of uniformity along the operation time of 1188 h. In the application of wastewater, at the end of the operation time, coefficients of uniformity of 77.77, 30.64 and 22.45% were obtained for the emitters E1, E2 and E3, respectively. The hydraulic performance of the emitters was affected by the biofouling and the formation of biofilm, resulting from the inadequate quality of the irrigation water, mainly represented by the intermediate risk of clogging by total coliforms and dissolved solids found in the analysis, according to Nakayama et al. (2006) (Table 1).

The amount of total coliforms in the freshwater was lower than in the wastewater (Table 1), obtaining a low risk of clogging of the piping, the only water quality parameter with difference in the classification of risk according to Nakayama et al. (2006).

In the application of freshwater, the emitters showed satisfactory performance at the end of the experiment and E1 showed the lowest coefficient of uniformity, 83.03%. The emitters E2 and E3 at the operation time of 1188 h showed coefficients of uniformity of 92.75 and 93.56%, respectively. The reductions in distribution uniformity were accentuated from 540 h of operation on (Figure 3), indicating the influence of the operating time; until this time, the coefficients of uniformity were all above 90%. In the use of treated sewage effluent, Yan et al. (2009) obtained significant reductions in the discharge rate and uniformity from 360 h of operation on.

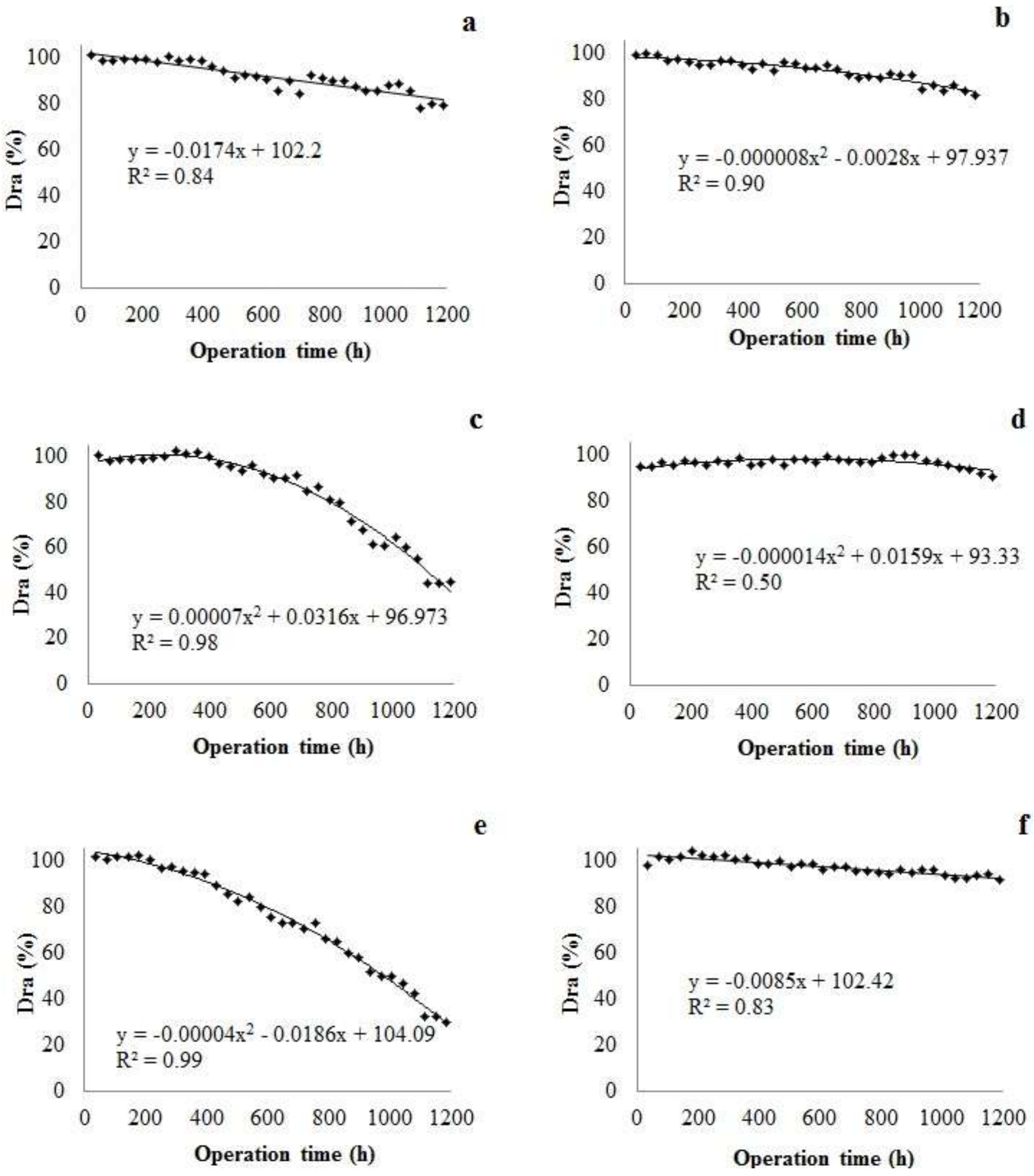

Figure 2. Variation of discharge rate as a function of operation time for the three models of emitters and each type of water. Wastewater: (a) E1, (c) E2 and (e) E3. Freshwater: (b) E1, (d) E2 and (f) E3

Table 3. Results of the t-test between two means of coefficient of uniformity (CU) for the emitters and types of water.

Water	Emitters	Wastewater			Freshwater		
		E1	E2	E3	E1	E2	E3
Wastewater	E1						
	E2	*					
	E3	*	ns				
Freshwater	E1	ns	*	*			
	E2	*	*	*	*		
	E3	*	*	*	*	*	

ns– not significant, *significant ($p < 0.05$).

Using reclaimed water, Zhou et al. (2013) observed linear correlation between the dry weight, PLFAs and extracellular polymers (EPS) of the biofilm and the variation in discharge rate (Dra) and the coefficient of uniformity, describing well the mechanism of clogging by biofilm. In the comparison between emitters through the hydraulic performance demonstrated by the coefficient of uniformity, the influence of water quality and internal arrangement of the emitter between the studied treatments was observed. The results of the t-test for the coefficient of uniformity in each emitter and type of water are shown in Table 3.

The coefficient of uniformity showed no statistical

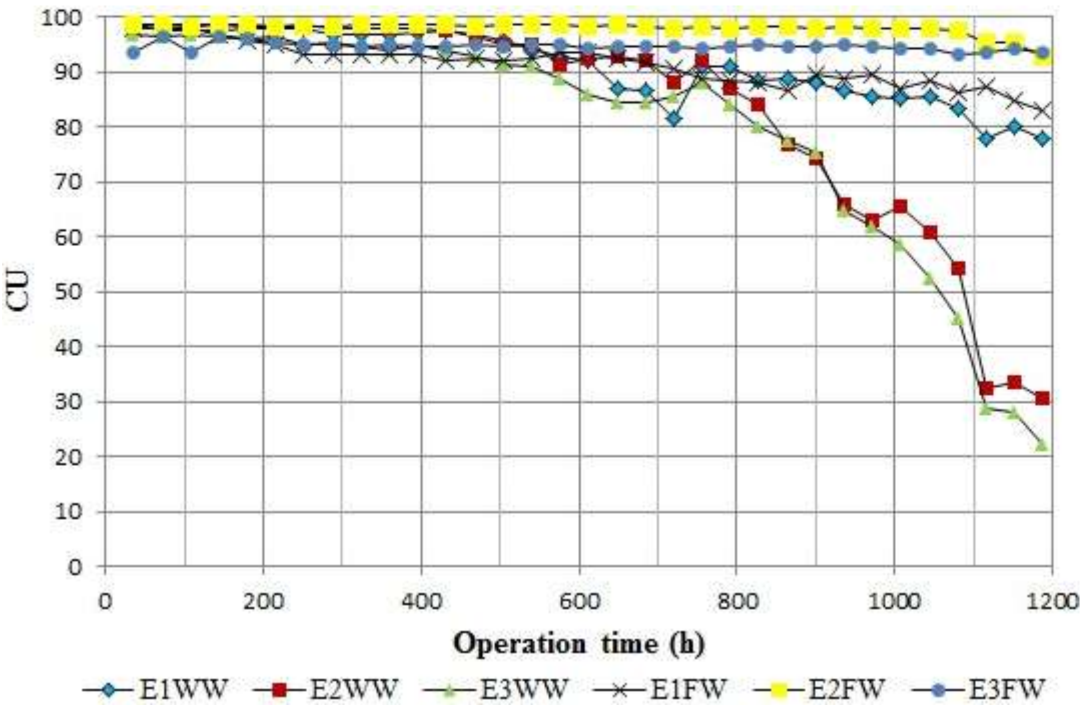

Figure 3. Coefficient of uniformity (CU) during the operation time for the three emitters and two types of water. E1WW, E2WW, E3WW, E1FW, E2FW, E3FW – Emitters 1, 2 and 3, respectively, with wastewater (WW) and freshwater (FW).

difference at 5% significance between the types of water for the emitter E1 (Table 3), in which the physicochemical and biological quality of the waters did not interfere with the water distribution uniformity with this type of emitter. The results do not indicate influence on the type of water in the drip E1.

For the application of wastewater, the emitters E2 and E3 did not differ statistically (Table 3). Additionally, the coefficients of uniformity are lower than those of E1 (Figure 3), demonstrating a dependence with the quality of the applied water, since, for freshwater, the coefficients of uniformity were higher for E2 and E3 (Figure 3) in relation to E1. The emitter E1 has no influence on the applied water.

Studies must be conducted in order to obtain information regarding the characteristics of biofouling and its origins, for the development of devices, emitters and systems with anti-clogging capacity. Thus, the application of water of lower quality or wastewater mainly found in regions with water scarcity may provide better performance indices and prolonged useful life for the localized irrigation systems.

Conclusions

The chemical elements identified in the characterization of the biofouling material were sodium, magnesium, aluminum, silicon, chlorine, calcium, iron, carbon and oxygen; the latter two were found in larger amounts. In addition, the presence of fluorine was also detected. The biofouling caused linear and quadratic reductions in the discharge rate of the emitters along the operation time; both wastewater and the hydraulic characteristics of the labyrinth contributed to the process of clogging of the emitters.

The coefficient of uniformity remained above 90% for all treatments until 540 h of operation; there was difference in relation to the application of wastewater and freshwater in hydraulic performance of emitters.

Conflict of Interests

The authors did not declare any conflict of interests.

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