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**CIRCULAR REUSE OF WATER PRODUCED IN DRIP IRRIGATION:
MITIGATING CLOGGING WITH ULTRA-LOW-FREQUENCY DYNAMIC
PULSES**

MOSSORÓ

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Dissertation submitted to the Graduate Program in Soil and Water Management at the Federal Rural University of the Semi-Arid Region as a requirement for obtaining the degree of Master in Soil and Water Management.

Research Line: Treatment and agricultural use of waste and its impacts on soil and water.

Advisor: Rafael Oliveira Batista, Prof. Dr.

Co-advisor: Jose Francismar de Medeiros, Prof. Dr.

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2025

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GENERAL ABSTRACT

The salinity of oil produced water is one of the barriers to agricultural reuse with localized irrigation, as chemical clogging of emitters compromises the efficiency of water and nutrient application. In this sense, the use of ultra-low frequency dynamic electronic pulses can mitigate the formation and adhesion of precipitates in emitters without the use of chemicals. Thus, the objective of this work was to analyze the behavior of hydraulic performance indices in mitigating the clogging of emitters operating with produced water from onshore oil in experimental setups. For this purpose, three experimental setups were assembled in an experimental area of the Universidade Federal Rural do Semi-Árido in Mossoró-RN, Brazil. The experiment was set up in a split-plot design in a completely randomized design with six replications. The plots contained the water sources (WS – supply water, OPW + EP – oil produced water with ultra-low frequency dynamic electronic pulses, and OPW – oil produced water), while the subplots contained the hydraulic performance evaluation times (0, 40, 80, 120, 160, 200, 240, 280, 320, 360, and 400 hours). The experimental setups were assembled with drip tapes, with a non-self-compensating emitter operating at a pressure of 80 kPa at the end of the lateral line. During the experimental tests, the physicochemical characterization of the water sources was carried out, as well as the evaluation of hydraulic performance through the average rate of change of flow (AFVR), flow rate variation coefficient (FVC), and the Coefficient of Uniformity of Distribution (DU). Water source quality data were subjected to descriptive statistics, while hydraulic performance data were analyzed using RT-1 analysis with Bonferroni post-hoc tests. The results indicated that oil produced water presented a high risk of clogging due to pH, hardness, and salinity. Water quality and operating time significantly affected the hydraulic performance and clogging rates of the emitters. The application of ultra-low frequency dynamic electronic pulses showed promise, reducing clogging, stabilizing flow, and improving hydraulic efficiency. Although conducted on a laboratory scale, the study presents unprecedented results for drip irrigation using ultra-low frequency dynamic electronic pulses. The findings corroborate the safe and efficient use of unconventional water sources, demonstrating the viability of agricultural reuse and clogging mitigation as strategies to address water scarcity. This research expands knowledge about the hydraulic performance of emitters with lower quality water, contributing to sustainable irrigation practices.

Keywords: Semi-arid; Wastewater; Descaling; Obstruction; Emitters.

RESUMO GERAL

A salinidade da água produzida do petróleo é uma das barreiras ao reúso agrícola com irrigação localizada, pois o entupimento químico de emissores compromete a eficiência de aplicação de água e nutrientes. Nesse sentido, o uso de impulsos eletrônicos dinâmicos de ultrabaixa frequência pode mitigar a formação e adesão de precipitados nos emissores sem o uso de produtos químicos. Assim, objetivou-se com o presente trabalho analisar o comportamento de índices de desempenho hidráulico na mitigação do entupimento de emissores operando com água produzida do petróleo em bancadas experimentais. Para isso, foram montadas três bancadas experimentais em área experimental da Universidade Federal Rural do Semiárido em Mossoró-RN, Brasil. O experimento foi montado no esquema de parcelas subdivididas em delineamento inteiramente casualizado com seis repetições. Nas parcelas foram dispostas as fontes de água (WS – água de abastecimento, OPW+EP – Água produzida do petróleo com impulsos eletrônicos dinâmicos de ultrabaixa frequência e OPW - Água produzida do petróleo), enquanto nas subparcelas os tempos de avaliação do desempenho hidráulico (0, 40, 80, 120, 160, 200, 240, 280, 320, 360 e 400 horas). As bancadas experimentais foram montadas com fitas gotejadoras, com emissor não autocompensante, que operaram com pressão de 80 kPa no final da linha lateral. Durante os ensaios experimentais realizou-se a caracterização físico-química das fontes de água, bem como a avaliação do desempenho hidráulico por meio da taxa média de variação da vazão (Dra), coeficiente de variação da vazão (CV) e o Coeficiente de Uniformidade de Distribuição (CUD). Os dados de qualidade das fontes de água foram submetidos à estatística descritiva, enquanto os dados de desempenho hidráulico foram analisados utilizando análise RT-1 com testes post hoc de Bonferroni. Os resultados indicaram que a água produzida do petróleo apresentou alto risco de entupimento devido ao pH, dureza e salinidade. A qualidade da água e o tempo de operação afetaram significativamente o desempenho hidráulico e os índices de entupimento dos emissores. A aplicação de impulsos eletrônicos dinâmicos de ultrabaixa frequência mostrou-se promissora, reduzindo o entupimento, estabilizando a vazão e melhorando a eficiência hidráulica. Embora conduzido em escala laboratorial, o estudo apresenta resultados inéditos para irrigação por gotejamento utilizando pulsos eletrônicos dinâmicos de frequência ultrabaixa. As descobertas corroboram o uso seguro e eficiente de fontes de água não convencionais, demonstrando a viabilidade da reutilização agrícola e da mitigação de entupimentos como estratégias para lidar com a escassez hídrica. Esta pesquisa amplia o conhecimento sobre o desempenho hidráulico de emissores com água de menor qualidade, contribuindo para práticas de irrigação sustentáveis.

Palavras-chave: Semiárido; Água residuária; Descalcificação; Obstrução; Emissores.

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LIST OF ABBREVIATIONS AND ACRONYMS

A	Water Supply
AFRV	Average Flow Rate Variation
APHA	American Public Health Association
ASAE	American Society of Agricultural Engineers
B	Oil and Gas Produced Water with Ultra-Low-Frequency Dynamic Electronic impulses
BSh	Köppen Climate Classification (Hot Semi-Arid)
C	Oil and Gas Produced Water
Ca	Calcium
CAERN	Water and Sewage Company of Rio Grande do Norte
Ca ²⁺	Calcium Ion
Cl ⁻	Chloride Ion
CO ₂	Carbon dioxide
CROSS	Cationic Structural Stability Ratio
CV	Coefficient of Variation
DU	Coefficient of Uniformity of Distribution
EC	Electrical Conductivity
EDTA	Ethylenediaminetetraacetic Acid
FAO	Food and Agriculture Organization of the United Nations.
Fe	Iron
Fe ²⁺	Reduced iron
Fe ³⁺	Insoluble iron
FVC	Flow Rate Variation Coefficient
H ₂ CO ₃	Carbonic Acid
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometry
K	Potassium
K ⁺	Potassium Ion
kHz	Kilo-Hertz
kPa	Kilo-Pascal
LASAP	Soil. Water and Plant Analysis Laboratory
Mg ²⁺	Magnesium Ion
Mn	Manganese

Na ⁺	Sodium Ion
NBR	Brazilian Standard
OPW	Oil and Gas Produced Water
OPW+EP	Oil and Gas Produced Water with Ultra-Low--Frequency Dynamic Electronic Impulses;
PVC	Polyvinyl chloride
SAR	Sodium Adsorption Ratio
SDG	Sustainable Development Goal
SEM	Scanning Electron Microscopy
TDS	Total dissolved solids
TSS	Total Suspended Solids
UFERSA	Federal Rural University of the Semi-Arid Region
UM	United Nations
US	United States of America
W	Watt
WS	Water Supply
WT	Water Temperature
X	Flow Exponent

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GENERAL INTRODUCTION

Irrigation is a technique that meets the water needs of crops, providing the right amount of water to reach their maximum potential for development and production. It is one of the most essential agricultural practices, especially in arid and semi-arid regions where water availability is limited (Souto, 2023). In this context, the Sustainable Development Goals Agenda 2030 (SDGs) proposed by the United Nations are highly relevant, particularly SDG 6, which seeks to ensure the availability and sustainable management of water and sanitation for all (Roy; Pramanick, 2019). The lack of water in semi-arid regions, aggravated by climate change, directly impacts agricultural production and, consequently, food security, according to SDG 2, which proposes to end hunger, achieve food security, improve nutrition, and promote sustainable agriculture. In addition, SDG 12, which aims to ensure sustainable production and consumption patterns, is directly related to the efficient use of water and the reduction of waste in agricultural practices (Carvalho, 2019).

Oil Produced water (OPW) is water trapped in underground formations that is brought to the surface along with oil and gas during the production of these fluids. Among the aspects of PW that deserve attention are its high volumes and the complexity of its composition (Rajbongshi; Gogoi, 2024). These aspects mean that OPW management requires specific care, not only in relation to technical and operational aspects, but also environmental ones. As a result, OPW management results in considerably high costs, which represent a significant percentage of production costs (Pica *et al.*, 2017).

Among the various irrigation systems used, drip irrigation stands out as one of the most efficient options for rational water use, allowing direct and controlled application to plant roots. This type of system increases crop productivity, reduces waste, and makes better use of soil nutrients. However, efficiency can be compromised by clogging of the drippers, caused mainly by the presence of physical, chemical, and biological agents in the irrigation water (Bhavsar *et al.*, 2023). In emitters, clogging occurs when the current flow rate is less than 75% of the design flow rate (ASAE Standards, 2003).

With the worsening of water scarcity and pollution, water sources for drip irrigation have been diversified. Thus, wastewater, brackish water, river water with high particle content, and other low-quality water are often used as water sources for drip irrigation (Wang *et al.*, 2025).

The use of OPW in drip irrigation systems rich in total dissolved solids can cause precipitation to form inside the drippers, impairing water flow and increasing maintenance costs. These components present in petroleum-produced water can be grouped into the following categories: oil; heavy metals; radionuclides; treatment chemicals; salt; and dissolved oxygen (Ray *et al.* 2012). The scarcity of freshwater sources, amplified by climate change, makes it even more urgent to adopt solutions that allow the use of water with higher salt concentrations without compromising the efficiency of irrigation systems. This challenge is also aligned with SDG 13, which proposes urgent action to combat climate change and its impacts, as water scarcity is becoming increasingly frequent in various regions of the planet (Heiba *et al.*, 2023).

On the other hand, Jiang *et al.* (2022) present a technological innovation that has shown potential to solve this problem: the application of electromagnetic fields to irrigation water. Studies suggest that these fields can alter the physical and chemical structure of the ions present in the water, hindering the formation of scale in irrigation systems. By reducing ion agglomeration, this approach can prevent deposits in drippers and improve water flow, aligning with SDG 6, which seeks to promote sustainable water management, and SDG 9, which consists of building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation by encouraging research and development of innovative technologies for the efficient use of water resources (Carvalho, 2019).

The use of electromagnetic fields or ultra-low frequency dynamic electronic pulses can also modify the properties of water, contributing to better distribution and flow in the emitters of drip irrigation systems (Zhou *et al.*, 2021). This approach represents an emerging research area that could be a crucial solution in arid and semi-arid regions, where water scarcity is a constant reality. Its implementation offers several technical, economic, and environmental benefits. Ultra-low frequency dynamic electronic pulse technology appears more promising than electromagnetic fields due to its greater ease of operation and installation, and lower installation and maintenance costs.

From a technical standpoint, improving the efficiency of irrigation systems through more rational water use is crucial to combating water scarcity. Increased efficiency directly contributes to the fulfillment of SDG 6 and SDG 2 by optimizing water use and improving food security. Reducing dripper clogging also ensures a continuous flow of water, which is essential for maintaining uniformity in irrigation systems and crop productivity. From an economic standpoint, reducing the maintenance and replacement

costs of irrigation system parts benefits producers by reducing expenses related to constant cleaning and replacement of damaged components. In addition, the application of electromagnetic fields would extend the useful life of drippers, generating long-term resource savings, which is in line with SDG 8, which is to promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all. From an environmental perspective, the use of technologies that increase irrigation efficiency also contributes to sustainability. By improving water use, reducing waste, and reducing the need for chemical treatments to prevent scaling, technology can help conserve water resources and promote more sustainable agricultural practices. This is directly aligned with SDG 15, which seeks to protect, restore, and promote the sustainable use of terrestrial ecosystems, since the use of electromagnetic fields can reduce the impact of agriculture on local ecosystems, benefiting both the soil and the surrounding ecosystems. In addition, by contributing to greater water use efficiency and reducing the need for chemical treatments, this technology also fits into SDG 3, ensuring healthy lives and promoting well-being for all at all ages by reducing exposure to substances that are potentially harmful to the environment and human health (Weiland *et al.*, 2021).

Therefore, research into the use of high-frequency electrical and dynamic pulses to prevent dripper clogging is of great importance not only for solving a specific technical problem, but also for contributing to improved agricultural sustainability, reduced operating costs, and maximized use of water resources. The application of this technology has the potential to generate significant benefits for agriculture, helping to achieve several water-related SDGs, such as SDG 6 (sustainable water management), SDG 2 (food security), SDG 9 (innovation and sustainable infrastructure), SDG 12 (sustainable consumption and production), SDG 13 (climate action), SDG 8 (sustainable economic growth), and SDG 15 (ecosystem protection).

Given the above, the objective of this work was to mitigate the chemical clogging of non-self-compensating drippers using ultra-low frequency dynamic electronic pulses in experimental setups operating with onshore produced water. Specifically, the following were studied: physicochemical characteristics that most contributed to clogging in the emitters; hydraulic performance and obstruction level of non-self-compensating emitters operating with different water sources; and analysis of the clogging-triggering material using scanning electron microscopy.

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CHAPTER I: INNOVATIVE USE OF ULTRA-LOW-FREQUENCY DYNAMIC ELECTRONIC IMPULSES FOR SUSTAINABLE PERFORMANCE OF DRIPPERS APPLYING PRODUCED WATER

ABSTRACT

Clogging is a major constraint to the agricultural reuse of produced water; however, ultra-low-frequency dynamic electronic pulses (EPs) can help control biofouling in drip emitters. This study aimed to evaluate the reduction in clogging in non-self-compensating emitters applying onshore oil-and-gas-produced water treated with EP. Three experimental benches were assembled using drip irrigation units supplied with different water sources: water supply (WS), produced water with EP (OPW + EP), and produced water without treatment (OPW). Hydraulic performance was monitored every 40 h for 400 h using average flow rate variation (AFVR), flow rate variation coefficient (FVC), and distribution uniformity (UD) indices. Data were analyzed using RT-1 analysis with Bonferroni post hoc tests. Results showed that the interaction between water sources and evaluation times significantly ($p \leq 0.01$) affected the hydraulic indices. After 400 h, the in-dices ranked as UD and FVC: $WS > OPW + EP > OPW$, and AFVR: $OPW + EP = WS > OPW$. Although OPW presented a low risk of clogging, the application of EP mitigated the obstruction and maintained higher uniformity by reducing clogging. These findings demonstrate that ultra-low-frequency electronic pulses are an innovative anti-clogging technology and provide insights for the sustainable application of produced water.

Keywords: localized irrigation; emitters; anti-clogging; industrial effluent; salinity.

1. INTRODUCTION

By 2050, the global population is projected to reach 9.7 billion, demanding a 55% increase in water supply, while climate change remains one of the main challenges for water resource management. Population growth and climate change are intensifying water scarcity, jeopardizing the achievement of Sustainable Development Goal (SDG) 6 - “to ensure availability and sustainable management of water and sanitation for all”—as global freshwater availability per capita has declined by more than 20% in the last two decades. Global freshwater withdrawals for agriculture, industry, and municipalities rose from 671.31 billion m³ in 1901 to 3.99 trillion m³ in 2014, with agriculture accounting for 72% of total withdrawals, 41% of which are environmentally unsustainable. Over 60% of irrigated cropland is already under high water stress [1–6].

Arid regions cover 41.1% of Earth’s land surface and support about 2 billion people, 90% of whom live in developing countries. Classified as hyper-arid, arid, and semi-arid, these areas represent 6.6%, 10.6%, and 15.2% of global land, hosting 1.7%, 4.1%, and 14.4% of the world’s population, respectively. They sustain 50% of global livestock and 44% of food production [7–9]. The Brazilian semi-arid region stands out as one of the most populated and biodiverse, covering 15.69% (1,335,298 km²) of the national territory across 11 states and 1,477 municipalities, dominated by the unique Caatinga biome [10–13].

Water reuse is an ancient practice, with knowledge dating back nearly 5,000 years [14]. Countries such as China, Mexico, the United States, Egypt, Saudi Arabia, Syria, Israel, Chile, Spain, and Japan are global leaders in reuse initiatives [15–20]. Water reuse extends the lifespan of freshwater resources, particularly for agricultural applications, which enhance nutrient cycling, decomposition, and microbial activity, reducing dependence on synthetic fertilizers and improving soil health [13,21].

Water scarcity severely impacts arid regions, compromising food and water security. Simultaneously, the oil and gas industry generates large and growing volumes of oil-produced water (OPW), which can be reused for irrigating non-food and bioenergy crops in these areas [22]. In 2024, global oil production reached 35.37 billion barrels, with the United States leading (7.33 billion barrels) and Brazil ranking ninth (1.28 billion barrels) [23]. OPW, a mixture of formation water, injected water, condensed gas water, and residues from treatment chemicals, is produced in higher volumes than oil, at estimated ratios of 2.4:1 worldwide, 10:1 in the United States, and 15.4:1 in Brazil. These

correspond to 5.62, 1.16, and 0.20 billion m³ of OPW, respectively, which, after adequate treatment, could irrigate 44.60, 9.21, and 1.61 million hectares of non-food and bioenergy crops in two 90-day cycles [23,24]. The composition of OPW depends on geological formation, reservoir age, and operational practices, and typically includes hydrocarbons, salts, metals, radioactive materials, and chemical additives such as corrosion inhibitors and biocides [25].

In Israel, combining drip irrigation with wastewater reuse has overcome water scarcity, increasing agricultural value by 1,600% over 65 years and recycling 86% of sewage, which supplies 50% of irrigation water. Drip irrigation aligns with SDG 6 by applying small, precise volumes of water and fertilizers directly to the root zone, reducing evaporation (5–15%), runoff and leaching (0–10%), while achieving 85–95% irrigation efficiency. Moreover, it mitigates human health risks, suppresses weed growth, and prevents diffuse pollution [26–28].

Emitter clogging remains one of the main limitations to the widespread adoption of drip irrigation systems, as it reduces emitter flow, irrigation uniformity, and system lifespan, while increasing maintenance costs and serving as a potential reservoir of pathogenic microorganisms harmful to humans, animals, and crops. Despite these challenges, the global area under localized irrigation increased by 69.43% from 2009 to 2020, mainly due to its high efficiency in mitigating water scarcity. Clogging is attributed to the small labyrinth dimensions (0.5–1.2 mm), which favor biofouling caused by the combined effects of physical, chemical, and biological factors. Physical clogging results from the deposition of organic and inorganic solids such as algae residues, plastics, sand, silt, and clay. Chemical clogging involves supersaturation, nucleation, crystallization, and precipitation of compounds including carbonates, phosphates, sulfates, hydroxides, Fe²⁺, Ca²⁺, and Mg²⁺. Biological clogging arises from biofilm formation by bacteria, protozoa, algae, cyanobacteria, and fungi that synthesize extracellular polymeric substances acting as biological adhesives, increasing viscosity and promoting the adhesion of particulates to emitter walls [28–37].

To mitigate clogging in drip irrigation system emitters, there are physical methods (lateral line flushing, filtration, electromagnetic treatment, generation of molecular oscillations, application of pulsating pressure, and ultrasonic treatment), chemical methods (acidified fertigation, nanoparticles, hydrogen peroxide, electrochemical methods and chlorination), and bacterial methods (treatment with antagonistic bacterial

strains) [38-41]. Another promising technology for mitigating clogging in localized irrigation system emitters is ultra-low-frequency dynamic electronic pulses.

This anti-clogging technology for residential water supply pipes is already available on the market and is based on physical water treatment. Compared to electromagnetic treatment, it offers common advantages, such as reduced calcite, no need for chemicals, low energy consumption, and easy operation. Furthermore, ultra-low-frequency dynamic electronic pulses, when in contact with water, generate small amounts of carbonic acid, which acts as a scale solvent, producing crystals with lower adhesive power and the ability to form larger aggregates. Electromagnetic treatment, on the other hand, alters the crystallization and precipitation processes of crystal masses in the water, instead of adhering to pipe surfaces. Thus, the electrophoresis effect generated by ultra-low frequency dynamic electronic impulses allows better performance in mitigating clogging than electromagnetic induction pulses, in addition to lower electrical energy consumption due to ultra-low frequencies, lower installation and maintenance costs, operational flexibility, lower electromagnetic interference and the ability to also mitigate biofilm formation [42-45].

Given the context of increasing water scarcity, the application of ultra-low-frequency dynamic electronic pulses to OPW for drip irrigation of non-food and bioenergy crops in arid lands represents an unprecedented alternative for promoting circularity in the oil and gas industry and advancing SDG 6 of the UN 2030 Agenda. However, research on the hydraulic performance and anti-clogging efficiency of emitters applying OPW treated with ultra-low-frequency dynamic electronic pulses remains scarce and poorly understood. The use of this technology is innovative and may enhance the agricultural reuse of treated OPW in arid environments by reducing clogging and improving system performance. Thus, this study hypothesizes that ultra-low-frequency dynamic electronic pulses can maintain adequate hydraulic performance and mitigate emitter clogging when applying OPW. The objective was to evaluate the effectiveness of ultra-low-frequency dynamic electronic pulses on the hydraulic performance and clogging mitigation of non-pressure-compensating flat emitters using OPW, an effluent with reuse potential for non-food and bioenergy crop production in the semi-arid region of Rio Grande do Norte, Brazil.

2. MATERIALS AND METHODS

2.1 Experimental area and types of water tested

The experiment was conducted between January and April 2025, in the outdoor area of the Rural Construction and Environment Laboratory of the Federal Rural University of the Semi-Arid Region (UFERSA), located in Mossoró, Rio Grande do Norte, Brazil (5°12'13.14" S; 37°19'26.93" W), at an average altitude of 16 m. The experimental area is located in the Brazilian arid lands known as the Potiguar semi-arid region (classification BSh, according to Köppen), characterized by an average annual temperature of 26.5 °C and average annual rainfall of 794 mm [46].

Three water sources were used in the experimental trials: 1) Treated water produced by the oil and gas industry, sourced from the Potiguar Basin and used in two test beds; 2) Water from the supply network provided by the Rio Grande do Norte Water and Sewage Company (CAERN) used in only one test bed (control); and 3) Desalinated water obtained from the Soil, Water, and Plant Analysis Laboratory (LASAP) at UFERSA to replenish the water in the reservoirs of the three benches and maintain salinity stable in the water sources during the experimental period. Table 1 presents the physicochemical parameters of the three water sources that supplied the experimental benches during the operating times of 0, 200 and 400 hours.

Table 1. Physicochemical parameters of the three water sources that supplied the experimental benches during the operating times of 0, 200 and 400 hours

Parameters	Operating time (h)								
	0			200			400		
	WS	OPW + EP	OPW	WS	OPW + EP	OPW	WS	OPW + EP	OPW
WT (°C)	31.1	31.7	31.1	31.1	30.7	30.7	31.5	32.5	31.2
TSS (mg L ⁻¹)	8	18	14	6	32	26	0	14	26
pH	8.15	8.1	8.19	6.7	6.1	8.22	8.16	8.26	8.19
EC (dS m ⁻¹)	0.46	4.93	4.97	0.69	7.31	7.36	0.57	5.36	5.3
Na ⁺ (mmol _c L ⁻¹)	3.33	33.33	31.99	5.38	54.32	53.01	4.06	40.21	39.77
K ⁺ (mmol _c L ⁻¹)	0.18	1.24	1.24	0.26	1.91	1.83	0.22	1.36	1.31
Ca ²⁺ (mmol _c L ⁻¹)	0.44	7.40	7.65	0.56	8.70	9.40	0.48	5.50	6.00
Mg ²⁺ (mmol _c L ⁻¹)	0.64	4.35	3.65	0.52	3.50	2.69	0.16	3.00	2.55
Fe (mg L ⁻¹)	0.018	0.185	0.241	0.049	0.093	0.079	0.017	0.021	0.009
Mn (mg L ⁻¹)	0.004	0.005	0.006	0.005	0.001	0.001	0	0.002	0.003

Note: WS – Water supply; OPW + PE – Water produced from the oil and gas industry subjected to ultra-low-frequency dynamic electronic pulses; OPW – Water produced from the oil and gas industry; WT – Water temperature measured in triplicate from 6:00 a.m. to 12:00 p.m.; TSS – Total suspended solids; EC – Electrical conductivity.

2.2 Experimental design

The experiment was set up in a split-plot design, using a completely randomized design, with six replicates. The plots consisted of three water sources: water produced by the oil and gas industry subjected to ultra-low-frequency dynamic electronic pulses (OPW + EP), water from the supply network (WS), and water produced by the oil and gas industry (OPW). The subplots corresponded to 11 evaluation times for emitter clogging (0, 40, 80, 120, 160, 200, 240, 280, 320, 360, and 400 hours).

2.3 Experiment setup and drip unit operation

To carry out the experimental tests, three test benches were assembled, each with a surface area of 8.30 m², measuring 1 m wide by 8.3 m long. The benches consisted of a reinforced concrete pillar base and a wooden structure used to fix the corrugated fiber cement tiles, installed with a 2.5% slope. This slope was designed to allow gravity drainage of the tested water and its recirculation [40].

A reservoir with a storage capacity of 0.31 m³ was installed on each workbench, in addition to a drip irrigation unit consisting of: a 368 W motor pump set, a 120 mesh disc filter, a gate valve, a sample collection point downstream of the filtration system, two pressure gauges for reading the operating pressure (one fixed upstream of the filtration system and the other mobile, used at the end of the side lines), a ultra-low-frequency dynamic electronic pulse generator, a 32 mm PVC main pipe, a 50 mm PVC branch pipe, six connectors with sealing rings, and six high-strength, durable polyethylene lateral lines with a diameter of 16 mm (Fig. 1).

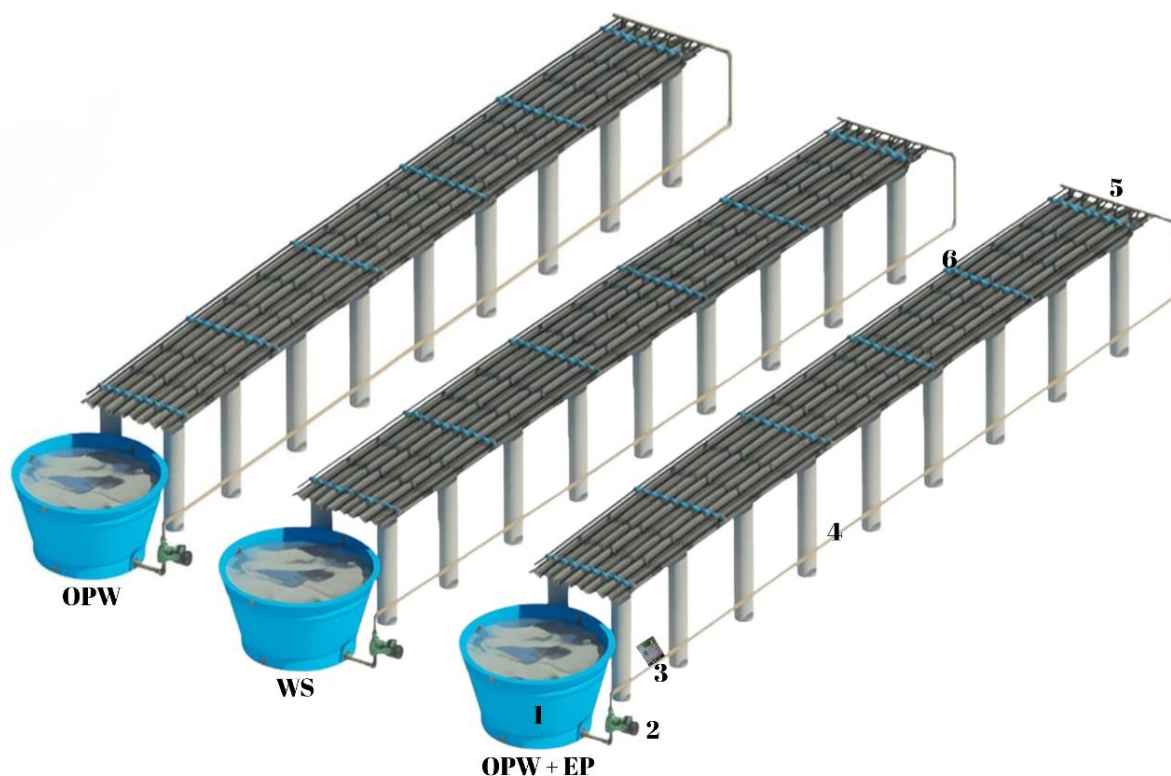


Fig. 1. Diagram of the three experimental benches operating with water supply (WS), water produced from the oil and gas industry (OPW), and water produced from the oil and gas industry subjected to ultra-low-frequency dynamic electronic pulses (OPW + EP), highlighting the 0.31 m³ water reservoir (1), 368 W motor pump set (2), ultra-low-frequency dynamic electronic pulse generator (3), main and branch lines (4, 5), and polyethylene lateral lines with non-self-compensating flat drippers (6).

The lateral lines were laid out on the experimental benches, which are 8.30 m long, and consisted of thin-walled drip tape with non-self-compensating flat emitters widely used in melon irrigation in the irrigated areas of the states of Rio Grande do Norte and Ceará. Six lateral lines were installed on each bench, all with drip tape with non-self-compensating emitters that serve 1 to 3 crops, with the following technical specifications: self-cleaning, nominal flow rate of 1.6 L h⁻¹ at 100 kPa, flow coefficient of 0.568, flow equation exponent (x) of 0.45 (characterizing the flow regime), emitter filtration area of 15 mm², spacing between emitters of 0.4 m, emitter water passage dimensions of 0.65 × 0.55 × 13 mm (width × depth × length), manufacturer-recommended filtration of 120 mesh, wall thickness of 0.20 mm.

The first bench applied OPW+EP throughout the 6-hour workday, using an ecological water treatment system with the following specifications: 0.15 m wide × 0.18 m long, maximum nominal pipe diameter of 1½", maximum capacity for 3.0 m³ h⁻¹,

power of 4.3 W, and frequency range of 3 to 32 KHz [42]. This device is based on the principle of physical water treatment, where special electronic pulses alter the calcium crystallization process so that calcium carbonate crystals are less likely to adhere to surfaces, reducing scale formation. The second bench served as a control operating with WS, and the third applied only OPW.

The three experimental benches operated, on average, 6 hours per day until completing a total of 400 hours of operation [40], distributed over 66 consecutive days, with the aim of inducing the process of emitter obstruction. The pressure at the end of the lateral lines was monitored during the experimental period and maintained at 80 kPa with the aid of a portable pressure gauge with a scale ranging from 0 to 400 kPa. This operating pressure value favors the clogging process of drippers, in addition to being widely used in the drip irrigation systems of melon producers in the region.

Every two days of operation, the three water sources in the 0.31 m³ reservoirs were replenished due to evaporation in the open-air experimental benches. When the salinity of the water increased by more than 10% from the initial value (0h), desalinated water with low electrical conductivity ranging from 0.020 to 0.040 dS m⁻¹ was added.

2.4 Characterization of the physical-chemical parameters of the three water sources over time during the operation of the experimental benches

To monitor the potential for clogging of the emitters by the three water sources (OPW+EP, WS, and OPW) that supplied the experimental benches, samples were collected downstream of the filtration system at operating times of 0, 200, and 400 h, using the recommendations of Standard Methods for the Examination of Water and Wastewater-APHA [47]. The parameters were temperature (WT) and electrical conductivity (EC) of the water sources, which were determined in situ with a mercury thermometer from 6:00 a.m. to 12:00 p.m. and a portable conductivity meter. The water source samples were sent to LASAP/UFERSA for quantification of the following parameters: pH by direct reading on a pH meter; Na⁺ and K⁺ ions were quantified using flame photometry in accordance with standard analytical procedures.; Ca²⁺ and Mg²⁺ ions by complexometry with EDTA, using eriochrome black T as an indicator for magnesium and calcon for calcium; Fe and Mn by optical emission spectrometry with inductively coupled plasma (ICP-OES) and total suspended solids (TSS) by the gravimetric method at 103-105 °C using the methodologies of the Brazilian Agricultural Research

Corporation [48] and Standard Methods for the Examination of Water and Wastewater-APHA [47].

The total dissolved solids content was estimated by Equation 1 for EC from 0.10 to 5.0 dS m⁻¹ and by Equation 2 for EC greater than 5.0 dS m⁻¹ according to FAO recommendations [49].

$$\text{TDS} = \text{EC} \times 640 \quad (1)$$

$$\text{TDS} = \text{EC} \times 800 \quad (2)$$

Where: TDS - Total dissolved solids, mg L⁻¹; and EC - Electrical conductivity, dS m⁻¹.

With the values of Na⁺, Ca²⁺, and Mg²⁺, the sodium adsorption ratio (SAR) proposed by the US Salinity Laboratory Staff [50] was estimated using Equation 3.

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{\frac{(\text{Ca}^{2+} + \text{Mg}^{2+})}{2}}} \quad (3)$$

Where: SAR – Sodium adsorption ratio, (mmol_cL^{-10.5}); Na⁺ – Sodium content in irrigation water, mmol_cL⁻¹; Ca²⁺ – Calcium content in irrigation water, mmol_cL⁻¹; and Mg²⁺ – Magnesium content in irrigation water, mmol_c L⁻¹.

The cationic ratio of structural stability (CROSS) was also calculated with the contents of Na⁺, K⁺, Ca²⁺, and Mg²⁺ as proposed by [51] using Equation 4.

$$\text{CROSS} = \frac{(\text{Na}^+ + 0,56 \times \text{K}^+)}{\sqrt{\frac{(\text{Ca}^{2+} + 0,60 \times \text{Mg}^{2+})}{2}}} \quad (4)$$

Where: CROSS – Cationic ratio of structural stability, (mmol_cL⁻¹)^{0.5}; Na⁺ – Sodium content in irrigation water, mmol_cL⁻¹; Ca²⁺ – Calcium content in irrigation water, mmol_cL⁻¹; and Mg²⁺ – Magnesium content in irrigation water, mmol_c L⁻¹.

In classifying the risk of dripper clogging by the three water sources as low, moderate, and severe, the criteria of [33] were used for the parameters pH, TDS, Fe, Mn, and TSS, and [34] for the parameters EC, Ca²⁺ and Mg²⁺.

2.5 Monitoring of hydraulic performance and clogging in drippers

To analyze the hydraulic performance and clogging of drippers using the three water sources, 16 emitters were marked on each side line of the experimental benches to measure flow, adapting the methodology proposed by [52]. The flow rates were obtained every 40 h by collecting water in 250 mL plastic containers, using graduated cylinders

and a digital stopwatch to control the collection time, set at five minutes, adapting the recommendations of NBR ISO 9261 [53].

The detection of clogging of the dripper units was performed using three hydraulic performance indicators: 1) Average flow variation rate (AFRV), proposed by [34] and presented in Equation 5; 2) Flow variation coefficient (FVC) described by standard ASAE EP 405.1 FEB03 [54] and presented in Equation 6; and 3) Distribution uniformity coefficient (DU) presented by [55] and described in Equation 7.

$$AFRV = \frac{\sum_{i=1}^n \frac{q_a}{q_i}}{n} \times 100 \quad (5)$$

Where: AFRV – Average flow variation rate, %; q_a – Current dripper flow, $L h^{-1}$; q_i – Initial dripper flow, $L h^{-1}$; and n – Number of drippers evaluated.

For the classification of AFRV values, the criterion proposed by [56] was adopted, where: $AFRV \geq 95\%$ no clogging; $80\% \leq AFRV < 95\%$ mild clogging; $50\% \leq AFRV < 80\%$ partial clogging; $25\% \leq AFRV < 50\%$ severe clogging; and $AFRV \leq 25\%$ complete clogging.

$$FVC = \frac{S_d}{q_{avg}} \times 100 \quad (6)$$

Where: FVC – Coefficient of Variation, %; S_d – Standard deviation of flow values, $L h^{-1}$; q_{avg} – Average flow values, $L h^{-1}$.

According to [57], the FVC classification is as follows: excellent ($FVC < 5\%$), average ($5\% \leq FVC < 7\%$); marginal ($7\% \leq FVC < 11\%$), poor ($11\% \leq FVC \leq 15\%$) and unacceptable ($FVC > 15\%$).

$$DU = \frac{q_{25\%}}{q_{avg}} \times 100 \quad (7)$$

Where: CUD – Coefficient of Uniformity of Distribution, %; $q_{25\%}$ – Average of the lowest 25% of flow rates, $L h^{-1}$; q_{avg} – Average flow rates, $L h^{-1}$.

The classification of CUD values was based on the criteria of [55]: excellent ($DU > 90\%$), good ($80\% < DU \leq 90\%$), regular ($70\% \leq DU \leq 80\%$) and poor ($DU < 70\%$).

2.6 Micrographs by electron microscopy and scanning (SEM)

Scanning Electron Microscopy (SEM) was used to identify biofouling in drippers. This technique allows high-resolution analysis of the internal surfaces of the emitters,

enabling visualization of the morphology and spatial distribution of the deposits responsible for biological and chemical clogging. Specifically, SEM images provide details of microbial colonization, biofilm formation, and the presence of EPS, which are typical indicators of biological clogging. Furthermore, SEM images allow visualization of the morphology of the precipitates, allowing distinctions between calcite, aragonite, and others to be made based on the morphology. Reduced biofilm formation and aragonite predominance may indicate biofouling attenuation by ultra-low-frequency dynamic electronic pulses.

At the end of the experimental period (400 h), representative samples of biofouled emitters were collected in duplicate for micrographic analysis. The emitters were removed from the lateral lines and carefully dissected manually. Subsequently, emitter samples containing biofilm from each water source were placed in a desiccator for 72 hours to reduce excess moisture. Thereafter, 10 mm sections of the clogged labyrinth channels were mounted on aluminum stubs (12.5 mm in diameter).

Representative dripper samples, prepared in duplicate, were then affixed to metallic stubs using carbon conductive adhesive tabs (PELCO Tabs™, Ted Pella, Inc., Redding, CA, USA) and sputter-coated (Q150R ES, Quorum Technologies Ltd., Laughton, East Sussex, England) with a thin gold layer (9 nm). This coating enhanced the electrical conductivity of the samples of obstructed emitters, ensuring the acquisition of high-resolution images. Micrographs were subsequently obtained using a secondary electron (SE) detector in a scanning electron microscope (SEM, VEGA 3 LMU, Tescan, Czech Republic) operated at an accelerating voltage of 20 kV, as recommended by [58].

A total of 53 micrographs were acquired, corresponding to the non-pressure-compensating dripper model evaluated in each experimental bench. Images were captured at magnifications of 30×, 40×, 100×, 1700×, and 5000×, with the highest magnification providing the greatest level of structural detail.

2.7 Statistical analysis

The values of the physical-chemical parameters ($n = 3$) of the three water sources were subjected to descriptive statistical analysis to obtain the mean and standard deviation. Furthermore, the data for the hydraulic performance and clogging indicators AFRV, FVC, and DU ($n = 198$) were subjected to the Shapiro-Wilk normality test ($p > 0.05$), due to its high power in small to moderate sample sizes and good sensitivity to asymmetry/kurtosis; additionally, its implementation in SISVAR adopts the AS R94

algorithm [59], recognized for numerical stability and speed, ensuring reproducibility, using the free statistical program SISVAR [60].

When normality (or homoscedasticity) was not met ($p \leq 0.05$), a predefined workflow was followed: (i) priority for non-parametric ranking procedures, applying RT-1 analysis with Bonferroni's post-hoc test ($p \leq 0.001$) to compare treatments over time; (ii) all results explicitly indicate whether they derive from parametric (when applicable) or non-parametric analysis. Finally, AFRV and FVC values were also presented using raincloud plots that show the upper and lower limits, median, and mean, with the covariate tool used to highlight operating times in each treatment. For this, the free open-source statistical program JASP [61] was used.

2.8 Economic analysis

To estimate the annual electricity consumption of an ultra-low frequency dynamic electronic pulse generator device, the following scenario was created: 1) Average kWh of electricity for the irrigator in the state of Rio Grande do Norte, Brazil, of US\$ 0.14; 2) Elephant grass cultivar with the potential to produce 50 t ha⁻¹ of dry matter per cycle; 3) Three elephant grass cuts per year; 4) Use of drip tapes; 5) Use of irrigation water with salinity between 4.5 and 5.5 dS m⁻¹; 6) Ultra-low frequency dynamic electronic pulse generator device with a power of 4.3 W [42]; and 5) Average irrigation time of 3 h day⁻¹. The annual cost of electricity used by the ultra-low-frequency dynamic electronic pulse generator was estimated using equation 8.

$$AEC = \frac{P \times J \times D \times T}{1000} \quad (8)$$

Where: AEC - Annual cost of electricity for using the ultra-low-frequency dynamic electronic pulse generator, US\$ year⁻¹; W - Working hours, hours day⁻¹; O - Operating period, days; A - Average electricity tariff for irrigators in the state of Rio Grande do Norte, US\$.

3. RESULTS

3.1 Analysis of the parameters of the three water sources used to supply the benches

Table 2 indicates that most parameters exhibited high standard deviations, reflecting temporal variability at 0, 200, and 400 hours. Among the 14 parameters, 86%, 93%, and 86% showed greater dispersion in WS, OPW+EP, and OPW, respectively.

Table 2. Mean, standard deviation, and coefficient of variation of the physical-chemical parameters of the three water sources that supplied the experimental benches during the operating times of 0, 200, and 400 hours.

Parameters	Mean $\pm$ Standard deviation (coefficient of variation in %)		
	AA	OPW + EP	OPW
WT	31.10 $\pm$ 0.23(0,7)	31.70 $\pm$ 0.90(2,8)	31.10 $\pm$ 0.26(0,8)
TSS (mg L ⁻¹)	6.00 $\pm$ 4.16(69)	18.00 $\pm$ 9.45(52)	26.00 $\pm$ 6.93(27)
EC (dS m ⁻¹)	0.57 $\pm$ 0.11(19)	5.36 $\pm$ 1.27(24)	5.30 $\pm$ 1.29(24)
TDS (mg L ⁻¹)	367 $\pm$ 74(29)	4430 $\pm$ 1352(30)	4436 $\pm$ 1364(31)
pH	8.15 $\pm$ 0.84(10)	8.10 $\pm$ 1.20(15)	8.19 $\pm$ 0.02(0,2)
Na ⁺ (mmol _e L ⁻¹)	4.26 $\pm$ 1.04(24)	42.62 $\pm$ 10.70(25)	41.59 $\pm$ 10.63(25)
Ca ²⁺ (mmol _e L ⁻¹)	0.48 $\pm$ 0.06(12,5)	7.40 $\pm$ 1.61(22)	7.65 $\pm$ 1.70(22)
Mg ²⁺ (mmol _e L ⁻¹)	0.52 $\pm$ 0.25(48)	3.50 $\pm$ 0.68(19)	2.69 $\pm$ 0.60(22)
K ⁺ (mmol _e L ⁻¹)	0.22 $\pm$ 0.04(18)	1.50 $\pm$ 0.36(24)	1.46 $\pm$ 0.32(22)
SAR (mmol _e L ⁻¹) ^{0,5}	6.34 $\pm$ 1.57(25)	18.42 $\pm$ 4.23(23)	18.08 $\pm$ 4.17(23)
CROSS (mmol _e L ⁻¹) ^{0,5}	7.17 $\pm$ 1.61(22)	20.16 $\pm$ 4.45(22)	19.55 $\pm$ 4.30(22)
Mg ²⁺ /Ca ²⁺	0,90 $\pm$ 0,56 (62)	0,51 $\pm$ 0.09(18)	0,40 $\pm$ 0.10(25)
Fe (mg L ⁻¹)	0.018 $\pm$ 0.018(100)	0.093 $\pm$ 0.082(88)	0.079 $\pm$ 0.119(150)
Mn (mg L ⁻¹)	0.004 $\pm$ 0.003(75)	0.002 $\pm$ 0.002(100)	0.003 $\pm$ 0.003(100)

Note: WS – Water supply; OPW+PE – Water produced from the oil and gas industry subjected to ultra-low-frequency dynamic electronic pulses; OPW – Water produced from the oil and gas industry; WT – Water temperature measured in triplicate from 6:00 a.m. to 12:00 p.m.; TSS – Total suspended solids; EC – Electrical conductivity; TDS – Total dissolved solids; SAR – Sodium adsorption ratio; CROSS – Cationic ratio of structural stability.

When comparing WS, OPW+EP, and OPW, only WT and pH showed similar mean values (14% similarity). Between OPW+EP and OPW, 50% of the 14 parameters were similar, while WT, pH, Mg²⁺, Mg²⁺/Ca²⁺, Fe, Mn, and TSS differed. The application of ultra-low-frequency dynamic electronic pulses reduced Mn and TSS by 50% and 44%, respectively, but increased Mg²⁺, Mg²⁺/Ca²⁺, and Fe by 30%, 27%, and 18%. Coefficients of variation ranged from low (<10%) for WT and pH to very high ($\geq$ 30%) for Fe, Mn, TSS, and Mg²⁺/Ca²⁺. Fe and Mn showed the greatest variability in all water sources, with CVs up to 150% in OPW, whereas pH exhibited the lowest variability (0.2%).

3.2 RT-1 analysis with Bonferroni post-hoc test for ranking treatments by time

Data analysis in irrigation experiments often faces statistical limitations due to non-normal and heterogeneous data [62]; thus, the RT-1 method with Bonferroni post-hoc testing was applied. Significant treatment differences ($p < 0.001$) were found. OPW+EP showed equal or superior hydraulic performance (AFRV) to WS and OPW up to 240 hours, indicating short-term anti-clogging efficiency, but its advantage declined after 280 hours, suggesting reduced pulse effectiveness over time due to water quality (Table 3).

Table 3. Rankings of the temporal evolution of hydraulic performance indices for water sources.

Time (hours)	AFRV (%)* Ranking	FVC (%)* Ranking	DU (%)* Ranking
0	OPW+EP ^a = WS ^a = OPW ^a	OPW ^a > WS ^b = OPW+EP ^b	OPW ^a > WS ^b > OPW+EP ^c
40	WS ^a = OPW+EP ^a OPW ^b	OPW+EP ^a = WS ^a > OPW ^b	OPW+EP ^a > WS ^b = OPW ^b
80	WS ^a = OPW+EP ^a > OPW ^b	OPW+EP ^a = WS ^a > OPW ^b	OPW+EP ^a = WS ^a > OPW ^b
120	OPW+EP ^a = WS ^a = OPW ^a	OPW+EP ^a > WS ^b = OPW ^b	OPW+EP ^a > OPW ^b = WS ^b
160	WS ^a = OPW+EP ^a > OPW ^b	OPW+EP ^a = WS ^a > OPW ^b	OPW+EP ^a = WS ^a > OPW ^b
200	OPW+EP ^a = WS ^a > OPW ^b	WS ^a = OPW+EP ^a > OPW ^b	WS ^a > OPW+EP ^b > OPW ^c
240	WS ^a = OPW+EP ^a > OPW ^b	WS ^a = OPW+EP ^a > OPW ^b	WS ^a = OPW+EP ^a > OPW ^b
280	WS ^a > OPW+EP ^b > OPW ^c	WS ^a > OPW+EP ^b = OPW ^b	WS ^a > OPW+EP ^b = OPW ^b
320	OPW+EP ^a = WS ^a > OPW ^b	WS ^a > OPW+EP ^b > OPW ^c	WS ^a > OPW+EP ^b > OPW ^c
360	WS ^a > OPW+EP ^b > OPW ^c	WS ^a > OPW+EP ^b = OPW ^b	WS ^a > OPW+EP ^b = OPW ^b
400	OPW+EP ^a = WS ^a > OPW ^b	WS ^a > OPW+EP ^b > OPW ^c	WS ^a > OPW+EP ^b > OPW ^c

Note: WS – Water supply; OPW + EP – Oil and gas produced water with ultra-low-frequency dynamic electronic impulses; OPW – Oil and gas produced water with. *Treatments followed by the same lowercase letter do not differ statistically according to the Bonferroni post-hoc test of the RT-1 analysis ($p < 0.001$).

Initially, OPW showed greater flow stability, but between 40 and 160 hours, OPW+EP exhibited lower FVC values and, at 200–240 h, performed similarly to WS, ensuring better water distribution. After 320 h, WS achieved the greatest stability, indicating that water quality prevails in prolonged operation. Regarding DU and OPW was initially more uniform, while OPW+EP maintained higher uniformity up to 280 hours. Beyond this point, WS again outperformed, confirming that better-quality water better preserves hydraulic performance over time.

3.3 Dynamics of the hydraulic performance of non-self-compensating drippers analyzing treatments and operating time

Fig. 2 presents the AFRV hydraulic performance index for drippers under three water treatments: WS (A), OPW+EP (B), and OPW (C).

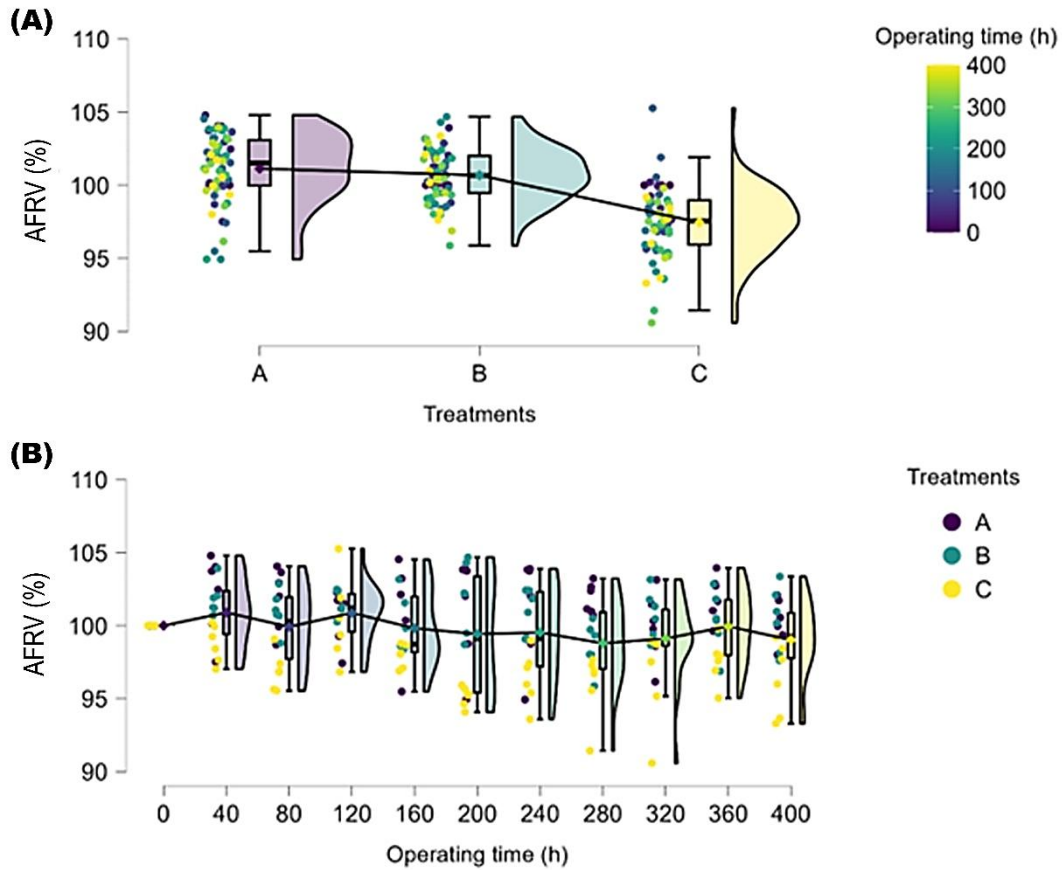


Fig. 2. Descriptive statistical analysis ($n = 198$) of the hydraulic performance index average flow variation rate (AFRV) using raincloud plots that show the upper and lower limits, median, and mean, and using the covariate tool to highlight the operating times in each treatment and the treatments at each operating time.

Fig. 2A shows that WS exhibited a concentrated distribution near 100%, indicating high efficiency and low variation, while OPW had greater dispersion (average 96.89%), reflecting higher clogging. OPW+EP displayed a concentrated distribution like WS, suggesting that ultra-low-frequency dynamic electronic pulses mitigated incrustation formation. Fig. 2B illustrates the effect of operating time: AFRV in OPW decreased most at 200 hours (95.15%), while WS remained stable (1% drop at 320 hours), and OPW+EP

showed consistent performance with only a 2% reduction at 280 hours. Across all time points, WS maintained the highest efficiency with low variability, OPW performed worst, and OPW+EP was a promising alternative, due to reduced scaling and particle accumulation. Some AFRV values exceeded 100% at various times for WS and OPW+EP, possibly due to flow increases from temperature-induced emitter expansion.

Fig. 3 shows the values of the flow coefficient of variation (FVC), used as an indicator of the hydraulic performance of the drippers.

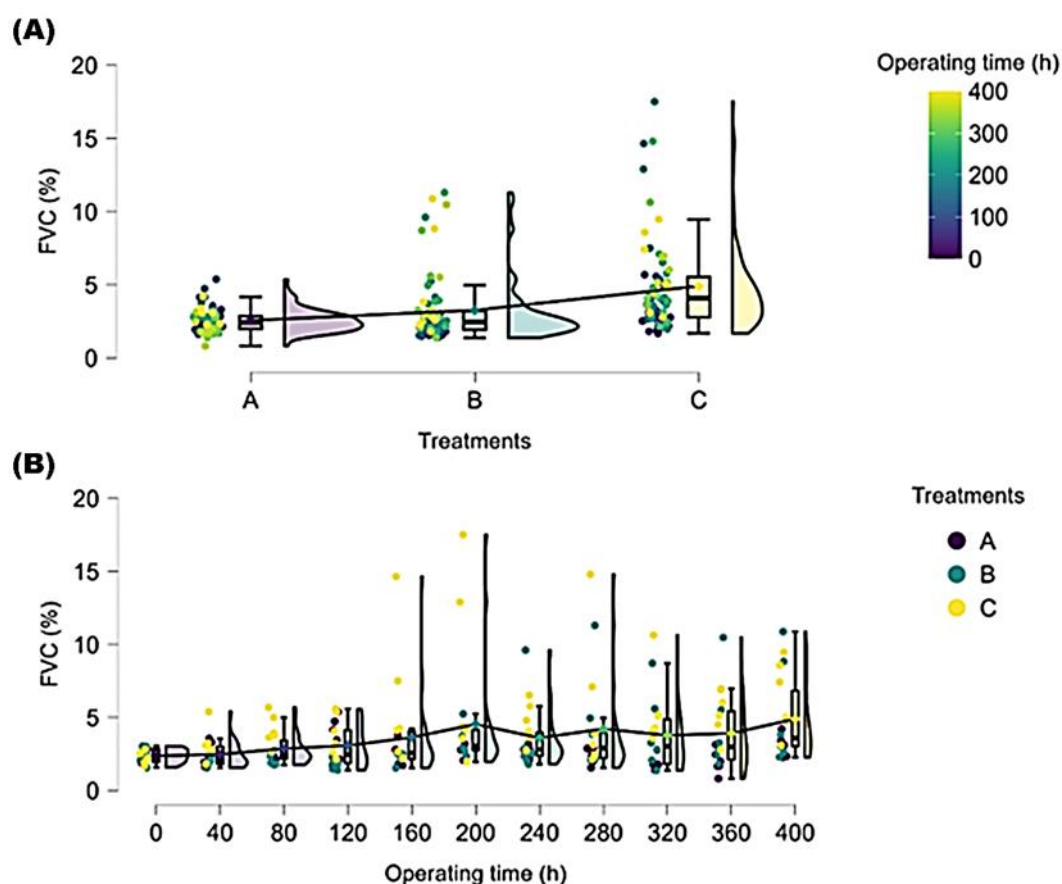


Fig. 3. Descriptive statistical analysis ($n = 198$) of the hydraulic performance index flow coefficient variation (FVC) using *raincloud plots* that show the upper and lower limits, median, and mean, and using the *covariate* tool to highlight the operating times in each treatment and the treatments at each operating time.

Fig. 3A shows that WS (A) had the most concentrated distribution (mean FVC 2.46%), indicating high uniformity and low flow variation, while OPW (C) exhibited greater dispersion (mean FVC 5.38%) due to obstructions from solids and incrustations. OPW+EP (B) showed intermediate, more controlled variability (mean FVC 3.52%), suggesting

reduced flow fluctuations via ultra-low-frequency dynamic electronic pulses. Fig. 3B shows that over time, FVC increased most in OPW, peaking at 20% at 200 hours, while WS and OPW+EP remained relatively stable, with B peaking at 12% at 280 h and A dropping to 5% at 120 h. Overall, WS performed best, OPW worst, and OPW+EP was a promising alternative, likely due to reduced particle deposition and biofilm formation.

Fig. 4 presents the distribution uniformity coefficient (DU) for the three water treatments.

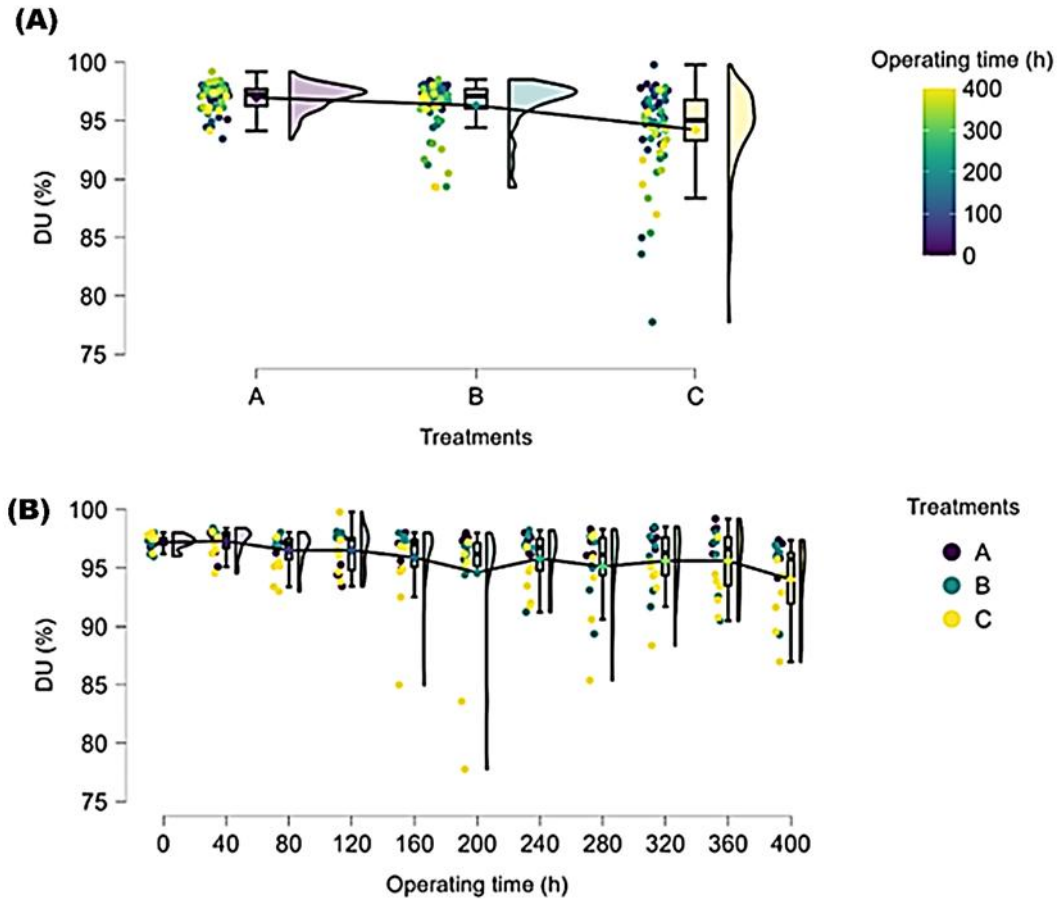


Fig. 4. Descriptive statistical analysis ($n = 198$) of the hydraulic performance index distribution uniformity coefficient (DU) using *raincloud plots* that show the upper and lower limits, median, and mean, and using the *covariate* tool to highlight the operating times in each treatment and the treatments at each operating time.

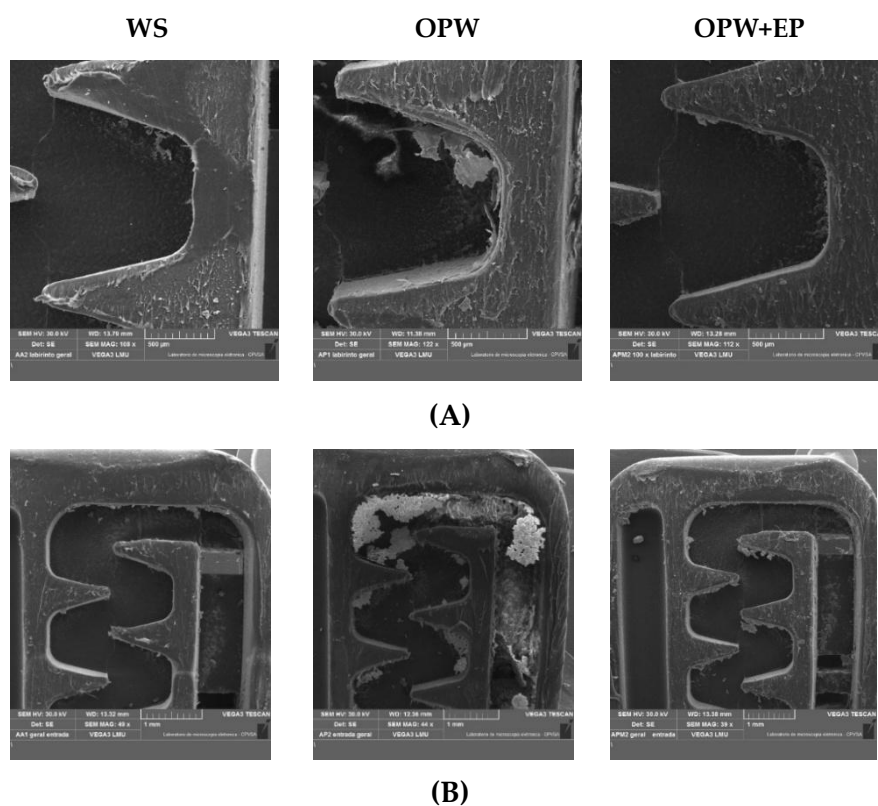
Fig. 4A shows that WS (A) had the most concentrated values and lowest variability, with an average DU of 97.17% after 400 h, indicating stable hydraulic performance. OPW (C) exhibited a dispersed distribution, averaging 93.74% and showing wide variation, reflecting greater clogging. OPW+EP (B) displayed intermediate performance, averaging 96.28%, suggesting that ultra-low-frequency dynamic electronic pulses helped maintain uniformity. Fig. 4B illustrates temporal trends: DU decreased over

time, especially in OPW, dropping $\sim 6\%$ from 97.45% to 91.85%. OPW+EP showed a smaller reduction of 3% (97% to 94.12%), approaching WS performance, which decreased only 2% (97.18% to 95.18%). These results indicate that electronic pulses effectively mitigate incrustation formation and particle adhesion, sustaining irrigation uniformity over time.

When comparing the treatments, treatment A maintained the most stable performance, reinforcing its suitability for irrigation systems that do not require additional water treatment. Treatment C proved to be more vulnerable to clogging, confirming the need for interventions to improve its quality before agricultural use. Treatment B, on the other hand, showed intermediate performance, which positions it as a viable alternative with the potential to reduce the negative impact associated with the use of produced water.

3.4 Micrographs of biofouling formed on non-self-compensating emitters that applied the three water sources

The micrographs obtained by SEM at the end of 400 h of operation revealed differences in the deposition of incrustations between the treatments (Fig. 5).



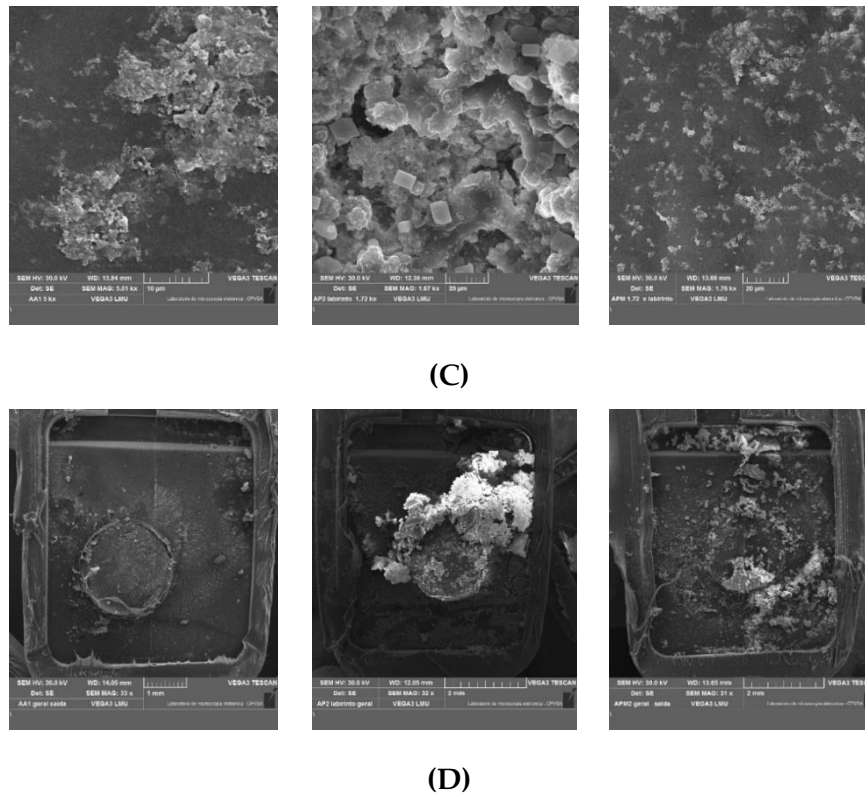


Fig. 5. Micrographs obtained by scanning electron microscopy (SEM) after 400 hours of operation with three water sources: water supply (WS), untreated produced water (OPW), and produced water subjected to ultra-low-frequency dynamic electronic pulses (OPW+EP), highlighting: (A) deflector region; (B) labyrinth inlet; (C) labyrinth interior; and (D) labyrinth outlet region.

In the emitters that applied WS, the inner surface was relatively clean, with only small scattered deposits. In those that operated with OPW, thick layers of crystalline incrustations associated with particulate matter and biofilm were found, mainly covering the inlet and outlet regions of the labyrinth. The emitters that applied OPW+EP, on the other hand, had more sparse deposits, composed of smaller and less adhesive crystals, distributed in a dispersed manner throughout the labyrinth.

3.5 Annual energy cost

Table 4 shows that even with a considerable increase in operating hours (6 h/day) and/or rate (US\$0.20/kWh), the annual electricity cost of the ultra-low-frequency dynamic electronic pulse generator device remains below US\$2 per year, a negligible value compared to the costs of implementing a drip irrigation system, applying agricultural inputs, or harvesting.

Table 4. Energy consumption and estimated annual operating cost (AEC) of the ultra-low frequency dynamic electronic pulse generator device for a bioenergy crop irrigation scenario in the semiarid region of Northeast Brazil.

Tariff (US\$ kWh ⁻¹)	Hours day ⁻¹	Annual consumption (kWh)	AEC (US\$ year ⁻¹)
0.10	1	1.57	0.16
0.10	3	4.71	0.47
0.10	6	9.42	0.94
0.14	1	1.57	0.22
0.14	3	4.71	0.66 (Baseline scenario)
0.14	6	9.42	1.32
0.20	1	1.57	0.31
0.20	3	4.71	0.94
0.20	6	9.42	1.88

4. DISCUSSION

The tests to monitor hydraulic performance and clogging of drip tapes in open-air experimental benches with recirculation of water sources have an important limitation in that they do not reflect the actual operating conditions of the irrigation equipment. This limitation is reinforced by the fact that recirculation increases the levels of physical-chemical parameters in the water due to evaporation losses, which are high in the semi-arid region of Brazil. In addition, in the field, irrigation equipment is shaded by plants, which mitigates temperature rise and expansion of plastic devices, which does not occur in open-air bench experiments, where lateral lines are placed on top of fiber cement tiles receiving solar radiation and, probably, having water temperatures inside the lateral lines that are different from field conditions. In addition, in the field, irrigation equipment is shaded by plants, which mitigates temperature rise and expansion of plastic devices, which does not occur in open-air bench experiments, where lateral lines are placed on top of fiber cement tiles receiving solar radiation and, probably, having water temperatures inside the lateral lines that are different from field conditions. The dynamics of dripper clogging in the field are also likely to be different due to the greater length of the lateral lines and shorter daily operating time. On the other hand, bench experiments enable

studies of hydraulic performance and clogging of drippers with wastewater, representing a low-cost alternative that provides quick results. Even though the conditions are not the same as in the field, this type of simulation reveals trends of likely problems in irrigation equipment. Another positive aspect of bench experiments with open-air recirculation is the increased risk of clogging, which can be more severe than in field conditions, and if this is the case, the anti-biofouling measure may also work in real conditions that are less extreme. In the present work, desalinated water was added to mitigate the effect of evaporation on the concentration of physical-chemical parameters. In addition, excessive heating could be avoided by operating the benches at night, and a more accurate simulation of clogging could be achieved by increasing the length of the lateral lines to about 20 m, as well as avoiding aeration of the water sources during the recirculation process, according to adaptations made to the recommendations of [40].

4.1 Water quality for irrigation purposes and risk of dripper clogging by the three water sources that supplied the experimental benches

The heterogeneity of the values of most of the physical-chemical parameters of the three water sources throughout the experimental period (Table 1) can be attributed to the evaporation of water on the benches, causing an increase in ion concentration, to the process of recirculation and replacement of water, and to the use of ultra-low-frequency dynamic electronic pulses.

Regarding the magnitude of the physical-chemical parameters, there is a large difference between WS and OPW+EP and OPW. This fact is associated with the origin of the water. For example, WS can have three quality compositions over time: surface water, groundwater, and a mixture of both, which explains some of the variations in the physical-chemical parameters. WS comes from the urban supply network, which has an average of 2.0 mg L⁻¹ of free residual chlorine, helping to mitigate biological clogging. The OPW+EP and OPW water sources have very similar quality but differ from WS as they are influenced by local geology and all the processes involved in drilling and operating oil wells.

When water sources are compared, it can be observed that the average values of the parameters WT, EC, TDS, pH, Ca²⁺, Na⁺, K⁺, SAR, and CROSS of OPW+EP and OPW were similar due to the same origin of these waters, while the parameters Mg²⁺, Fe, Mn, and TSS presented different averages, probably due to the action of ultra-low-frequency dynamic electronic impulses. It should be emphasized that the

physicochemical properties of OPW vary considerably depending on the geographical location of the oil field, the geological formation with which the water has been in contact for thousands of years, the presence of seawater, and the type of hydrocarbon produced [63, 64]. In the case of the TSS parameter, the suspended particles probably formed larger aggregates in OPW+EP through flocculation and were subsequently removed by the 120-mesh filter medium in the recirculation process. The presence of particles in a solution favors the crystallization phase and is essential for crystal growth [45].

The high levels of Mg^{2+} and Fe in OPW+EP may be due to greater precipitation. In the case of OPW, because it is located in deeper layers of reservoirs, there is little oxygen and thus Fe can be found in the ferrous state (FeO). However, reduced Fe (Fe^{3+}), which is soluble, can oxidize as it passes through the filtration system and the aeration process, which provides and recirculation, becoming insoluble (Fe^{3+}) and eventually precipitating and causing clogging of the drippers [31, 33, 34, 65, 66].

The average WT values for the WS and OPW sources were practically identical, while for the OPW+EP source, the average pH was slightly higher, about 0.60 °C higher than for WS and OPW. This slight increase in WT in OPW+EP may be related to the passage of electric current in this water source, thus causing an increase in WT due to the Joule effect, especially in the case of solutions with high ionic concentration, directly affecting the properties of the liquid (viscosity, density, dielectric constant, thermal conductivity, electrical conductivity, and pH) [67], such as OPW, which has an EC greater than 5 dS m^{-1} . WT is a parameter that interferes with the chemical and biological reactions that occur in water, generating agents that cause dripper clogging. Chemical clogging of drippers is enhanced at $WT > 55 \text{ °C}$ due to increased precipitate formation, while biological clogging is favored when WT is between 20 and 30 °C. In this case, $WT > 45 \text{ °C}$ deactivates enzymes, impairing bacterial growth and, consequently, biofouling [33-35].

SST represented by organic and inorganic particles suspended in water cause physical clogging of emitters due to their deposition in the small dimensions of the labyrinth, the presence of low-velocity flow regions, and lower vortex magnitude [39]. However, in the present study, their average levels were less than 50 mg L^{-1} in the three water sources, thus representing a low risk of emitter obstruction [33, 49]. OPW+EP and OPW water sources also have higher average TSS levels than WS, probably due to the difference in the origin of WS and OPW [68].

There was a slight reduction in pH from 8.19 (OPW) to 8.10 in (OPW+EP), probably due to the release of small amounts of H_2CO_3 caused by ultra-low-frequency dynamic electronic pulses, first through the aqueous solvation of CO_2 and then through hydration [69]. These average pH values are within the range of 8.1 to 8.6 characterized by [70] in OPW in Iraq. In the three water sources, the three average pH values were moderately alkaline and above 8.0, indicating a severe risk of dripper clogging [33].

Based on the FAO standard for water quality for irrigation purposes, the average values of the three water sources were higher than the upper limit of the pH range of 6.5 to 8.0, but ultra-low-frequency dynamic electronic pulses brought the average pH of OPW+EP closer to the upper limit by adding carbonic acid [49]. The EC and TDS parameters are related to the salinity of water sources. Thus, WS is classified as non-saline water ($\text{EC} < 0.7 \text{ dS m}^{-1}$ and $\text{TDS} < 450 \text{ mg L}^{-1}$), while OPW+EP and OPW are classified as moderately saline waters ($2 \text{ dS m}^{-1} \leq \text{EC} < 10 \text{ dS m}^{-1}$ and $1500 \text{ mg L}^{-1} \leq \text{TDS} < 6500 \text{ mg L}^{-1}$) based on FAO standards [49]. On the other hand, the EC standards of the US Salinity Laboratory Staff classify WS as water with a medium risk of soil salinization (C2 – Indicated with moderate leaching and plants with moderate salinity tolerance can be grown in most cases without special salinity control practices) and OPW+EP and OPW as having a very high risk of soil salinization (C4 – May be used occasionally in very special circumstances, requiring permeable soils with good drainage, and irrigation water must be applied in excess to provide considerable leaching, being indicated only for crops that are very tolerant to salinity) [50, 65]. Regarding dripper clogging, salinity poses a chemical risk in two ways: first, due to the formation of precipitates, and second, due to the formation of aggregates with small particles, where salinity reduces the zeta potential of water, making the forces of attraction stronger than those of repulsion [71]. The average EC and TDS values of WS, OPW+EP, and OPW represent low, severe, and severe risk, respectively [33, 34]. The study by [39] emphasizes that chemical clogging results from the precipitation of elements in solutions in irrigation water and, therefore, depends mainly on the pH and conductivity of the water. A pH above 8.0 and/or a conductivity above 3.0 dS m^{-1} , as well as a temperature above 55°C and a low partial pressure of CO_2 tend to increase the risk of chemical clogging. High SDT values (199,000 to 269,000 mg L^{-1}) were found in the Arabian Gulf OPW [63], which is about 45 to 61 times higher than the average OPW+EP and OPW values found in this study, again indicating that local geological conditions alter the salinity of the OPW.

The Na^+ levels in the three water sources are significant, with the concentration of Na^+ in the OPW+EP and OPW water sources being about 10 times higher than in WS. The Na^+ of WS, OPW+EP, and OPW presents a slight to moderate, severe, and severe risk, respectively, to the growth of plants that are not tolerant to Na^+ , according to the FAO. It should be noted that excess Na^+ can lead to K and Ca deficiency or reduced NO_3^- absorption in saline environments dominated by Cl^- . Irrigation with sodium-rich water requires the provision of a source of free calcium (limestone) to mitigate the effects of Na^+ [49]. Particularly in OPW, the Na^+ cation is the most common [63]. Even though Na^+ is not a parameter for dripper clogging risks, this cation forms precipitates that are deposited inside the emitters, forming biofouling [72].

Analyzing Ca^{2+} and Mg^{2+} in water sources separately, the prediction of chemical clogging risk is distinct. The impact of Ca^{2+} on chemical clogging is low ($\text{Ca}^{2+} < 12.5 \text{ mmol}_e \text{ L}^{-1}$) in the three water sources. Mg^{2+} , on the other hand, had a low clogging risk ($\text{Mg}^{2+} < 2.0 \text{ mmol}_e \text{ L}^{-1}$ in WS, but a moderate impact ($2.0 \text{ mmol}_e \text{ L}^{-1} \leq \text{Mg}^{2+} \leq 7.3 \text{ mmol}_e \text{ L}^{-1}$ in OPW+EP and OPW. On the other hand, when the Ca^{2+} and Mg^{2+} parameters are analyzed together as equivalent hardness of $\text{CaCO}_3 \text{ mL}^{-1}$, the risk of chemical clogging by prediction increases considerably in the OPW+EP and OPW water sources. With the Ca^{2+} and Mg^{2+} concentrations of the water sources (Table 1), hardness levels of 50, 545, and 517 mg L^{-1} are estimated for WS, OPW+EP, and OPW, respectively, with low, severe, and severe clogging risk [34, 73]. It should be noted that OPW+EP had a 5.41% increase in hardness compared to OPW, as ultra-low-frequency dynamic electronic pulses reduce the formation of precipitates and a higher concentration of Mg^{2+} is present in OPW+EP. The Ca^{2+} and Mg^{2+} parameters can cause chemical clogging problems in drippers due to the formation and deposition of calcium and magnesium carbonates in the labyrinths, in addition to jointly representing the hardness parameter [72, 74]. WT and pH of water sources affect the formation and adhesion of chemical precipitates, acting as indirect factors that affect emitter clogging [75]. A concentração de Ca^{2+} e Mg^{2+} na OPW depende da origem e idade da água, das rochas envolvidas, do tipo de rocha e do tipo de argila presente na rocha. The concentration of Ca^{2+} and Mg^{2+} in OPW depends on the origin and age of the water, the surrounding rocks and the types of rock and clay present in the rock. Reactions such as ion exchange, dolomite formation, and chlorite formation affect Ca^{2+} concentrations in OPW, while the main reaction affecting Mg^{2+} concentration is dolomite formation. This reaction reduces Mg^{2+} concentration and increases Ca^{2+} concentration

[63]. The three water sources had an $\text{Mg}^{2+}/\text{Ca}^{2+}$ ratio < 1 , in which case Mg^{2+} does not cause the same deleterious effects on the soil as Na^+ [49].

The concentration of K^+ in the OPW+EP and OPW water sources was almost 7 times higher than in WS. It should also be noted that the ultra-low-frequency dynamic electronic pulses enabled a slightly higher concentration of K^+ in OPW+EP (2.74%) than in OPW due to the lower formation of precipitates with K^+ . K^+ is a parameter that may also be present in the material causing dripper clogging due to the formation of precipitates or adsorbed to organic and inorganic particles, particularly when applying potassium fertilizers in the fertigation process. This can also reduce hydraulic conductivity and water infiltration into the soil due to the dispersion of clays [76].

Comparing the SAR and EC averages with FAO standards, there is a slight to moderate risk of reduced water infiltration into the soil in WS and no risk in OPW+EP and OPW. It is known that Na^+ directly contributes to total salinity and can also be toxic to sensitive crops, such as fruit trees, but the main problem with a Na^+ concentration higher than those of Ca^{2+} and Mg^{2+} is its effect on the physical properties of the soil, which disperses clays and, consequently, degrades the soil structure. Therefore, it is recommended to avoid using water with an RAS value greater than $10 (\text{mmol}_c \text{L}^{-1})^{0.5}$, if water is the only source of irrigation for long periods, which can occur in many arid lands. However, if the soil contains an appreciable amount of gypsum, this RAS value may exceed [49, 65].

The average CROSS value in OPW+EP and OPW was almost three times higher than that of WS, but in the three water sources there is no problem with reduced soil permeability and sodicity [76]. It should be emphasized that CROSS is a generalization of SAR for lower quality water, capable of predicting the impact of soil structure degradation by quantifying the contents of Na^+ , K^+ , Mg^{2+} , and Ca^{2+} where the effect of K^+ on clay dispersion is about one-third that provided by Na^+ [77].

The average values of Fe and Mn were well below the lower limits of 0.20 and 0.10 mg L^{-1} , respectively, for the classification of chemical clogging risk of drippers [33]. Fe and Mn can cause both chemical clogging (precipitate formation) and biological clogging (bacterial slime formation) in dripper labyrinths [30, 33, 34, 39, 66, 74].

4.2. Analysis of hydraulic performance index rankings for water sources as a function of operating times

The results presented in Table 1 show that OPW+EP is effective in reducing the risk of clogging and maintaining the uniformity of drip irrigation, especially in the first 280 h of operation with the non-self-compensating emitter. This effect can be attributed to the action of ultra-low-frequency dynamic electrical impulses, which potentially fragment or destabilize precipitates through the solvent action of carbonic acid, reducing their ability to form clogs in the emitters. Generally, carbonic acid reacts with Ca^{2+} , Fe^{2+} , and Mg^{2+} cations [78]. Ultra-low-frequency dynamic electrical pulses modify the shape of the precipitates, usually to a characteristic needle-like morphology (aragonite) with very weak adhesion to the substrate, which can be carried away by the liquid flow [79].

However, with continued operation of the system, a tendency toward loss of OPW+EP effectiveness was observed, which may be related to the formation of more structured biofilms that are resistant to the effects of ultra-low-frequency dynamic electronic pulses. On the other hand, WS demonstrated consistent and superior performance after 280 h, suggesting that, for systems operating for extended periods, water quality may be decisive for maintaining hydraulic performance. In the computer simulation of the CaSO_4 fouling process in a heat exchanger used in industrial processes. In this case, sinusoidal pulsating flow with variable frequency (1.59 to 12.73 Hz) and amplitude (10-70) was studied. Note that the pulse frequencies in that study were much lower than the ultra-low-frequency dynamic electronic pulses (3 to 32 KHz) [42]. Even so, these variations in the frequency and amplitude of the pulsating flow can introduce instability into the flow, making it unstable with the formation of vortices that are important in energy transport. For the turbulent flow region, the increase in frequency proportionally increased the resistance to fouling. The amplitude pulsation caused greater turbulent fluctuation and, therefore, greater shear tension on the heat transfer surface; thus, the mass removal rate increased over time [80].

The use of Bonferroni's RT-1 test was essential to ensure the accuracy of comparisons between treatments, identifying statistically significant differences ($p < 0.001$) at each evaluation interval. These findings reinforce the importance of considering not only the initial performance of treatments but also their stability over time.

From a practical standpoint, the use of ultra-low-frequency dynamic electronic pulses represents a viable strategy for systems operating in medium-term regimes,

enabling savings in maintenance and reducing the risk of failure. For prolonged operations, however, it is recommended to combine this technology with additional water quality management practices, such as filtration and preventive maintenance.

4.3 Effect of ultra-low -frequency dynamic electronic pulses on hydraulic performance and mitigation of dripper clogging

Drip irrigation has established itself as the most water-efficient technology, promoting higher productivity with less waste [81]. However, the quality of the water used can compromise the hydraulic performance of the system over time, as detected in the present study.

In the experimental tests, a drip tape with a non-self-compensating flat self-cleaning emitter with a flow exponent (x) of 0.45 was used, indicating a turbulent flow regime ($x \approx 0.5$), where the dripper flow varies with the square root of the pressure. In addition, this emitter has an average flow velocity in the labyrinth of 1.24 m s^{-1} . The magnitude of the flow velocity inside the labyrinth directly affects the formation and accumulation of all components of the obstructive substances [82].

The AFRV index was highly influenced by the type of water treatment and the obstruction mitigation strategies adopted in drip irrigation systems (Fig. 2).

The results indicate that the quality of the water used directly affects the efficiency of drip irrigation systems (Fig. 2A). The AFVR averages were interconnected by a line, where: Treatment C (OPW) showed the greatest variability and reduction in AFRV, possibly due to the formation of biofouling that caused partial clogging of the emitters; and treatment B (OPW+EP), which was subjected to ultra-low-frequency dynamic electronic pulses, showed values similar to treatment A (WS), which applied good quality water, used as a control. Treatments A and B show AFRV values between 95 and 105% ($\text{AFRV} \geq 95\%$ no clogging), while treatment C shows almost all data between 103 and 90%, falling between the classifications of no clogging and slight clogging ($80\% \leq \text{AFRV} < 95\%$ slight clogging) [56]. It should be noted that the evaluations were made in the open air from 6:00 a.m. to 12:00 p.m. in a semi-arid region, where air temperatures are higher and there is a greater incidence of global solar radiation, factors that may have contributed to the heating of the side lines (black color that absorbs radiation and heats up) and, consequently, increased water temperature, causing plastic materials to expand.

Variations in operating pressures, expansion of emitters, and changes in water viscosity may have led to the flow increase values expressed by $ARFV > 100\%$.

In the present study, the mean AFRV values were 101.13, 100.68, and 97.46% in treatments A, B, and C, respectively, very similar to the medians of 101.50, 100.68, and 97.55%. These results indicate that the use of ultra-low-frequency dynamic electronic pulses contributed to maintaining uniformity of water application at levels similar to those obtained with clean water, while the use of untreated OPW resulted in increased clogging. In the study by [83], with electromagnetic fields, there was also an increase in the hydraulic efficiency of the irrigation system, due to a significant reduction in the clogging rate of the emitters. In another study with permanent magnetic fields [84], there was also a reduction in chemical clogging in the emitter labyrinths that applied brackish water in relation to the control. Corroborating the results of the present study, it was evident that the use of electromagnetic fields in treated wastewater [85] mitigated the formation of biofouling in drip irrigation system emitters.

Fig. 2B shows the AFVR behavior over the operating time for the three treatments. It can be observed that above the line connecting the AFVR averages for each operating time, the data from treatments A and B without clogging predominate [56]. On the other hand, below the line connecting the averages, there is a predominance of AFR data from treatment C, indicating the occurrence of partial clogging. It should be noted that after 200 hours, there was slight clogging in treatment C [56], with the most significant clogging occurring at 320 hours.

Therefore, the results of this study prove that the application of ultra-low-frequency dynamic electronic pulses can be a viable and sustainable solution to preserve the efficiency of irrigation systems when using wastewater or lower quality water. Thus, treatment B proved promising in mitigating these effects, indicating that this approach can be effective in reducing biofouling adhesion and improving the efficiency and service life of drip irrigation systems.

Fig. 3 shows the results of the FVC index over the operating time for the treatments applied. FVC is essential for evaluating the dispersion of flows in relation to the average, where greater dispersions express a loss of hydraulic performance and the presence of clogging in the emitters. Fig. 3A shows that the WS (A) control presents less variability in FVC data, with a predominance of excellent classification ($FVC < 5\%$), indicating less clogging due to the presence of fewer physical and chemical clogging agents (Table 1). Probably, the presence of 2.0 mg L^{-1} of free residual chlorine in WS

minimized the presence, diversity, and activity of biological clogging agents, thus mitigating biofouling. Furthermore, in this figure, the FVC values in OPW+EP (B) show less dispersion in relation to OPW (C) due to the action of ultra-low-frequency dynamic electronic impulses that minimized biofouling. Regarding treatments A, B, and C, the mean FVC values were 2.56, 3.26, and 4.91%, higher than the median values of 2.41, 2.45, and 4.08%, respectively. Treatment C had more FVC data in the poor classification ($11\% \leq \text{FVC} \leq 15\%$), being the only treatment with data in the unacceptable classification ($\text{FVC} > 15\%$) [57]. Fig. 3B shows an intensification of emitter clogging in treatment C after 160 hours, as well as the random unclogging process that occurs due to pressure variation, growth and maturation of biofouling, and movement of the lateral lines at the time of evaluation. At 200 h of operation, the FVC of C reached its maximum, classified as unacceptable [57], resulting in a higher level of clogging of the emitters. In B, ultra-low-frequency dynamic electronic pulses reduced the magnitude of FVC in relation to C, with less oscillation of FVC values after 240 hours. The same FVC variability observed in this study was found by [57] in their study with water qualities without physical treatment. Their results highlighted the negative impact of the presence of solids and salts on the magnitude of FVC, especially in scenarios with saline or reused water. The absence of treatments led to greater dispersion of flow data in relation to the mean, reflecting an increase in flow variability between emitters and susceptibility to clogging. On the other hand, in the study by [86] with the use of magnetic fields in water treatment, a reduction in FVC is noted, suggesting that magnetization positively influenced the properties of the water, reducing particle aggregation and scale formation. Magnetic treatment promoted a more uniform distribution of flow over time, especially when compared to the use of untreated water. The results obtained corroborate the potential of physical treatments to maintain the hydraulic stability of irrigation systems. In another study with an electromagnetic field [87], but with water with salinity levels, a reduction in flow variability was also detected under high salinity conditions, maintaining the FVC at acceptable levels even with lower quality water. This highlights the ability of magnetic fields to modify the structure of dissolved salts and prevent emitter clogging over time.

The present study advances the application of physical treatments by employing ultra-low-frequency dynamic electronic pulses as a technique to mitigate clogging. Unlike the magnetic fields used in previous studies, ultra-low-frequency dynamic electronic pulses promote variations that interfere with the physical-chemical interactions of the components dissolved in water. As a result, the use of OPW+EP (B) resulted in

lower FVC variations over time, approaching the performance observed with the WS control (A) and overcoming the instability observed with OPW (C).

The DU index expresses the uniformity of water application in a drip irrigation system and stands out for being very sensitive to flow variation, as does the FVC index (Fig. 4). In treatments A, B, and C, the mean DU values were 96.98; 96.31, and 94.23% (Fig. 4A), classified as excellent ($DU > 90\%$) [55], being slightly lower than the values of their respective medians (97.27; 97.10, and 95.04%). As with the AFRV and FVC indices, the OPW (C) treatment presented DU values that represent a greater presence of emitters with clogging. Meanwhile, the WS (A) and OPW + EP (B) treatments presented very similar water application uniformity due to the use of ultra-low-frequency dynamic electronic pulses. From 160 h onwards, there was a significant drop in DU, reaching a minimum value at 200 h, with a regular classification ($70\% \leq DU \leq 80\%$) at that time [55].

The results obtained in this study were compared with those of [88], which compared the hydraulic performance of emitters applying hard water synthesized with CaCO_3 , with and without magnetic treatment. The average DU values with magnetic treatment were higher than those of the control. This performance result is consistent with the results of treatment B in the present study, which maintained the consistency and efficiency of the DU, even higher than that of the supply water itself in the first 160 hours of operation.

Similarly, [85] evaluated the application of magnetized saline water together with salinity levels. The DU values recorded varied, being slightly higher with magnetic treatment. The stability observed during the investigation, even at high salinities, shows that the use of magnetization contributed to reducing dripper clogging. Thus, physical water treatment was shown to maintain high levels of uniformity, which reinforces the potential of non-chemical technologies for the use of lower quality water.

The findings reported by [43] are consistent with those of the present study, indicating that ultra-low-frequency dynamic electronic pulse and electromagnetic pulse technologies act synergistically to mitigate chemical precipitation through the polymorphic transformation of calcite into aragonite. Specifically, electromagnetic pulse treatment promotes the formation of suspended microcrystals, thereby inhibiting surface crystallization, altering the surface charge characteristics of suspended particles, enhancing electrostatic repulsion, and limiting both flocculation and deposition. This process disrupts the synergistic interactions between chemical and particulate fouling.

Consequently, the reduced particle load diminishes the number of available nucleation sites for scale formation, while enhanced calcium crystallization lowers cation concentrations, ultimately suppressing particle aggregation by reducing charge neutralization.

A similarity can be observed between our findings and those reported by [44], who evaluated the combined and isolated effects of electromagnetic pulse and ultraviolet radiation technologies on mitigating biofouling in emitters operating with saline water. The combined technologies significantly reduced biofouling content and decreased the complexity of microbial networks compared with individual treatments. Consistent with our results, their study also demonstrated a marked reduction in precipitate content and particle incrustation, accelerating the transformation rate of CaCO_3 crystals from compact calcite to amorphous, hydrated, and loosely bound CaCO_3 , thereby enhancing the flocculation process.

4.4 Morphology and formation pattern of biofouling observed by SEM

The micrographs obtained by SEM (Fig. 5) at the end of the experiment (400 h) revealed marked differences in the nature and intensity of the deposits formed on the emitters under the three water sources. In the drippers operated with WS, the surface of the emitter can be seen to be relatively clean, with only small, scattered incrustations, which is consistent with the high-performance indices observed. In contrast, the emitters that applied OPW presented extensive layers of incrustations, formed by crystalline agglomerates and adhered particulate material, in addition to dense biofilm, which explains the greater drop in performance observed over time. The emitters subjected to OPW+EP, on the other hand, showed fewer and less cohesive deposits, with smaller crystals and modified morphology, distributed more sparsely in the labyrinth. This result is consistent with studies that have shown that the application of electromagnetic fields or magnetization of water can alter the morphology of crystals, especially CaCO_3 , favoring the formation of aragonite over calcite, which has less adhesion to surfaces and can be more easily removed by hydraulic flow [89-90].

Also in Fig. 5, it can be observed that the incrustation occurred mainly at the entrance to the labyrinth, a region with low flow velocity, a condition that favors particle deposition and crystal nucleation, a result that is consistent with previous findings in the literature [71, 91, 92]. These results corroborate the hypothesis that the local hydrodynamics of the emitter play a crucial role in the spatial distribution of incrustations.

Intense deposition was also observed in the exit zone of the labyrinth, mainly in the OPW treatment, possibly associated with the reduction in partial CO₂ pressure due to the contact of water with the atmosphere. This condition is consistent with the use of an open hydraulic circuit with recirculation, in which the continuous loss of dissolved CO₂ favors decarbonation, increasing supersaturation and CaCO₃ precipitation in this region.

[85] demonstrated that the application of electromagnetic fields not only reduced carbonate deposition in the emitters but also inhibited the formation of phosphates, silicates, and quartz, modified the network parameters and crystalline volumes of carbonates, and altered the composition of bacterial communities and the levels of extracellular polymeric substances (EPS). Consequently, electromagnetic fields effectively mitigated biofilms and incrustations, reducing obstructive substances. These findings corroborate the structural alteration of precipitates observed in OPW+EP in this study, suggesting that the treatment reduced the tendency of salts to adhere and limited biofilm attachment, which explains the better performance results compared to the direct use of OPW.

In field experiments, [93] observed that water magnetization reduced the dry mass of deposits in drippers under fertigation by up to 75%, in addition to modifying the morphology of the deposits to more fragile and dispersed structures. Therefore, the structural change in precipitates observed in OPW+EP suggests that physical treatment reduced the tendency of salts to adhere and limited biofilm consolidation, corroborating the results of better anti-clogging performance recorded in this treatment compared to the direct use of produced water.

4.5 Economic analysis and environmental impacts of ultra-low frequency dynamic electronic impulses

The simulation results presented in Table 4 indicate that the annual electricity cost for operating an ultra-low-frequency electronic pulse generator (~4.3 W) [42] for 3 h/day over a year is extremely low (~US\$0.66). When this cost is diluted over a simulated productivity of 150 t of elephant grass dry matter per hectare per year (three cuts), the energy input corresponds to approximately US\$0.0044 per ton of dry matter, a value practically irrelevant compared to typical production costs in forage or agricultural production systems. Additionally, factors such as energy efficiency, capital investment, and fixed operating costs have a more significant impact on the total cost of production than the current energy costs of low-power devices [94].

In addition to low operating costs, ultra-low-frequency dynamic electronic pulse technology stands out for two central environmental advantages: 1) It eliminates the use of chemicals that can affect the soil-plant system; and 2) It extends the life of drip tapes in the field, reducing production costs and the consumption of plastic materials, thus contributing to reducing the carbon footprint and environmental contamination with microplastics.

5. CONCLUSIONS

Produced water from the oil and gas industry with and without the application of ultra-low-frequency dynamic electronic pulses presented a severe risk of clogging in relation to pH, hardness, and salinity parameters.

The quality of water sources and operating time significantly influenced the values of hydraulic performance and emitter clogging indices in irrigation units.

The application of ultra-low-frequency dynamic electronic pulses to produced water proved to be a promising alternative, contributing to the mitigation of biofouling in emitters, greater temporal stability of flow values, and improving hydraulic efficiency indicators.

In water produced by the oil and gas industry, the flow variation coefficient and distribution uniformity coefficient indices were more sensitive to biofouling problems than the average flow variation rate index.

Comparative analysis with other studies in the literature confirms that the adoption of physical treatments, such as electromagnetic fields and electrical pulses, has the potential to reduce the negative impacts associated with the use of wastewater or low-quality water in drip irrigation. Although the tests were conducted on a bench, the findings with ultra-low-frequency dynamic electronic pulses are unprecedented in drip irrigation, contributing important information for the safe and efficient application of unconventional water sources, reinforcing the viability of agricultural reuse combined with clogging mitigation practices with actions to cope with water scarcity. Thus, this study strengthens existing knowledge about the hydraulic performance of emitters applying lower quality water, contributing to sustainable strategies in irrigated agriculture.

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