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ORIGINAL ARTICLE

Canonical correlation between clogging agents and performance of drippers operating with aquaculture effluents[1]

Correlação canônica entre agentes de entupimento e desempenho de gotejadores operando com efluente da aquicultura

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HIGHLIGHTS:

Clogging agents have inverse canonical correlation to hydraulic performance coefficients of non-self-compensating emitters.
Canonical analysis indicates that clogging of drippers is caused by combination of physical, chemical, and biological agents.
The dripper most susceptible to clogging was the ST (1.6 L h^{-1}), and the least susceptible was the SL (1.6 L h^{-1}).

ABSTRACT: The canonical correlation is used to correlate groups of distinct variables. The objective of this study was to use canonical correlation analysis to evaluate the interaction between water quality attributes clogging-causing and the hydraulic performance of non-pressure compensating drippers operating with dilutions of aquaculture effluent in well water. The experiment was in a completely randomized design in a split-split-plot scheme with three replicates, with five dilutions in the plots (Dilution 1: 100% aquaculture effluent; Dilution 2: 75% aquaculture effluent + 25% well water; Dilution 3: 50% aquaculture effluent + 50% well water; Dilution 4: 25% aquaculture effluent + 75% well water; and Dilution 5: 100% well water), three emitters in the sub-plots (ST (1.6 L h^{-1}), SL (1.6 L h^{-1}) and NJ (1.7 L h^{-1})), and three operating times in the sub-subplots (0, 80 and 160 hours, in which 0 hours operating time means the start of evaluations). The statistical analyses performed were correlation matrix and canonical analysis. The canonical correlation analysis indicated that when the concentrations of attributes increase, the hydraulic performance of the drippers decreases. The interaction of this group of attributes indicates that the clogging of drippers operating with the five dilutions of aquaculture effluent in well water occurs by the combined action of physical, chemical, and biological agents. The ST dripper was the least sensitive to the group of quality attributes of the dilutions, whereas the most sensitive was the SL dripper.

Key words: agricultural reuse, multivariate statistics, emitters

RESUMO: A correlação canônica é usada para correlacionar grupos de variáveis distintas. O objetivo deste estudo foi utilizar análise de correlação canônica para avaliar a interação entre atributos de qualidade da água causadores de entupimento e o desempenho hidráulico de gotejadores não autocompensantes operando com diluições de efluente de aquicultura em água de poço. O experimento foi conduzido em delineamento inteiramente casualizado, em esquema de parcelas subsubdivididas, com três repetições, com cinco diluições nas parcelas (Diluição 1: 100% de efluente de aquicultura; Diluição 2: 75% de efluente de aquicultura + 25% de água de poço; Diluição 3 : 50% efluente de aquicultura + 50% água de poço; Diluição 4: 25% efluente de aquicultura + 75% água de poço; e Diluição 5: 100% água de poço), três emissores nas subparcelas (ST (1,6 L h^{-1}) , SL (1,6 L h^{-1}) e NJ (1,7 L h^{-1})), e três tempos de operação nas subsubparcelas (início do experimento, 80 e 160 horas, em que 0 horas de operação significa o início das avaliações). As análises estatísticas realizadas foram matriz de correlação e análise canônica. A análise de correlação canônica indicou que quando as concentrações dos atributos aumentam, o desempenho hidráulico dos gotejadores diminui. A interação desse grupo de atributos indica que o entupimento dos gotejadores que operam com as cinco diluições de efluente de aquicultura em água de poço ocorre pela ação combinada de agentes físicos, químicos e biológicos. O gotejador ST foi o menos sensível ao grupo de atributos de qualidade das diluições, enquanto o mais sensível foi o gotejador SL.

Palavras-chave: reúso agrícola, estatística multivariada, emissores

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Introduction

Aquaculture, which corresponds to the controlled cultivation of aquatic organisms, is prominent in Brazil. The main segments of aquaculture in the semi-arid Brazil region are fish farming, with notoriety the production of tilapia (*Oreochromus niloticus*) (Cardoso et al., 2016), and shrimp farming, especially the production of whiteleg shrimp (*Litopenaeus vannamei*) (Monteiro et al., 2019).

However, this activity generates effluents with high concentrations of nutrients (0.17 and 66.40 mg L^{-1} of PO_4^- and NO_3^-, respectively) and solids (1750 mg L^{-1}), which cause pollution and eutrophication of water bodies, soil salinization, and loss of biodiversity; thus, strategies are needed for agricultural reuse of these effluents (Soliman et al., 2020).

The drip irrigation system is the main tool for wastewater application in agriculture (Suryawanshi, 2018). The biggest limitation of these irrigation systems is susceptibility to clogging of drippers (Amaral et al., 2022; Feng et al., 2019; Vale et al., 2021). Due to their reduced dimensions, drippers can be affected by clogging caused by irrigation water quality attributes (Bansal et al., 2021; Dhayal et al., 2023; Wang et al., 2020).

Conventional research on the clogging of drippers operating with wastewater uses univariate or bivariate statistics to assess the correlation between two variables (Batista et al., 2018; Vale et al., 2020), limiting the understanding of the problem. Multivariate analysis, especially canonical analysis, can facilitate the global understanding of the data collected by correlating several variables from different data groups (Lu et al., 2021).

The hypothesis that the quality attributes of aquaculture effluent cause a reduction in hydraulic performance is best observed using canonical analysis. Therefore, this study aimed to use canonical correlation analysis to evaluate the interaction between water quality attributes clogging-causing and the hydraulic performance of non-pressure compensating drippers operating with dilutions of aquaculture effluent in well water.

Material and Methods

The experiment was conducted in November and December 2021 in the external experimental area of the Laboratory of Rural Constructions and Ambience of the Engineering and Environmental Sciences Department of the Engineering Center on the East Campus of the Federal Rural University of the Semi-arid (UFERSA) in Mossoró city, state of Rio Grande do Norte, Brazil, located at 5° 12' 13.14" S, 37° 19' 26.93" W, and altitude of 20 m.

The aquaculture effluent was obtained at the Aquaculture Sector of the East campus of UFERSA in Mossoró city, where several experiments are carried out to produce aquatic organisms in nurseries with fresh and saline water. The dilution water comes from a well also installed on the East campus of UFERSA in Mossoró city, managed by the Companhia de Águas e Esgotos do Rio Grande do Norte (CAERN).

The experiment was conducted in a completely randomized design in a split-split-plot scheme with three replicates, as recommended by Batista et al. (2018). Five dilutions of aquaculture effluent (AE) in well water (WW) were established in the plots (the dilution were: D1 - 100% aquaculture effluent; D2 - 75% aquaculture effluent + 25% well water; D3 - 50% aquaculture effluent + 50% well water; D4 - 25% aquaculture effluent + 75% well water; and D5 - 100% well water) to evaluate the susceptibility to clogging of three types of emitters in the subplots (ST (1.6 L h^{-1}), SL (1.6 L h^{-1}), and NJ (1.7 L h^{-1})), based on variations in the concentrations of the physical, chemical, and microbiological agents that cause clogging, evaluated by the hydraulic performance until completing a total of operating time of 160 hours, according to the recommendation of Vale et al. (2020). In all trials, three hydraulic performance evaluations were performed at operating times in the sub-subplots of 0, 80, and 160 hours, in which 0 hours of operating time means the start of evaluations.

For this, five experimental benches were set up (Figure 1). Each of them operated with one dilution of aquaculture effluent in well water and had three types of emitters. The emitters and

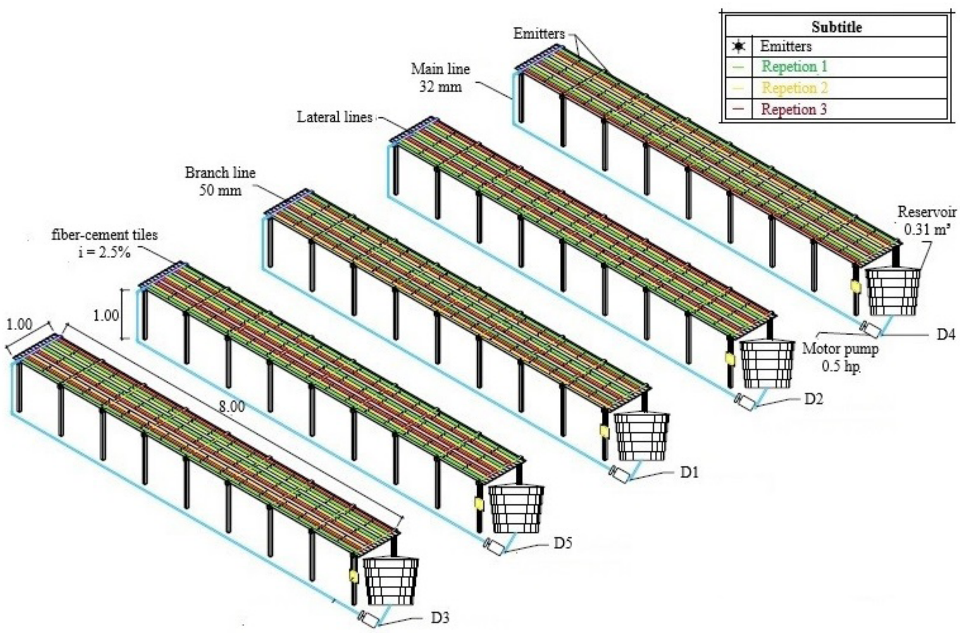

Figure 1. Sketch of the experimental benches to evaluate the hydraulic performance of the emitters

dilutions were arranged on the benches, which have an area of 8 m² (1 m wide by 8 m long) and consisted of a wooden base supporting 1 m high corrugated fiber-cement tiles installed with a slope of 2.5% to promote the recirculation of the effluent.

At the lowest end of each bench, a 0.31 m³ reservoir was installed and connected to a drip irrigation system equipped with a control head composed of a 0.5 hp motor pump, a disc filter with 130-µm openings, a gate valve, two points for collecting effluent samples, and two analog glycerin pressure gauges (0 to 400 kPa) for reading the working pressure.

The disc filters were installed, as indicated by Vale et al. (2020). At the end of the eight daily operating hours, the disc filters on each bench were removed for cleaning.

The drip irrigation system installed to apply the five dilutions was divided into three drip units, following the recommendations of Vale et al. (2020), and operated for eight hours daily, on average. Each of these units had three lateral lines, in which 16 emitters were randomly chosen to evaluate hydraulic performance. The specifications of the non-pressure compensating drippers used in the experiment are presented in Table 1.

Table 1. Technical specifications of the non-pressure compensating drippers evaluated in the experiment

Dripper	Specifications
ST	Nominal flow rate: 1.60 L h $^{-1}$; flow rate coefficient: 0.53; exponent of the flow rate that characterizes the flow regime: 0.48; filtration area: 34 mm²; labyrinth length: 23 mm; coefficient of variation of manufacture ±7; recommended pressure range: 60 to 300 kPa; spacing between emitters: 0.30 m.
SL	Nominal flow rate: 1.60 L h $^{-1}$; flow rate coefficient: 0.57; exponent of the flow rate that characterizes the flow regime: 0.45; filtration area: 17 mm²; labyrinth length: 13 mm; coefficient of variation of manufacture ±7; recommended pressure range: 90 to 100 kPa; spacing between emitters: 0.30 m.
NJ	Nominal flow rate: 1.70 L h $^{-1}$; flow rate coefficient: 0.56; exponent of the flow rate that characterizes the flow regime: 0.46; filtration area: 6.0 mm²; labyrinth length: 44 mm; coefficient of variation of manufacture ±5; recommended pressure range: 70 to 300 kPa; spacing between emitters: 0.20 m.

Hydraulic performance evaluations were carried out according to the recommendations of NBR ISO 9261, and the results obtained were used to calculate six hydraulic performance coefficients (Table 2).

The operating pressure of the drip units was 80 ± 10 kPa, which, according to Batista et al. (2018), is the pressure value that enhances biofilm formation in emitters of drip irrigation systems that operate with wastewater. Periodic adjustment of the operating pressure in the drip units was carried out using pressure gauges graduated from 0 to 400 kPa with an accuracy class of ± 1% of full scale.

The quality attributes of the aquaculture effluent and its dilutions in well water were characterized based on the presence of physical, chemical, and microbiological agents. For this, samples of the five dilutions were collected in the reservoirs of each bench at the beginning (0 hours), in the middle (80 hours), and at the end of the experiment (160 hours).

Part of these samples was taken to the Laboratory of Soil, Water and Plant of the Semi-arid (LASAPSA - UFERSA), following the recommendations of EMBRAPA (Parron et al., 2011) and the Standard methods for the examination of water and wastewater (Baird et al., 2017), to determine the following attributes: hydrogen potential (pH) using a benchtop pH meter; electrical conductivity (EC) using a benchtop conductivity meter; calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^{+}) using a flame photometer; carbonate (CO_3^{2-}) and bicarbonate (HCO_3^{-}) by the titration method; total suspended solids (TSS) and total solids (TS) by the gravimetric method; and turbidity (Tur) using a benchtop turbidimeter. It is worth pointing out

Table 2. Hydraulic performance coefficients, equations, and variables

Coefficient	Equation	Variables	Reference	N° of equation
Flow rate	$Q = \frac{Vol}{1000\ t_{em}} \cdot 60$	Q: Emitter flow rate, L.h^{-1}; Vol: Volume of effluent collected, mL; and t_{em}: Time of effluent collection, min.		(1)
Relative flow rate	$QR = \frac{q_a}{q_i}$	QR: Relative flow rate, L h^{-1}; q_a: Actual flow rate, L h^{-1}; and q_i: Initial flow rate, L h^{-1}.	Capra & Scicolone (1998)	(2)
Reduction in relative flow rate	$RQR = 100\left(\frac{q_i - q_a}{q_i}\right)$	RQR: Reduction in relative flow rate, %; q_i: Initial flow rate, L h^{-1}; and q_a: Actual flow rate, L h^{-1}.	Capra & Scicolone (1998)	(3)
Distribution uniformity coefficient	$DUC = 100\frac{q_{25\%}}{\bar{q}}$	DUC: Distribution uniformity coefficient, %; $q_{25\%}$: Average of the 25% lowest flow rate values of the emitters, L h^{-1}, and q: Average flow rate of the emitters, L h^{-1}.	Keller & Karmeli (1975)	(4)
Coefficient variation of flow rate	$CVQ = 100\frac{\sqrt{\sum_{i=0}^{n}\frac{(q_i - \bar{q})^2}{n_e - 1}}}{\bar{q}}$	CVQ: Coefficient of variation of flow rate, %; q_i: Flow rate of each emitter, L h^{-1}; q: Average flow rate of the emitters, L h^{-1}, and n_e: Number of emitters evaluated.	Bralts et al. (1987)	(5)
Statistical uniformity coefficient	$Us = 100(1\text{-}CVQ)$	Us: Statistical uniformity coefficient of effluent application, %; and CVQ: Coefficient of variation of flow rate, %.	Bralts et al. (1987)	(6)

that the total dissolved solids (TDS) were obtained by the difference between TSS and TS. After the concentrations of Na^+, Ca^{2+}, Mg^{2+}, CO_3^{2-}, and HCO_3^- were defined, the tendency for calcium carbonate ($CaCO_3$) formation was calculated using the Langelier Saturation Index (LSI), proposed by Ayers & Westcot (1976).

Another part of the samples was sent to the Laboratory of Organic Matter and Residues and Atomic Spectrophotometry of the Universidade Federal de Viçosa (UFV) in Minas Gerais state, Brazil, and analyzed by the plasma atomic adsorption method to quantify the contents of total manganese (Mn^+), iron (Fe^+) and sulfur (S^+). The last part of the samples was taken to the CACIM Laboratory, where the population levels of total coliforms (TC) and thermotolerant coliforms (TTC) were quantified using the Colilert technique. The results were expressed in colony-forming units per 100 mL (CFU 100 mL^{-1}), following the recommendations of the Standard methods for the examination of water and wastewater (Baird et al., 2017). The temperature of the AE dilutions in WW was determined in loco using a thermometer with 0.5 °C precision.

These variables (water quality attributes and hydraulic performance coefficients) were established as a function of the five dilutions of aquaculture effluent in well water, D1, D2, D3, D4, and D5, at the operating times of 0, 80, and 160 hours. The multivariate analyses performed were correlation matrix and canonical correlation analysis (CCA), using Statistica 14.0 software.

A selection was necessary to form the two data sets of CCA. The first set aggregates the water quality attributes. In this selection, the seven attributes with the strongest correlations with hydraulic performance variables in the correlation matrix ($p \leq 0.05$) were chosen, which are also cited by Capra & Scicolone (1998) and Nakayama et al. (2006) as quality attributes with potential for clogging of drippers. These same attributes were used in the three canonical analyses performed.

The second set of variables refers to the hydraulic performance coefficients of the ST, SL, and NJ drippers. For the software to process these data in the canonical analysis with the six coefficients (Q, QR, RQR, DUC, CVQ, and Us) of the three drippers, it was necessary to perform three canonical analyses. Each of these analyses used two hydraulic performance coefficients of the three drippers. QR and DUC coefficients were used in the first analysis, Q and Us were used in the second analysis, and RQR and CVQ were used in the third analysis.

The chi-square test was carried out, and $p \leq 0.05$ was chosen as the significance reference to attest to the correlation between the canonical pairs formed (Huang et al., 2022).

Results and Discussion

The results of the analysis of the quality attributes of aquaculture effluent and its dilutions in well water are presented in Table 3. The hydraulic performance coefficients of the ST, SL, and NJ drippers, operating with the dilutions D1, D2, D3, D4, and D5, are presented in Table 4.

The data presented in Tables 3 and 4 were used to create the Pearson correlation matrix with $p \leq 0.05$ (Table 5). Values with (*) in the correlation matrix represent the significant correlations between the studied variables. Positive correlations indicate that variables increase or decrease together, whereas negative correlations indicate opposite behavior; the closer to 1 or -1, the stronger these correlations are.

The first information obtained from the correlation matrix is a high correlation between the quality attributes of aquaculture effluent in well water and the hydraulic performance coefficients, justifying the use of CCA.

The second refers to choosing the seven water quality attributes with the potential for clogging the drippers. According to the established criteria, the attributes chosen for the first set of variables were EC, Ca^{2+}, Mg^{2+}, TC, TSS, Fe^+, and S^+, while the second set represents the hydraulic performance coefficients Q, QR, RQR, DUC, CVQ, and Us of the ST, SL, and NJ drippers.

Six canonical pairs were formed in each CCA. However, only the first canonical pair was significant, with $p \leq 0.05$

Table 3. Quality attributes of aquaculture effluent and its dilutions in well water, D1, D2, D3, D4, and D5, at 0, 80, and 160 hours of operation

Dilutions and time of operation	Water quality attributes															
	pH	EC	Ca^{2+}	Mg^{2+}	CO_3^{2-}	HCO_3^-	TC	TTC	TSS	TDS	Mn^+	Fe^+	S^+	Na^+	LSI	Tur	T
D1 – 0 hours	7.93	5.88	20.40	33.80	0.14	1.78	180.00	16.00	44.00	6850.00	0.05	0.45	0.11	42.70	-0.20	9.9	30
D2 – 0 hours	8.04	5.01	13.50	25.80	0.20	1.76	70.00	12.00	26.00	5608.00	0.00	0.06	0.04	35.03	0.01	3.9	34
D3 – 0 hours	8.06	3.60	11.90	17.80	0.25	1.94	120.00	20.00	4.00	3738.00	0.02	0.34	0.10	25.66	0.01	4.8	34
D4 – 0 hours	7.92	2.26	5.30	13.10	0.12	1.51	110.00	15.00	14.00	2138.00	0.02	0.11	0.04	15.26	-0.46	5.5	33
D5 – 0 hours	7.05	0.52	0.60	0.28	0.05	1.66	20.00	0.00	2.00	452.00	0.00	0.00	0.01	7.98	-2.12	0.23	35
D1 – 80 hours	7.62	8.45	16.90	41.80	0.00	1.89	420.00	60.00	6.00	6644.40	0.02	0.06	0.08	70.42	-1.46	4.2	28
D2 – 80 hours	7.61	5.37	12.60	17.90	0.00	1.71	70.00	20.00	4.00	4300.00	0.02	0.09	0.08	45.44	-0.14	2.6	29
D3 – 80 hours	7.67	4.18	8.70	11.50	0.05	1.66	60.00	30.00	4.00	3246.00	0.00	0.01	0.11	35.55	0.13	1.5	28
D4 – 80 hours	7.64	3.34	6.90	11.40	0.07	1.53	150.00	60.00	4.00	2470.00	0.00	0.08	0.08	29.62	-0.24	1.36	27
D5 – 80 hours	7.55	0.59	0.67	0.13	0.23	1.42	40.00	10.00	2.00	392.00	0.00	0.04	0.04	6.52	-1.31	0.19	30
D1 – 160 hours	7.65	10.33	18.00	54.70	0.00	2.40	460.00	90.00	68.00	7778.00	0.00	0.35	0.23	83.43	-2.27	10.7	29
D2 – 160 hours	8.20	5.49	10.00	23.10	0.09	1.72	70.00	20.00	6.00	3878.00	0.01	0.05	0.10	42.84	0.59	3.8	26
D3 – 160 hours	8.28	4.26	6.80	21.20	0.15	1.51	60.00	10.00	6.00	2864.00	0.00	0.15	0.19	33.99	0.47	2.5	26
D4 – 160 hours	8.47	3.70	6.00	15.70	0.20	1.45	50.00	10.00	4.00	2414.00	0.00	0.03	0.16	31.50	0.62	3	26
D5 – 160 hours	8.50	0.67	0.52	0.31	0.33	1.40	70.00	20.00	2.00	308.00	0.00	0.03	0.17	8.60	-0.28	0.5	27

pH - Hydrogen potential; EC - Electrical conductivity (dS m^{-1}); Ca^{2+} - Calcium ($mmol_c$ L^{-1}); Mg^{2+} - Magnesium ($mmol_c$ L^{-1}); CO_3^{2-} - Carbonate ($mmol_c$ L^{-1}); HCO_3^- - Bicarbonate ($mmol_c$ L^{-1}); TC - Total coliforms (CFU 100mL^{-1}); TTC - Thermotolerant coliforms (CFU 100mL^{-1}); TDS - Total dissolved solids (mg L^{-1}); TSS - Total suspended solids (mg L^{-1}); Mn^+ - Manganese (mg L^{-1}); Fe^+ - Iron (mg L^{-1}); S^+ - Sulphur (mg L^{-1}); Na^+ - Sodium ($mmol_c$ L^{-1}); LSI - Langelier saturation index; Tur - Turbidity (NTU); T - Temperature (°C); D1 - 100% aquaculture effluent (AE), D2 - 75% AE and 25% well water (WW), D3 - 50% AE and 50% WW, D4 - 25% AE and 75% WW, and D5 - 100% WW

Table 4. Hydraulic performance coefficients of the ST, SL, and NJ drippers with 0, 80, and 160 hours of operation

Dilutions and time of operation	Hydraulic performance coefficients								
	QR ST	QR SL	QR NJ	DUC ST	DUC SL	DUC NJ	Q ST	Q SL	Q NJ
D1 – 0 hours	1.00	1.00	1.00	95.63	93.63	94.42	1.5	1.19	1.32
D2 – 0 hours	1.00	1.00	1.00	92.20	95.85	96.40	1.48	1.22	1.34
D3 – 0 hours	1.00	1.00	1.00	99.07	97.90	97.87	1.48	1.25	1.37
D4 – 0 hours	1.00	1.00	1.00	97.13	96.54	96.98	1.47	1.23	1.35
D5 – 0 hours	1.00	1.00	1.00	95.93	97.39	97.76	1.47	1.24	1.34
D1 – 80 hours	0.96	0.73	0.90	91.11	92.58	91.49	1.43	1.09	1.35
D2 – 80 hours	0.86	0.82	0.88	77.97	95.26	91.95	1.28	1.21	1.31
D3 – 80 hours	1.00	0.81	0.89	95.46	90.11	84.59	1.48	1.2	1.31
D4 – 80 hours	1.04	0.88	0.94	95.27	91.42	91.46	1.52	1.29	1.38
D5 – 80 hours	0.95	0.80	0.89	92.78	92.74	92.78	1.4	1.18	1.31
D1 – 160 hours	0.90	0.63	0.81	84.80	58.70	85.71	1.34	0.95	1.21
D2 – 160 hours	0.77	1.02	1.12	74.92	90.72	89.73	1.14	1.21	1.34
D3 – 160 hours	0.99	0.73	0.83	94.47	82.16	75.02	1.46	1.08	1.23
D4 – 160 hours	1.00	0.79	0.91	95.44	93.24	94.90	1.46	1.16	1.33
D5 – 160 hours	0.95	0.79	0.90	94.64	96.14	92.40	1.4	1.17	1.32
	Hydraulic performance coefficients								
	RQR ST	RQR SL	RQR NJ	CVQ ST	CVQ SL	CVQ NJ	Us ST	Us SL	Us NJ
D1 – 0 hours	0.00	0.00	0.00	6.26	7.54	6.52	93.74	92.46	93.48
D2 – 0 hours	0.00	0.00	0.00	8.86	5.66	6.72	91.14	94.34	93.28
D3 – 0 hours	0.00	0.00	0.00	2.86	3.44	4.3	97.14	96.56	95.7
D4 – 0 hours	0.00	0.00	0.00	5.71	6.13	5.88	94.29	93.87	94.12
D5 – 0 hours	0.00	0.00	0.00	6.64	6.28	6.92	93.36	93.72	93.08
D1 – 80 hours	4.10	8.54	-2.38	8.08	6.95	8.71	91.92	93.05	91.29
D2 – 80 hours	13.87	0.10	2.85	37.7	9.94	12.97	62.3	90.06	87.03
D3 – 80 hours	0.00	4.06	4.56	5.88	16.49	19.35	94.12	83.51	80.65
D4 – 80 hours	-3.74	-5.15	-2.00	5.66	10.26	9.99	94.34	89.74	90.01
D5 – 80 hours	4.78	4.96	2.39	6.63	6.53	9.39	93.37	93.47	90.61
D1 – 160 hours	10.37	20.61	8.17	21.51	40.24	18.55	78.49	59.76	81.45
D2 – 160 hours	23.1	0.24	0.59	59.27	13.19	14.97	40.73	86.81	85.03
D3 – 160 hours	0.99	13.75	10.21	9.22	25.33	30.97	90.78	74.67	69.03
D4 – 160 hours	0.48	5.76	1.57	8.44	9.64	8.59	91.56	90.36	91.41
D5 – 160 hours	4.98	6.23	1.58	7.96	7.09	9.34	92.04	92.91	90.66

QR - Relative flow rate; DUC - Distribution uniformity coefficient (%); Q - Flow rate (L h^{-1}); RQR - Reduction in relative flow rate (%); CVQ - Coefficient of variation of flow rate (%); Us - Statistical uniformity coefficient (%); D1 - 100% aquaculture effluent (AE), D2 - 75% AE and 25% well water (WW), D3 - 50% AE and 50% WW, D4 - 25% AE and 75% WW, and D5 - 100% WW; ST - Dripper; SL - Dripper; NJ - Dripper

in the chi-square test for the three analyses. The significant canonical pairs of the three analyses are represented in Table 6.

In the first CCA, it can be observed that all water quality attributes present in the first set are negative, while the QR and DUC of the three drippers are positive. This shows that the decrease in the concentrations of these attributes in the dilutions improves the results of the hydraulic performance coefficients of the drippers.

It can also be noticed that the water quality attribute that most affect the QR and DUC of the drippers is TSS, and the one that least affects them is Ca^{2+}. On the other hand, the most sensitive hydraulic performance coefficient to water quality attributes is the DUC of the SL dripper, while the one with the lowest sensitivity is the QR of the TS dripper.

The second CCA used Q and Us in the hydraulic performance data set. As a result, in the first data set, all factors were positive, with the strongest being S+ and the weakest being Ca^{2+} and Fe^{+}. These results were contrary to some of the variables of the second set, which were mostly negative, following a decreasing trend when the concentrations of the first attributes increased.

The exception was the Q of the ST dripper, which was also positive, revealing an increase in flow rate when there is also an increase in the concentrations of the attributes in the aquaculture effluent and its dilutions. The Q and Us variables of the SL dripper were the most sensitive to the water quality attributes.

The third CCA evaluated the correlation between the water quality attributes chosen, RQR and CVQ. For the first data set, all factors were positive. TSS stood out with the highest factor, and Fe^{+} stood out with the lowest factor. In the second data set, all the factors were also positive, the highest for the RQR and CVQ of the SL dripper and the lowest for the RQR and CVQ of the ST dripper.

In this case, the factors are in the same direction, differing from the result of previous canonical analyses. However, it is important to highlight that, despite being in the same direction, the behavior between the two data sets is opposite and similar to the result of the previous analyses since the higher the values of RQR and CVQ, the worse the hydraulic performance of the drippers.

When observing the three canonical analyses, it is clear that some water quality attributes stand out. The first is TSS, which has the strongest significant correlation in two analyses. This attribute has been reported as one of the most common causes of clogging of drippers operating with other types of water, such as aquaculture effluent (Soliman et al., 2020) and produced water from oil exploration (Vale et al., 2020).

Although TSS is an important physical agent of obstruction, clogging of drippers by this attribute can be attenuated by a wastewater treatment system with a higher level (Green et

Table 5. Correlation matrix ($p \leq 0.05$) between the quality attributes of aquaculture effluent in well water and the hydraulic performance coefficients of the ST, SL, and NJ drippers at 0, 80, and 160 hours of operation

	pH	EC	Ca^{2+}	Mg^{2+}	CO_3^{2-}	HCO_3	TC	TTC	TSS	TDS	Mn^+	Fe^+	S^+	Na^+	LSI	Tur	T	QR ST	QR SL	QR NJ	DUC ST	DUC SL	DUC NJ	Q ST	Q SL	Q NJ	RQR ST	RQR SL	RQR NJ	CVQ ST	CVQ SL	CVQ NJ	Us ST	Us SL	Us NJ
pH	1.00																																		
EC	-0.03	1.00																																	
Ca^{2+}	-0.02	0.89*	1.00																																
Mg^{2+}	0.02	0.97*	0.89*	1.00																															
CO_3^{2-}	0.64*	-0.59*	-0.43	-0.48	1.00																														
HCO_3	-0.28	0.81*	0.76*	0.82*	-0.48	1.00																													
TC	-0.20	0.81*	0.67*	0.84*	-0.48	0.77*	1.00																												
TTC	-0.22	0.71*	0.50	0.66*	-0.52*	0.66*	0.87*	1.00																											
TSS	-0.06	0.66*	0.67*	0.76*	-0.24	0.73*	0.63*	0.52*	1.00																										
TDS	-0.03	0.94*	0.98*	0.95*	-0.47	0.80*	0.74*	0.57*	0.73*	1.00																									
Mn^+	-0.01	0.30	0.62*	0.37	-0.13	0.21	0.25	-0.05	0.34	0.50	1.00																								
Fe^+	0.06	0.47	0.67*	0.59*	0.00	0.60*	0.46	0.28	0.71*	0.61*	0.66*	1.00																							
S^+	0.51*	0.46	0.25	0.45	0.06	0.31	0.38	0.43	0.42	0.31	-0.07	0.38	1.00																						
Na^+	-0.07	0.99*	0.84*	0.94*	-0.63*	0.79*	0.83*	0.75*	0.62*	0.90*	0.24	0.40	0.48	1.00																					
LSI	0.73*	-0.15	-0.03	-0.21	0.38	-0.46	-0.54*	-0.43	-0.37	-0.11	0.06	-0.10	0.13	-0.20	1.00																				
Tur	0.08	0.73*	0.81*	0.84*	-0.25	0.73*	0.66*	0.45	0.88*	0.82*	0.61*	0.84*	0.39	0.67*	-0.16	1.00																			
T	-0.44	-0.24	0.00	-0.13	0.08	0.21	-0.11	-0.29	0.12	-0.02	0.15	0.17	-0.62*	-0.30	-0.38	0.10	1.00																		
QR ST	-0.09	-0.33	-0.16	-0.24	0.25	-0.26	-0.10	-0.11	-0.08	-0.19	0.02	0.07	-0.19	-0.35	-0.03	-0.12	0.33	1.0																	
QR SL	-0.03	-0.38	-0.05	-0.31	0.20	-0.18	-0.48	-0.55*	-0.17	-0.15	0.30	0.05	-0.67*	-0.46	0.27	-0.02	0.58*	0.1	1.00																
QR NJ	0.07	-0.22	0.00	-0.18	0.14	-0.10	-0.33	-0.41	-0.17	-0.07	0.23	-0.03	-0.56*	-0.29	0.27	0.02	0.36	-0.2	0.92*	1.00															
DUC ST	0.04	-0.46	-0.29	-0.34	0.45	-0.31	-0.16	-0.22	-0.15	-0.33	0.01	0.09	-0.14	-0.48	-0.02	-0.14	0.34	0.9	0.12	-0.10	1.00														
DUC SL	0.06	-0.65*	-0.36	-0.65*	0.38	-0.64*	-0.63*	-0.70*	-0.71*	-0.48	0.18	-0.38	-0.72*	-0.67*	0.37	-0.53*	0.31	0.2	0.65*	0.55*	0.30	1.00													
DUC NJ	-0.16	-0.33	-0.08	-0.26	0.25	-0.06	-0.15	-0.27	-0.10	-0.14	0.25	-0.02	-0.64*	-0.36	-0.16	-0.01	0.64*	0.2	0.63*	0.57*	0.21	0.61*	1.00												
Q ST	0.42	0.05	-0.30	0.01	0.09	-0.19	-0.02	0.12	-0.09	-0.21	-0.48	-0.24	0.57*	0.10	0.16	-0.17	-0.72*	-0.4	-0.54*	-0.34	-0.37	-0.44	-0.51	1.00											
Q SL	-0.09	-0.64*	-0.36	-0.68*	0.24	-0.54*	-0.68*	-0.54*	-0.59*	-0.49	0.06	-0.29	-0.73*	-0.67*	0.39	-0.48	0.35	0.2	0.78*	0.65*	0.23	0.84*	0.57*	-0.45	1.00										
Q NJ	-0.06	-0.40	-0.17	-0.41	0.18	-0.34	-0.28	-0.26	-0.53*	-0.27	0.13	-0.28	-0.71*	-0.41	0.22	-0.33	0.30	0.2	0.67*	0.67*	0.25	0.82*	0.74*	-0.46	0.83*	1.00									
RQR ST	0.09	0.34	0.17	0.25	-0.26	0.27	0.11	0.13	0.09	0.20	-0.02	-0.07	0.20	0.36	0.02	0.13	-0.34	-1.0	-0.08	0.17	-0.94*	-0.26	-0.17	0.42	-0.26	-0.24	1.0								
RQR SL	0.13	0.49	0.18	0.52*	-0.12	0.43	0.55*	0.45	0.46	0.31	-0.21	0.21	0.76*	0.52*	-0.35	0.34	-0.34	-0.2	-0.81*	-0.71*	-0.12	-0.81*	-0.63*	0.50	-0.97*	-0.86*	0.2	1.00							
RQR NJ	0.15	0.22	0.00	0.21	-0.08	0.18	0.04	0.11	0.30	0.08	-0.27	0.18	0.69*	0.24	0.01	0.14	-0.32	-0.2	-0.60*	-0.65*	-0.16	-0.70*	-0.81*	0.48	-0.66*	-0.93*	0.2	0.76*	1.00						
CVQ ST	0.09	0.33	0.19	0.22	-0.35	0.20	-0.01	0.07	0.04	0.21	-0.01	-0.10	0.12	0.34	0.19	0.10	-0.34	-0.9	0.07	0.30	-0.95*	-0.19	-0.17	0.39	-0.08	-0.14	0.9*	-0.01	0.11	1.0					
CVQ SL	-0.01	0.59*	0.29	0.56*	-0.41	0.53*	0.48	0.59*	0.60*	0.40	-0.23	0.30	0.76*	0.61*	-0.23	0.43	-0.39	-0.3	-0.64*	-0.56*	-0.32	-0.97*	-0.74*	0.48	-0.79*	-0.87*	0.3	0.80*	0.82*	0.2	1.0				
CVQ NJ	0.14	0.28	0.02	0.20	-0.27	0.06	0.04	0.18	0.08	0.09	-0.31	-0.03	0.60*	0.32	0.17	-0.03	-0.57*	-0.2	-0.56*	-0.52*	-0.28	-0.60*	-0.98*	0.54*	-0.54*	-0.77*	0.2	0.61*	0.86*	0.3	0.8*	1.0			
Us ST	-0.09	-0.33	-0.19	-0.22	0.35	-0.20	0.01	-0.07	-0.04	-0.21	0.01	0.10	-0.12	-0.34	-0.19	-0.10	0.34	0.9	-0.07	-0.30	0.95*	0.19	0.17	-0.39	0.08	0.14	-0.9*	0.01	-0.11	-1.0*	-0.2	-0.3	1.0		
Us SL	0.01	-0.59*	-0.29	-0.56*	0.41	-0.53*	-0.48	-0.59*	-0.60*	-0.40	0.23	-0.30	-0.76*	-0.61*	0.23	-0.43	0.39	0.3	0.648	0.56*	0.32	0.97*	0.74*	-0.48	0.79*	0.87*	-0.3	-0.80*	-0.82*	-0.2	-1.0*	-0.8*	0.2	1.0	
Us NJ	-0.14	-0.28	-0.02	-0.20	0.27	-0.06	-0.04	-0.18	-0.08	-0.09	0.31	0.03	-0.60*	-0.32	-0.17	0.03	0.57*	0.2	0.56*	0.52*	0.28	0.60*	0.98*	-0.54*	0.54*	0.77*	-0.2	-0.61*	-0.86*	-0.3	-0.8*	-1.0*	0.3	0.8*	1.0

Values with (*) are significant at a 95% significance level (two-tailed test)

pH - hydrogen potential; EC - electrical conductivity (dS m^{-1}); Ca^{2+} - Calcium ($mmol_c\ L^{-1}$); Mg^{2+} - Magnesium ($mmol_c\ L^{-1}$); CO_3^{2-} - Carbonate ($mmol_c\ L^{-1}$); HCO_3^- - Bicarbonate ($mmol_c\ L^{-1}$); TDS - Total dissolved solids (mg L^{-1}); TSS - Total suspended solids (mg L^{-1}); TC - Total coliforms (CFU 100 mL^{-1}); TTC - Thermotolerant coliforms (CFU 100 mL^{-1}); Mn - Manganese (mg L^{-1}); Fe - Iron (mg L^{-1}); S - Sulphur (mg L^{-1}); Na^+ - Sodium (mg L^{-1}); LSI - Langelier saturation index; Tur - Turbidity (NTU); T - Temperature (°C); QR - Relative flow rate; DUC - Distribution uniformity coefficient (%); Q - Flow rate (L h^{-1}); RQR - Reduction in relative flow rate (%); CVQ - Coefficient of variation of flow rate (%); Us -Statistical uniformity coefficient; ST - Dripper; SL - Dripper; NJ - Dripper

Table 6. Canonical correlation analyses with a significance level of $p \leq 0.05$ by chi-square test between the quality attributes of aquaculture effluent and its dilutions in well water and the hydraulic performance coefficients of the ST, SL, and NJ drippers

Groups	Canonical analysis 1		Canonical analysis 2		Canonical analysis 3	
	Variables	Canonical pair 1	Variables	Canonical pair 1	Variables	Canonical pair 1
Water quality attributes	EC	-0.67	EC	0.65	EC	0.67
	Ca^{2+}	-0.42	Ca^{2+}	0.34	Ca^{2+}	0.38
	Mg^{2+}	-0.68	Mg^{2+}	0.64	Mg^{2+}	0.67
	TC	-0.64	TC	0.60	TC	0.61
	TSS	-0.80	TSS	0.69	TSS	0.73
	Fe^{+}	-0.45	Fe^{+}	0.34	Fe^{+}	0.37
	S^{+}	-0.62	S^{+}	0.74	S^{+}	0.72
Hydraulic performance coefficients	QR - ST	0.32	Q - ST	0.51	RQR - ST	0.38
	QR - SL	0.51	Q - SL	-0.83	RQR - SL	0.77
	QR - NJ	0.41	Q - NJ	-0.79	RQR - NJ	0.66
	DUC - ST	0.38	US - ST	-0.30	CVQ - ST	0.31
	DUC - SL	0.97	US - SL	-0.95	CVQ - SL	0.95
	DUC - NJ	0.43	US - NJ	-0.56	CVQ - NJ	0.54
R		0.995		0.999		0.998
($p \leq 0.05$)		0.02		0.00002		0.0003

R - Canonical radius; EC - Electrical conductivity (dS m^{-1}); Ca^{2+} - Calcium ($mmol_c$ L^{-1}); Mg^{2+} - Magnesium ($mmol_c$ L^{-1}); TSS - Total suspended solids (mg L^{-1}); TC - Total coliforms (CFU 100 ml^{-1}); Fe^{+} - Iron (mg L^{-1}) S^{+} - Sulphur (mg L^{-1}); QR - Relative flow rate; DUC - Distribution uniformity coefficient (%); Q - Flow rate (L h^{-1}); RQR - Reduction in relative flow rate (%); CVQ - Coefficient of variation of flow rate (%); Us - Statistical uniformity coefficient (%). ST - Dripper; SL - Dripper; NJ - Dripper

al., 2018) and, mainly, by a filtration system more efficient in removing suspended particles (García Nieto et al., 2020).

S^{+} is another element that has a strong correlation in the group of water quality attributes, being the most significant in the second canonical analysis. The indication of this element in the dilutions of aquaculture effluent in well water is due to the presence of sulfates and sulfides in the composition of the feed offered to aquatic organisms grown in the aquaculture sector of UFERSA.

Other studies using irrigation systems operating with aquaculture effluent have also reported the presence of sulfur in the forms of sulfate and sulfide in this wastewater (Soliman et al., 2020). These substances are nutritional sources for bacteria, which can proliferate, form more robust biofilms, and cause clogging of drippers.

Electrical conductivity (EC) and magnesium (Mg^{2+}) were strongly correlated in the group of water quality attributes for the three canonical analyses. One of the relationships between them is that magnesium ions contribute to increasing water EC (Cunha et al., 2020). The high concentration and strong correlation of these attributes can be explained by the use of bittern from the salt pans of Mossoró city in some experiments set up in the aquaculture sector of UFERSA.

The action of Mg^{2+} ion in the emitters is due to its precipitation in the form of magnesium carbonates (Mg-calcite, $CaMgCO_3$; dolomite, and $CaMg(CO_3)_2$), which obstructs the pipe walls and emitters, since the EC indicates the amount of ions present in the dilutions that can also precipitate and form fouling (Zhangzhong et al., 2019).

The population level of TC also had a strong correlation in the group of quality attributes and an opposite correlation to the group of hydraulic performance coefficients, demonstrating that TC is an attribute of great importance in the risk of clogging of drippers operating with dilutions of aquaculture effluent in well water. The main action of TC in reducing the hydraulic performance of drippers occurs through the formation of biofilm (Yuan & Olivier, 2019).

Bacteria present in the water expel a slimy material called the self-produced polymeric matrix (extracellular polymeric substances - EPS), which unites them together with the internal parts of the drip system, forming the biofilm, which grows and aggregates suspended particles to become more robust and safer against adverse conditions and also makes them absorb better the nutrients present in the water and responsible for bacterial metabolism (Green et al., 2018).

Ca^{2+} and Fe^{+} were the water quality attributes with the weakest correlation in the three canonical analyses, indicating that the action of these ions on the hydraulic performance of the drippers is lower than those of the other attributes. However, both influence clogging, the first by the precipitation of calcium carbonate ($CaCO_3$), which causes fouling (Ribeiro et al., 2018), while the second precipitates in the form of Fe^{3+} when oxidized and also favors the occurrence of fouling and assists in the formation of biofilm (Carvalho et al., 2016).

Given the opposite relationship between dripper clogging agents and hydraulic performance, it is worth pointing out that the robust and obstructive biofilm that reduces the hydraulic performance of emitters is formed not only by coliforms (biological clogging agent) but also by other attributes, such as TSS (physical clogging agent) and fouling elements such as Mg^{2+} and EC (chemical clogging agents), which have strong correlations observed in the three canonical analyses.

This relationship suggests that the clogging of the drippers may be caused by the joint action of physical, chemical, and biological agents, which makes the clogging mechanism more complex. This type of clogging caused by the joint action of agents with different natures has also been observed in other studies with wastewater from the processing of cashew nuts (Batista et al., 2018), domestic sewage (Costa et al., 2019), and dairy effluent (Cunha et al., 2017).

Finally, the results of the three canonical analyses indicate that the hydraulic performance of the drippers operating with aquaculture effluent and its dilutions in well water was better for ST, followed by NJ, and finally SL. This is evidenced by the fact that the factors of the coefficients representing the ST dripper have the lowest factors in correlation with the water quality attributes, even increasing the flow rate, which has the factor in the same direction as the factors of the water quality attributes.

This result is corroborated by Vale et al. (2020), who tested these same types of drippers operating with produced water from oil exploration diluted in well water and obtained the best hydraulic performance results for the ST dripper and the lowest uniformity with the SL dripper. Also, this result is similar to that reported by Cunha et al. (2017), who tested these same drippers operating with dairy effluent diluted in well water and obtained the best results for the RQR and CVQ of the ST, SL, and NJ drippers, in this order.

The reuse of aquaculture effluent in agriculture can generate an increase in the income of aquaculture producers, and the data obtained in this research helps in making decisions about which dripper is most suitable for this type of wastewater without causing greater costs with maintenance and equipment changes of irrigation. For future research, one suggestion is to test some products that minimize the reduction in the hydraulic performance of the emitters due to the action of the attributes indicated in this study as causing clogging.

Conclusions

1. The results obtained in the canonical correlation analysis indicated that when the concentrations of attributes increase, the hydraulic performance of the drippers decreases.

2. The interaction of this group of attributes indicates that the clogging of drippers operating with the five dilutions of aquaculture effluent in well water occurs by the combined action of physical, chemical, and biological agents.

3. The ST dripper was the least sensitive to the group of quality attributes of the dilutions of the aquaculture effluent in well water. In contrast, the most sensitive was the SL dripper.

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