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Preliminary Physicochemical Assessment of Aquaculture Effluents for Irrigation Reuse in the Brazilian Semi-Arid

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Abstract Aquaculture effluents are increasingly recognized as a strategic resource for agricultural water reuse, especially in semi-arid regions, where water scarcity and fertilizer costs intensify pressure on production systems. Within a circular economy framework, these effluents may simultaneously supply water and nutrients; however, their physicochemical composition must be carefully assessed, since excessive salt loading may impair soil quality and threaten long-term agricultural sustainability. This study performed a preliminary physicochemical assessment of raw and diluted aquaculture effluents to determine their potential for irrigation reuse in the Brazilian semi-arid, with emphasis on salinity, sodicity, ionic composition, nutrient-related parameters, and trace elements. The experiment was conducted at the Federal Rural University of the Semi-Arid (UFERSA), Mossoró, northeastern Brazil, from October 2022 to December 2023. Five treatments were evaluated: T1 (100% freshwater), T2 (75% freshwater + 25% effluent), T3 (50% freshwater + 50% effluent), T4 (25% freshwater + 75% effluent), and T5 (100% effluent). Samples were analyzed for pH, electrical conductivity (EC), major ions, nutrients, and trace elements, while sodium adsorption ratio, magnesium hazard, residual sodium carbonate, and hardness were also determined. Dilution with freshwater partially improved irrigation suitability but increasing effluent proportion intensified hydrochemical restrictions.

Highlights

- Aquaculture effluent dilution reduced sodicity risk for irrigation reuse.
- Salinity and chloride were the main constraints to reuse suitability.
- Water quality changed markedly across the effluent dilution gradient.
- Multivariate analysis identified the main drivers of reuse potential.
- Reuse feasibility depends on continuous monitoring in semi-arid regions.

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Although effluents supplied relevant amounts of Ca^{2+}, Mg^{2+}, N, and P, reuse potential was mainly limited by salinity, particularly EC and Cl^-, whereas sodicity remained secondary. Multivariate analysis identified EC, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^-, P, SAR, Mn, Zn^{2+}, and N as the main drivers of water quality variation, supporting irrigation reuse under controlled dilution, drainage, and continuous monitoring protocols.

Keywords Water quality · Salinity hazard · Sodicity · Nutrient recovery · Multivariate analysis

1 Introduction

Aquaculture has expanded markedly over the last four decades and is now recognized as an important component of global food systems, particularly for the supply of high-quality animal protein (Das et al., 2023). Beyond its contribution to food security, aquaculture and related production chains have also been associated with the generation of products and inputs of industrial relevance, including pharmaceuticals, cosmetics, and bioenergy-related materials (Siqueira, 2018). In this context, the continued growth of fisheries and aquaculture production worldwide reinforces the strategic importance of the sector for both economic development and resource management (FAO, 2022). China remains one of the leading countries in global aquaculture production (Ahmad et al., 2021), while Brazil has strengthened its position in this sector in recent years, with the Northeast region playing a particularly relevant role and Rio Grande do Norte standing out in regional aquaculture production, especially in shrimp farming and tilapia production (Ayres et al., 2022; Ximenes, 2021).

Despite its socioeconomic importance, aquaculture also poses important environmental challenges, particularly regarding water use and effluent management (Abreu et al., 2023). The characteristics of aquaculture effluents are strongly influenced by the quality of the source water, production system management, cultivated species, and feed composition (Macedo & Sipauba-Tavares, 2010). Under semi-arid conditions, these concerns become even more relevant because the repeated application of low-quality water may promote salt accumulation in the soil and intensify the risk of salinization over time (Fonseca et al., 2021).

At the same time, water scarcity in drylands demands technically sound alternatives capable of expanding water availability without increasing pressure on conventional sources. Within this framework, the agricultural use of aquaculture effluents emerges as a promising strategy for mitigating water scarcity (Bellver-Domingo & Hernández-Sancho, 2022). This perspective is also consistent with circular-economy principles, since waste streams may be reinserted into productive use when properly assessed and managed (Chen et al., 2021). Such an approach is especially relevant in the Brazilian semi-arid region, which comprises 1,427 municipalities distributed across the nine northeastern states and municipalities in northern Minas Gerais and part of Espírito Santo (Brasil, 2021). In Rio Grande do Norte, most municipalities are located within this semi-arid setting (Souza, 2018), where agricultural production frequently depends on adaptive strategies and social technologies designed to improve water-use efficiency (Amaral et al., 2021).

In addition to serving as an alternative water source, aquaculture effluents may also contain nutrients of agronomic interest, particularly nitrogen, phosphorus, and potassium, which can partially contribute to crop nutrition. This aspect is especially relevant in Brazil, where agricultural production depends heavily on mineral fertilizers and where reliance on imported inputs remains high. In this context, nutrient recovery from alternative water sources may help reduce production costs and mitigate part of the environmental burden associated with conventional fertilization

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(Oliveira et al., 2019). However, the agronomic potential of these effluents cannot be assessed independently of their associated risks. Dissolved salts, specific ions, and sodium may impair soil quality, reduce water availability to plants through osmotic effects, and compromise irrigation performance when not properly monitored and managed (Drechsel et al., 2023). Therefore, their agricultural use requires appropriate management strategies to limit salt accumulation within the effective root zone. Practical and effective measures include blending effluents with lower-salinity water, applying an adequate leaching fraction when drainage conditions are favorable, adopting efficient drainage systems, monitoring soil salinity over time, and prioritizing crops with greater salt tolerance where necessary.

For this reason, aquaculture wastewater should be viewed not simply as a discarded by-product, but as a potential alternative water source whose agricultural utilization must be technically validated before recommendation. This possibility is particularly attractive in semi-arid regions, where water scarcity limits agricultural intensification and where reuse practices may reduce pressure on freshwater resources (Franco et al., 2019; Pedrosa et al., 2024). The topic is also highly relevant in developing regions, where wastewater treatment infrastructure is often insufficient and where the safe recovery of water and nutrients remains a major challenge (Omotade et al., 2019). Accordingly, environmental degradation, climate change, and the growing demand for water and food reinforce the need to expand the evidence base for agricultural reuse practices and to better understand the variables that control their environmental and agronomic feasibility (Franco et al., 2019).

This need is supported by a growing body of studies addressing the reuse of fish-farming and aquaculture effluents in field and greenhouse crops, including Jerusalem artichoke (Gengmao et al., 2010), potato, soybean, and onion (Abdelraouf, 2017), wheat (Abdelraouf & Ragab, 2017), forage sorghum (Guimarães et al., 2018), ornamental sunflower (Rêgo, 2018), creole corn (Souza, 2018), basil (Kaab Omeir et al., 2020), lettuce (Ulaş et al., 2022), quince (Andrade et al., 2023), tomato (Allali et al., 2023; Diatta et al., 2023; Guo et al., 2023), rice (Chen et al., 2022; Hao et al., 2024; Xie et al., 2019), pepper (Mechouma & Mezerdi, 2024), cowpea (Diatta et al., 2024; Santos et al., 2025a, 2025b), and spinach (Makwana et al., 2025). For drought-adapted forage species such as forage cacti, efficient water use is particularly important, which makes this production context especially relevant in semi-arid environments (Voltolini et al., 2022). Nevertheless, although these studies support the growing interest in reuse practices, they do not eliminate the need for a careful physicochemical diagnosis of the water source before its agricultural application.

This point is especially important in Brazil, where the absence of a fully consolidated national regulatory framework for agricultural water reuse still constrains broader adoption of this practice (Rocha et al., 2025), although some state regulations already provide guidance for specific reuse contexts (CERH, 2023; COEMA, 2017; CONERH, 2010; CONSEMA, 2020). Under these circumstances, physicochemical assessment becomes a fundamental step for decision-making, particularly in regions where irrigation water quality can directly affect soil functionality and crop performance.

In agricultural reuse systems, waters with different salinity levels must be evaluated cautiously and according to well-established technical criteria that consider water quality, soil properties, and crop tolerance to salts (Voltolini et al., 2022). This assessment is essential because salinity primarily imposes osmotic stress, which reduces water uptake by plants and may limit productivity. Likewise, sodicity expresses the relative effect of sodium in irrigation water and may deteriorate soil physical and chemical quality, especially by reducing infiltration capacity and permeability (Drechsel et al., 2023). Therefore, the feasibility of reuse depends not only on the presence of potentially useful nutrients, but also on the balance between agronomic opportunity and environmental risk.

Although previous studies have demonstrated the agricultural interest of aquaculture effluents, there is still a limited body of evidence integrating the preliminary physicochemical characterization of raw and diluted effluents, the diagnosis of salinity- and sodicity-related constraints, and the identification of the main water-quality drivers under semi-arid conditions, particularly in the Brazilian semi-arid. Thus, the key question addressed in this study is: can raw and diluted aquaculture effluents meet the physicochemical requirements for irrigation reuse in the

Brazilian semi-arid without increasing salinity and sodium-related risks to the production system? We hypothesized that dilution with freshwater would reduce the main restrictions associated with salinity and sodium while preserving part of the nutrient load, thereby improving the potential of aquaculture effluents for irrigation reuse from a physicochemical perspective. Therefore, this study aimed to perform a preliminary physicochemical assessment of raw and diluted aquaculture effluents to evaluate their potential for irrigation reuse in the Brazilian semi-arid, with emphasis on salinity, sodicity, ionic composition, nutrient-related parameters, and trace elements. Finally, the study seeks to contribute to sustainable solutions that align aquaculture production with the Sustainable Development Goals (SDGs), in particular SDG 6 (clean water and sanitation), SDG 12 (responsible consumption and production), and SDG 14 (life below water).

2 Material and Methods

2.1 Description and Characterization of the Experimental Area

The experiment was conducted at the Experimental Water Reuse Unit (UWRU) of the Universidade Federal Rural do Semi-Árido (UFERSA), located in Mossoró, Rio Grande do Norte, northeastern Brazil, at UTM coordinates 686300.71 m E and 9424020.25 m N, SIRGAS 2000 datum, zone 24S (Fig. 1). According to the Brazilian Soil Classification System (SBCS), the soil in the experimental area was classified as a eutrophic Red Yellow Argisol, which corresponds to an Ultisol in the USDA Soil Taxonomy (Santos et al., 2025a, 2025b).

The experiment was conducted using *Nopalea cochenillifera* (L.) Salm-Dyck, popularly known as "palma miúda" (Senar, 2018), irrigated with dilutions

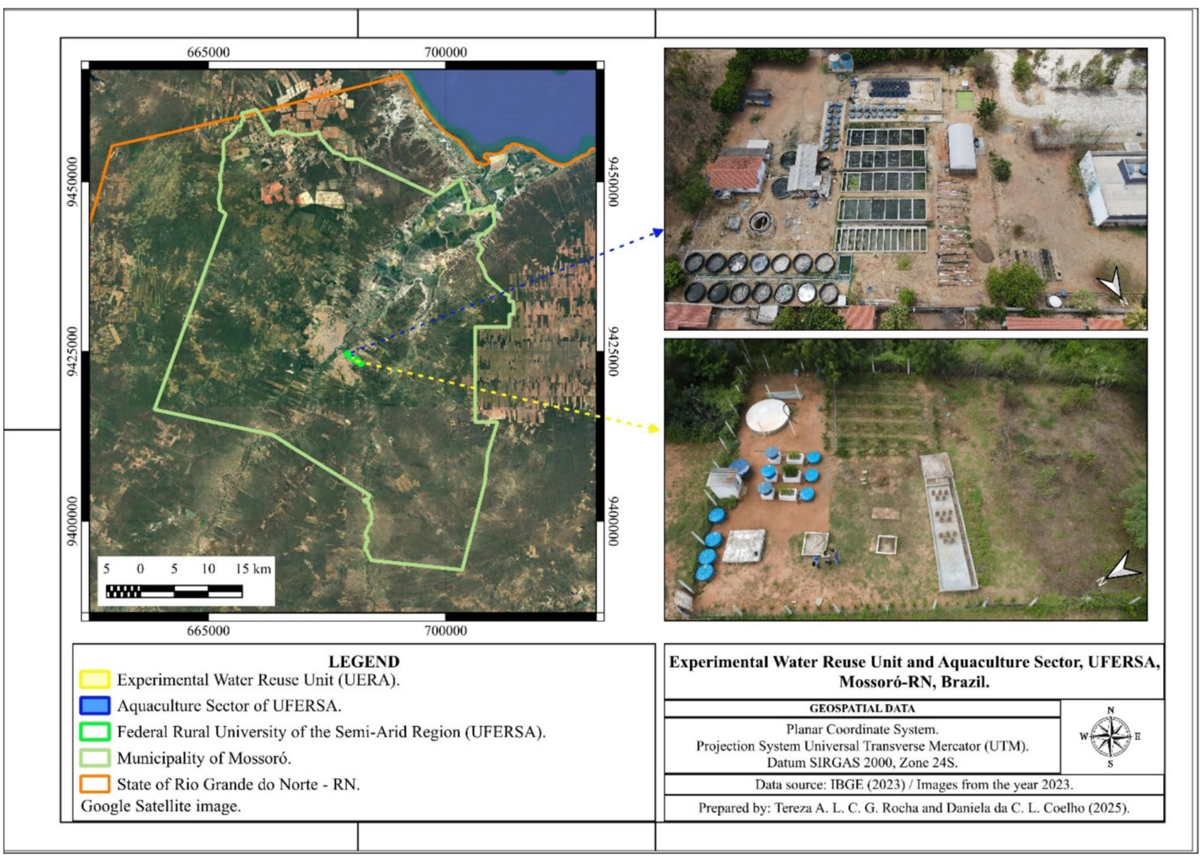


Fig. 1 Location of the Experimental Water Reuse Unit (UWRU), located on the East campus of UFERSA, in the municipality of Mossoró, state of Rio Grande do Norte, Brazil

of aquaculture effluents from October 20, 2021 to December 20, 2023. The first cultivation cycle, which extended until October 25, 2022, resulted in Pedrosa's thesis (2023) and the study published by Pedrosa et al. (2024). The second cultivation cycle, carried out from October 26, 2022 until the end of the experimental period, formed the basis of the present study.

According to the Köppen-Geiger climate classification, the study region has a BSh climate, characterized as hot semi-arid, with highly irregular precipitation, an average annual precipitation of 794 mm, and an average air temperature of 26.5 °C (Dubreuil et al., 2018). Meteorological data were obtained from a Campbell automatic weather station, located approximately 900 m from UWRU, in Mossoró, Rio Grande do Norte, Brazil. The climatic variables monitored throughout the experimental period included average air temperature (Temp, °C), rainfall (Precip, mm), solar radiation (Rad, MJ m^{-2}), and reference evapotranspiration (ETo, mm d^{-1}), as shown in Fig. 2.

2.2 Establishment of an Experimental Area, Origin and Management of Irrigation with Freshwater, Aquaculture Effluents and Dilutions

The experiment was established at the UWRU using freshwater (FW), aquaculture effluent (AE), and three AE dilutions prepared with FW as irrigation sources for the fertigation of "palma miúda". Accordingly, the treatments consisted of: T1 (100% FW), T2 (75% FW + 25% AE), T3 (50% FW + 50% AE), T4 (25% FW + 75% AE), and T5 (100% AE).

Aquaculture effluent was collected from the Aquaculture Sector of UFERSA, located on the East Campus in Mossoró, Rio Grande do Norte, Brazil. After use in the production system, the effluent was conveyed to a concrete tank (maximum storage capacity of 92 m^3; surface area of 35 m^2), where it underwent preliminary and primary treatment, mainly through the removal of settleable and suspended solids. The effluent originated from production ponds with different salinity levels (saline, brackish, and freshwater), used for rearing "pirá" (*Conorhynchos conirostris*), "tambaqui" (*Colossoma macropomum*), "tambatinga" (*Piaractus brachypomus*), "Nile tilapia" (*Oreochromis niloticus*), "Zanzibar tilapia" (*Oreochromis urolepis hornorum*), and shrimp (*Litopenaeus vannamei*). Animals were fed according to species-specific requirements and developmental stage. No medications were used during the experimental period, although lime, caustic soda, and chlorine were applied for tank sanitation. Salinity was adjusted with sodium chloride and, when necessary, with diluted brine from the Mossoró salt flats. Brackish water for aquaculture production was supplied by an on-campus well tapping the Jandaíra aquifer, whose water quality is variable due to rainfall influence and contributions from the Barreiras Formation, which functions as a transfer aquifer (Peixoto et al., 2021). Freshwater used to prepare the effluent dilutions, aiming to mitigate soil

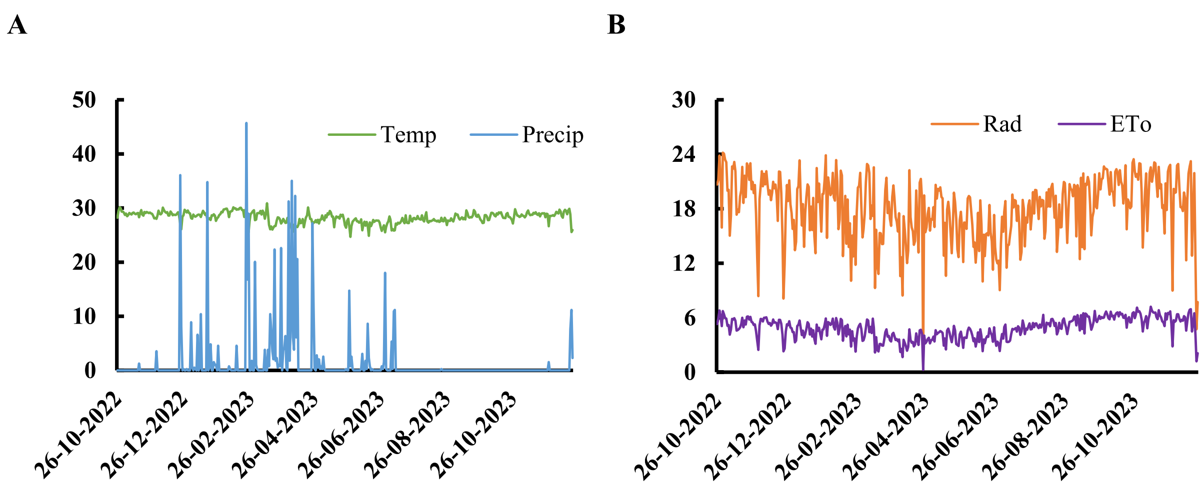


Fig. 2 Monitoring of average temperature (°C) and precipitation (mm) from October 2022 to December 2023 **A**; monitoring of global solar radiation (MJ m^{-2}) and reference evapotranspiration (mm d^{-1}) in the same period **B** in the experiment area

salinization and sodification risks, was supplied by the Rio Grande do Norte Water and Sewage Company (CAERN), using water from deep wells in the Açu Aquifer, the Armando Ribeiro Gonçalves Reservoir, or a combination of both sources.

Irrigation was applied at 7-day intervals, alternating weekly between freshwater and aquaculture effluent dilutions. Irrigation was withheld whenever rainfall in the previous 24 h was ≥ 20 mm. Freshwater application started at planting, using a drip system operated at 60 ± 10 kPa (Fig. 3).

Effluent dilutions were applied manually and locally with a watering can, according to the volume required to meet the calculated irrigation depth. Crop water demand was estimated from on-site reference evapotranspiration (ETo) and a fixed crop coefficient (Kc) of 0.70, as proposed by Lima et al. (2021) for Brazilian semi-arid conditions. The gross irrigation depth was then determined by water balance, considering irrigation and rainfall as inputs and forage cactus evapotranspiration (ETc) as output (Eq. 1).

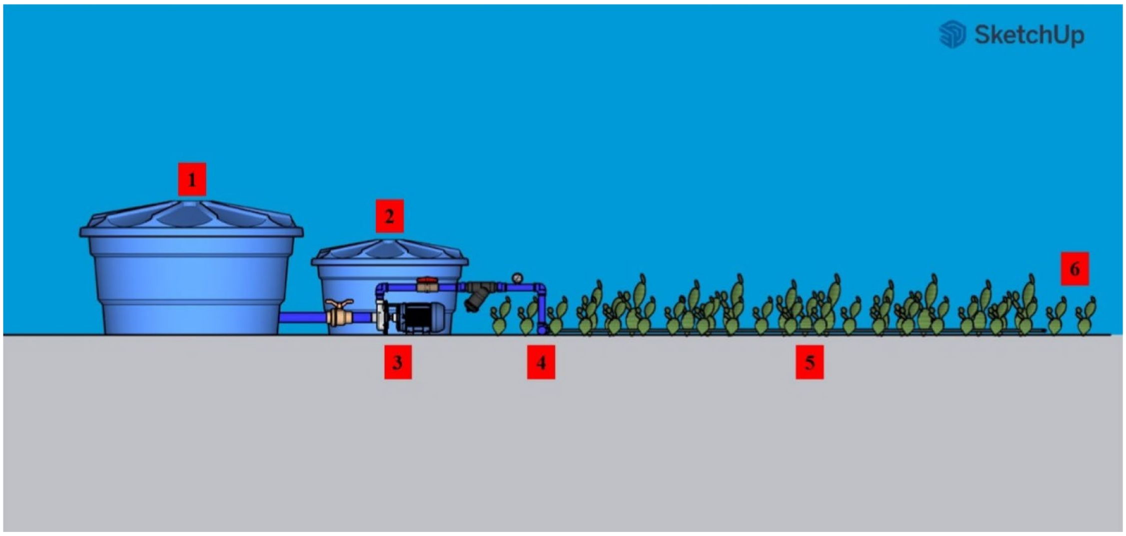
$$ET_c = ET_0.K_c \quad (1)$$

where: ET_c—Crop evapotranspiration, in mm d^{-1}; ET_0—Reference evapotranspiration, in mm d^{-1}; K_c—Crop coefficient, dimensionless.

2.3 Experimental Design, Irrigation Water Sampling, and Physicochemical Analyses

For the physicochemical attributes of the water sources used in irrigation, a 5 × 5 factorial arrangement was considered, corresponding to five dilutions of the aquaculture effluent and five sampling times, with three repetitions. As the same dilutions were monitored throughout the experimental period, the structure was interpreted as repeated measures over time, with the treatment factor fixed and the time factor corresponding to the temporal repetition of the evaluations.

During the second crop cycle, five composite irrigation water samples were collected from each



Note: 1 – Water supply reservoir (1,000 L); 2 – Aquaculture effluent reservoir (300 L); 3 – Control header containing ball valve, 0.5 hp motor pump, pressure gauge graduated from 0 to 400 kPa, and screen filter with 130 µm aperture; 4 – Branch line; 5 – Side lines with non-self-compensating emitters of 1.6 L h^{-1}; and 6 – Border.

Fig. 3 Diagram of the experimental area with irrigation system components.

treatment to characterize physicochemical attributes potentially affecting forage cacti development and soil quality. Sampling was performed whenever the stored effluent changed, specifically on December 16, 2022, June 14, 2023, July 27, 2023, September 22, 2023, and December 8, 2023.

Sampling and analyses followed Standard Methods for the Examination of Water and Wastewater (Lipps et al., 2023) and EMBRAPA (Parron et al., 2011). Samples were collected in 1 L polyethylene bottles and preserved in insulated boxes with ice at approximately 4 °C until physicochemical analysis at the UFERSA Soil, Water, and Plant Analysis Laboratory (LASAP).

The following variables were determined: pH, electrical conductivity (EC), potassium (K^+), sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), total Kjeldahl nitrogen (N), phosphorus (P), iron (Fe), manganese (Mn), zinc (Zn^{2+}), copper (Cu^{2+}), lead (Pb), cadmium (Cd), nickel (Ni), and chromium (Cr), according to Lipps et al. (2023) and Parron et al. (2011).

Based on the concentrations of Na^+, Ca^{2+}, Mg^{2+}, CO_3^{2-}, and HCO_3^-, the following irrigation water quality indices were determined: Sodium Adsorption Ratio (SAR), according to Richards (1954); Residual Sodium Carbonate (RSC), as proposed by Eaton (1950); magnesium hazard (MH), based on El-Amier et al. (2021); and hardness, as described in Eqs. 2, 3, 4, and 5.

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}} \tag{2}$$

$$MH = \frac{Mg^+}{Ca^{2+} + Mg^{2+}} \times 100 \tag{3}$$

$$RSC = \left(CO_3^{2-} + HCO_3^-\right) - \left(Ca^{2+} + Mg^{2+}\right) \tag{4}$$

$$Hardness = \left(Ca^{2+} + Mg^{2+}\right).50 \tag{5}$$

where: SAR – Sodium adsorption ratio; MH—Magnesium hazard, in %; RSC – Residual sodium carbonate, in $mmol_c\ L^{-1}$; and Hardness in $mg\ L^{-1}$.

The water quality attributes were evaluated against regulatory standards related to effluent discharge and agricultural and forestry reuse (Brasil, 2011; CERH, 2023; COEMA, 2017; CONERH, 2010; CONSEMA, 2020), as well as against criteria reported in the literature for irrigation water quality. Based on these references, the waters were classified and interpreted in terms of salinity and sodicity risks according to the criteria established by the United States Salinity Laboratory (USSL), Riverside, as originally proposed by Richards (1954). This assessment was further supported by the FAO guidelines for irrigation water quality evaluation (Drechsel et al., 2023) and by the approach adopted by El-Amier et al. (2021) for irrigation water quality assessment. Subsequently, the most relevant variables were identified and interpreted with respect to their potential implications for irrigation reuse.

2.4 Statistical Analysis

The physicochemical data of the aquaculture effluent dilutions were first subjected to descriptive statistical analysis. Pearson's correlation matrix was used to examine the interrelationships among variables and to verify the suitability of the data set for multivariate analysis, considering 17 variables measured in 25 irrigation water samples in treatments T1 to T5. The reduction in the number of variables was performed after the Pearson correlation matrix revealed strong multicollinearity among some attributes. High correlations were observed for hardness, MH, and RSC (r = 0.99, 0.98, 0.98, 0.98, and −0.98, respectively), indicating substantial redundancy and potential instability in subsequent multivariate analyses. In addition, lead, cadmium, and nickel were excluded due to their near-zero variance, which limited their discriminatory power. Thus, six of the 23 original variables were removed to obtain a more parsimonious, stable, and interpretable dataset for the multivariate analyses. Cluster analysis was subsequently performed using Euclidean distance as the dissimilarity measure and Ward's method as the clustering algorithm. Principal component analysis (PCA) was then applied to identify the main sources of variation in the data set, and, for interpretative purposes, only variables with factor loadings ≥ 0.70 were retained (Hair Júnior et al., 2009). The number of principal components retained was defined according to Kaiser's criterion, adopting eigenvalues > 1 and cumulative explained variance ≥ 70% (Kaiser, 1958; Rencher & Christensen, 2012). Factor analysis was then performed with normalized Varimax rotation, and factor loadings ≥ 0.70 were considered significant. All analyses were conducted using Statistica® 14 software (StatSoft, 2020).

3 Results and Discussion

3.1 Analysis of Aquaculture Effluent Dilutions Considering Brazilian Legislation

The physicochemical composition of the aquaculture effluent stored in covered 310 L tanks should be regarded as dynamic rather than constant. Even under covered storage, partial water loss by evaporation may concentrate dissolved salts and increase electrical conductivity (EC), particularly for relatively conservative ions such as Na^+, K^+, and Cl^-. At the same time, storage may favor biogeochemical transformations associated with organic matter decomposition and microbial activity, which can modify pH, the HCO_3^-/CO_3^{2-} equilibrium, and the solubility of Ca^{2+} and Mg^{2+}. In addition, N and P may be affected by mineralization, volatilization, precipitation, and crystallization processes, whereas Fe, Mn, Zn, Cu, Pb, Cd, Ni, and Cr may vary according to pH, redox conditions, suspended solids, and interactions with organic ligands (Qiu et al., 2024). Therefore, storage may alter both the absolute magnitude of the measured attributes and the relative contribution of more labile and more recalcitrant fractions, reinforcing the need for periodic monitoring when aquaculture effluents are stored before irrigation reuse (Mascolo et al., 2010; Wilson et al., 2001).

The progressive replacement of freshwater by aquaculture effluent from T1 to T5 produced clear changes in irrigation water composition, indicating that the effluent fraction was the main driver of nutrient enrichment and ionic loading. This pattern highlights the dual role of aquaculture effluent in irrigation systems. On the one hand, it may supply nutrients of agronomic interest; on the other, it may intensify salinity-related constraints, depending on the dilution level.

Table 1 places these results in the context of Brazilian regulations for effluent discharge and agricultural and forestry reuse. At the same time, the comparison reveals important regulatory gaps, since several parameters directly relevant to irrigation management, including RSC, K^+, Ca^{2+}, Mg^{2+}, CO_3^{2-}, HCO_3^-, N, and P, are not explicitly addressed in the Brazilian legal instruments considered here. Freshwater used in T1 is consistent with the classification of fresh water under CONAMA Resolution No. 357/2005, which provides a useful baseline for interpreting the progressive changes observed as the proportion of aquaculture effluent increased (Brasil, 2005).

Mean pH remained within the ranges established for treated effluent discharge and for reuse in the selected state regulations. In addition, the values were within the range usually recommended for irrigation water (Drechsel et al., 2023). Although all treatments remained within these limits, pH values were consistently in the neutral to slightly alkaline range, which is common in wastewater and may influence nutrient availability, particularly that of phosphorus and some micronutrients. In the present case, pH did not represent an immediate legal restriction, but it should still be considered in irrigation management because it interacts with precipitation reactions and emitter performance.

EC was one of the clearest indicators of the effect of increasing effluent proportion. Mean EC rose from 0.48 dS m^{-1} in T1 to 4.74 dS m^{-1} in T5, showing a marked increase in salinity with increasing effluent content. Based on the reuse criteria considered, T1, T2, and T3 remained within the most restrictive EC limits, whereas T4 was borderline and T5 exceeded the threshold values. From an agronomic perspective, this result indicates that salinity, rather than sodicity, is the main factor limiting irrigation reuse in the more concentrated treatments. The gradual increase in EC also agrees with the progressive enrichment in dissolved ions observed in the chemical analyses. Thus, forage cactus has a salinity threshold of 3.6 dS m^{-1} for maintaining 90% of its potential yield (Gheyi et al., 2016). In the present study, the mean EC value observed in T5 exceeded this threshold.

In contrast, SAR remained below the regulatory thresholds adopted by the states of Ceará and Paraná for all treatments. This indicates that the waters did not present a marked sodium hazard when evaluated exclusively by SAR. However, the combined interpretation of SAR and EC is more informative than either parameter alone (Richards, 1954). In this study, the relatively low SAR values should not be interpreted

Table 1 Guiding standards and values regarding effluent discharge (1 and 3), and agricultural and forestry reuse (2, 3, 4, and 5), comparing aquaculture effluent (AE) dilutions in freshwater (FW)

Parameters	(1) CONAMA No. 430/11	(2) CERH No. 122/23	(3) COEMA No. 2/17	(4) CONERH No. 75/10	(5) CONSEMA No. 419/20	Observed values (mean ± standard deviation)				
						T1	T2	T3	T4	T5
pH	5 a 9.0	5 a 9.0	6 a 8.5	-	6 a 9.0	8.24 ± 0.52	7.66 ± 0.31	7.68 ± 0.29	7.59 ± 0.16	7.40 ± 0.23
EC (dSm^{-1})	-	≤3.20	≤3.00	0.20 a 3.00[1]	0.20 a 2.90[1]	0.48 ± 0.04	1.55 ± 0.18	2.65 ± 0.42	3.08 ± 0.94	4.74 ± 0.39
SAR	-	15.00	15.00	0 a 40.00[1]	0 a 12.00[1]	4.43 ± 1.31	2.94 ± 0.86	1.34 ± 1.21	1.33 ± 1.07	1.33 ± 1.05
MH (%)	-	-	-	-	-	33.76 ± 11.90	37.36 ± 6.5	42.67 ± 2.6	46.86 ± 7.1	40.41 ± 10.41
RSC (mmol$_c$ L^{-1})	-	-	-	-	-	1.94 ± 0.35	−4.89 ± 2.76	−11.90 ± 4.58	−18.51 ± 6.08	−26.78 ± 10.79
K^+ (mg L^{-1})	-	-	-	-	-	6.70 ± 5.40	10.08 ± 7.35	15.61 ± 10.93	20.80 ± 14.29	28.69 ± 17.48
Na^+ (mg L^{-1})	-	920.00	-	70.00	-	77.14 ± 22.20	134.31 ± 37.32	76.14 ± 54.06	90.34 ± 55.54	106.42 ± 62.06
Ca^{2+} (mg L^{-1})	-	-	-	-	-	12.75 ± 2.40	84.88 ± 26.97	142.45 ± 31.33	197.65 ± 41.69	294.27 ± 88.21
Mg^{2+} (mg L^{-1})	-	-	-	-	-	6.83 ± 3.92	51.06 ± 22.46	103.38 ± 36.85	145.70 ± 52.11	215.54 ± 105.18
Cl^- (mg L^{-1})	-	30.00	-	100 a 350.00	106.50	99.97 ± 31.75	475.03 ± 222.15	627.94 ± 263.07	787.94 ± 319.11	1081.93 ± 451.60
CO_3^{2-} (mg L^{-1})	-	-	-	-	-	7.60 ± 4.54	12.04 ± 3.53	11.84 ± 3.98	12.70 ± 3.78	12.70 ± 4.38
HCO_3^- (mg L^{-1})	-	-	-	-	-	176.66 ± 15.05	195.57 ± 46.71	209.80 ± 86.25	280.56 ± 36.81	333.47 ± 60.33
N (mg L^{-1})	-	-	-	-	-	7.48 ± 2.39	8.52 ± 3.21	10.00 ± 4.23	10.01 ± 4.34	10.16 ± 4.08
P (mg L^{-1})	-	-	-	-	-	0.00 ± 0.00	3.60 ± 3.02	7.85 ± 2.97	11.75 ± 4.28	17.69 ± 7.44
Hardness (mg L^{-1})	-	-	-	-	-	60.33 ± 15.79	424.93 ± 146.78	786.90 ± 227.58	1101.20 ± 312.24	1633.73 ± 560.88
Fe (mg L^{-1})	15.00	5.00	15.00	5.00	5.00	0.014 ± 0.030	0.126 ± 0.061	0.083 ± 0.089	0.117 ± 0.136	0.288 ± 0.274
Mn (mg L^{-1})	1.00	0.50	1.00	0.20	0.20	0.000 ± 0.000	0.017 ± 0.027	0.010 ± 0.012	0.009 ± 0.008	0.019 ± 0.014
Zn^{2+} (mg L^{-1})	5.00	5.00	5.00	2.00	2.00	0.005 ± 0.005	0.031 ± 0.019	0.030 ± 0.022	0.030 ± 0.015	0.043 ± 0.023
Cu^{2+} (mg L^{-1})	1.00	0.013	1.00	0.20	0.20	0.000 ± 0.000	0.003 ± 0.003	0.004 ± 0.004	0.005 ± 0.003	0.008 ± 0.005
Pb (mg L^{-1})	0.50	0.033	0.50	5.00	0.50	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.004 ± 0.009	0.028 ± 0.038
Cd (mg L^{-1})	0.20	0.01	0.20	0.01	0.01	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.001
Ni (mg L^{-1})	2.00	0.025	2.00	0.20	0.20	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Cr (mg L^{-1})	0.10	0.10	0.10	0.10	0.10	0.001 ± 0.002	0.002 ± 0.002	0.003 ± 0.004	0.003 ± 0.004	0.010 ± 0.006

T1—100% FW; T2—75% FW + 25% AE; T3—50% FW + 50% AE; T4—25% FW + 75% AE; and T5—100% AE; pH—Hydrogen ion potential; EC—Electrical conductivity; SAR—Sodium adsorption ratio; MH—Magnesium hazard; RSC—Residual sodium carbonate; K^+—Potassium; Na^+—Sodium; Ca^{2+}—Calcium; Mg^{2+}—Magnesium; Cl^-—Chloride; CO_3^{2-}—Carbonate; HCO_3^-—Bicarbonate; N—Total Kjeldahl nitrogen; P—Phosphorus; Fe—Iron; Mn—Manganese; Zn^{2+}—Zinc; Cu^{2+}—Copper; Pb—Lead; Cd—Cadmium; Ni—Nickel; and Cr—Chromium as evidence of unrestricted reuse, because the progressive rise in EC still imposes significant salinity management requirements, especially under semi-arid conditions.

Mean magnesium hazard (MH) remained below the critical threshold of 50% in all treatments when average values were considered, although T4 was the closest to this limit. This pattern suggests increasing relative participation of Mg^{2+} in the divalent cation balance as the effluent proportion increased, but without a generalized exceedance of the critical threshold (El-Amier et al., 2021). Likewise, RSC values indicated that, except for T1, the treatments were generally acceptable from the standpoint of carbonate-related sodicity hazard (Almeida, 2010; Pedrosa et al., 2024). Therefore, the overall interpretation of MH and RSC supports the view that sodicity was not the main restriction in the evaluated waters.

Potassium, calcium, magnesium, nitrogen, and phosphorus increased consistently with the proportion of aquaculture effluent, evidencing the fertilizing potential of this water source. This nutrient enrichment may partially contribute to crop nutrition and reduce the dependence on mineral fertilizers. However, the agronomic benefit cannot be interpreted independently of the associated risks. Potassium concentrations were above the ranges usually recommended for irrigation water, and Mg^{2+} exceeded the guideline values in the more concentrated treatments (Drechsel et al., 2023). Phosphorus also rose markedly from T2 onward, indicating relevant nutrient input but also suggesting greater potential for precipitation and clogging problems in localized irrigation systems (Almeida, 2010).

Sodium concentrations ranged from 76.14 to 134.31 mg L^{-1}, and despite these moderate values, all waters remained in the S1 class, indicating low immediate sodicity risk. Nevertheless, under long-term irrigation, Na^{+} may still adversely affect soil physical quality by reducing infiltration and permeability, particularly in fine-textured or poorly drained soils under semi-arid conditions. In contrast, chloride showed a much more pronounced increase from T1 to T5 and emerged as one of the main constraints to agricultural reuse. Mean Cl^{-} concentration increased from 99.97 mg L^{-1} in T1 to 1081.93 mg L^{-1} in T5, exceeding several of the legal and guideline values considered, especially in the more concentrated dilutions. This finding is agronomically relevant because chloride may contribute not only to overall salinity stress, but also to specific ion toxicity, depending on crop sensitivity, irrigation method, and long-term salt accumulation in the root zone. However, there is a consensus that chloride values above 700 mg L^{-1} can cause damage, even to the most tolerant species, such as beets, cotton, and wheat (Amaral et al., 2021). In addition, high chloride levels in water are a strong indicator of pollution from human and/or warm-blooded animal excreta (Pires et al., 2007). This pattern is consistent with the saline nature of aquaculture effluents, in which sodium chloride is commonly used during processing and cleaning operations to facilitate the removal of sludge, blood, and other residues, as well as to improve cleaning efficiency and water removal (Venugopal & Sasidharan, 2021).

Carbonate and bicarbonate concentrations were also relevant in the interpretation of reuse potential. Although bicarbonate remained below the upper guideline values generally considered acceptable for irrigation, carbonate concentrations were above the usual range reported in the literature. From a practical standpoint, this deserves attention because elevated CO_3^{2-} and HCO_3^{-} may favor precipitation reactions and increase the risk of clogging in localized irrigation systems, particularly when combined with high Ca^{2+} and Mg^{2+} concentrations (Burt et al., 1998).

The total hardness of water represents the presence of alkaline earth metal salts and heavy metal salts, which can cause inconvenience to consumers or organisms that depend on water for their survival (Pires et al., 2007). Very hard water is not recommended for heavy and compact soils; however, when it comes to recovering soils with excessive sodium content, the use of hard water is highly advisable (Almeida, 2010).

Regarding trace elements, Fe, Mn, Zn, Cu, Pb, Cd, Ni, and Cr generally remained below the regulatory limits considered for effluent discharge and agricultural reuse. Therefore, under the conditions evaluated here, these elements did not constitute the main immediate restriction to irrigation reuse. Even so, Pb should continue to be monitored because the mean value observed in T5 approached the most restrictive threshold adopted in Paraná, and potentially toxic elements introduced through wastewater irrigation may accumulate in soil over time depending on changes in salinity and geochemical conditions.

3.2 Analysis of Aquaculture Effluent Dilutions for Salinity and Sodicity

The agricultural use of brackish or saline water, often referred to as biosaline agriculture, is an important strategy in arid and semi-arid regions. Nevertheless, its successful adoption depends on the interaction among water quality, soil properties, crop salt tolerance, irrigation method, and drainage conditions. In this context, irrigation water quality was interpreted here based on two complementary dimensions: salinity and sodicity (Santos et al., 2020; Voltolini et al., 2022).

From an agronomic perspective, salinity mainly exerts an osmotic effect, reducing the energy available for plant water uptake and potentially limiting crop development. Sodicity, in turn, expresses the relative effect of sodium on soil exchange sites and is associated with deterioration of soil physical quality, especially reduced infiltration and permeability. Therefore, EC is a useful indicator of salinity hazard, whereas SAR is a classical indicator of sodicity hazard (Murtaza et al., 2021).

According to the US Salinity Laboratory classification proposed by Richards (1954), T1 was consistently classified as C2S1, indicating medium salinity hazard and low sodicity hazard. T2 was classified as C3S1, indicating high salinity hazard but still low sodicity hazard. In contrast, T3, T4, and T5 were predominantly classified as C4S1, indicating very high salinity hazard associated with low sodicity hazard. This pattern demonstrates that increasing the effluent fraction intensified salinity restrictions much more clearly than sodicity restrictions (Table 2).

These results are particularly relevant because they show that the more concentrated effluent treatments cannot be interpreted as broadly suitable for irrigation simply because SAR remained low. In practice, low sodicity risk does not offset very high salinity hazard. Waters classified as C4S1 require highly specific conditions for use, including well-drained or highly permeable soils, careful salinity management, and crops with relatively high salt tolerance (Richards, 1954). Thus, the dominant restriction associated with aquaculture effluent dilution in the present study was soil salinization risk rather than sodium-induced sodification.

Under this approach, T1 showed no salinity risk but increasing sodicity concerns, whereas T2 and T3 were generally classified as having moderate salinity risk and no sodicity problems. T4 and T5, in turn, were classified as having severe salinity risk and no sodicity problems. Although the terminology differs from the USSL system, both approaches converge in identifying salinity as the main limitation to reuse.

This distinction is agronomically important under semi-arid conditions, where root-zone salinity is strongly controlled by irrigation water quality, evapotranspiration demand, and the amount of water percolating below the root zone. Under such conditions, the safe use of water with higher EC depends on adequate drainage and on an appropriate leaching fraction capable of preventing excessive salt accumulation in the soil profile (Drechsel et al., 2023). However, in water-scarce environments, leaching must be carefully planned, since the long-term use of saline water without efficient salt removal may intensify soil degradation.

The RSC results complement this interpretation. Except for T1, the treatments were generally classified as suitable. This indicates that carbonate and bicarbonate related sodicity hazard was not the principal issue in the evaluated waters (Murtaza et al., 2021). Likewise, most MH values remained below the critical threshold of 50%, although isolated exceedances were observed in T1 on December 16, 2022 and in T5 on July 27, 2023 (El-Amier et al., 2021). These isolated events do not change the overall interpretation, but they do reinforce the need for temporal monitoring because water quality varied across sampling dates.

Another relevant point is that the higher Mg^{2+} and K^{+} concentrations observed in T3, T4, and especially T5 may also contribute to soil structural degradation when present at elevated levels (Smith et al., 2015). Their deleterious effects are generally smaller than those of Na^{+}, but they are not negligible, especially in soils already susceptible to physical degradation or under conditions of limited leaching. Therefore, salinity hazard in the present study should be interpreted in a broader sense, involving not only total dissolved salts but also the combined effect of cation composition on long-term soil functionality.

Taken together, the salinity and sodicity analyses indicate that aquaculture effluent dilutions have reuse potential, but this potential is conditional rather than unrestricted. Freshwater (T1) showed the lowest overall limitation. T2 may be considered the most

Table 2 Integrated classification of the salinity and sodicity risks associated with irrigation water under different sampling dates and dilution treatments, based on EC, SAR, MH, and RSC, according to the criteria of Richards (1954), Drechsel et al. (2023), El-Amier et al. (2021), and Eaton (1950)

Collections	Treatments	EC ds m^{-1}	SAR	MH %	RSC $mmol_c\ L^{-1}$	Richards (1954)	Drechsel et al. (2023)	El-Amier et al. (2021)	Eaton (1950)
December 16, 2022	T1	0.51	4.40	50.66	1.60	C2-S1	N-PC	UN	PR
	T2	1.66	3.70	40.86	−5.55	C3-S1	M-SP	SU	R
	T3	2.75	0.79	42.53	−14.81	C4-S1	M-SP	SU	R
	T4	3.29	0.86	44.68	−16.42	C4-S1	S-SP	SU	R
	T5	4.89	1.02	46.51	−28.01	C4-S1	S-SP	SU	R
June 14, 2023	T1	0.45	5.36	40.77	2.17	C2-S1	N-PC	SU	PR
	T2	1.44	3.50	25.32	−4.27	C3-S1	M-SP	SU	R
	T3	2.52	0.32	44.07	−12.90	C4-S1	M-SP	SU	R
	T4	3.79	0.35	43.12	−20.70	C4-S1	S-SP	SU	R
	T5	5.16	0.05	48.47	−34.63	C4-S1	S-SP	SU	R
July 27, 2023	T1	0.54	5.83	36.53	1.55	C2-S1	N-PC	SU	PR
	T2	1.80	3.17	36.25	−4.54	C3-S1	M-SP	SU	R
	T3	2.33	0.58	46.75	−14.73	C4-S1	M-SP	SU	R
	T4	1.67	0.70	47.89	−22.47	C3-S1	M-SP	SU	R
	T5	4.33	0.50	51.43	−35.35	C4-S1	S-SP	UN	R
September 22, 2023	T1	0.43	2.45	22.60	2.33	C2-S1	N-PC	SU	PR
	T2	1.37	1.53	43.52	−8.88	C3-S1	M-SP	SU	R
	T3	2.33	1.70	39.69	−13.23	C4-S1	M-SP	SU	R
	T4	2.67	1.70	38.78	−18.51	C4-S1	M-SP	SU	R
	T5	4.33	1.80	26.93	−27.27	C4-S1	S-SP	SU	R
December 8, 2023	T1	0.46	4.12	18.23	2.07	C2-S1	N-PC	SU	PR
	T2	1.50	2.79	40.87	−1.22	C3-S1	M-SP	SU	R
	T3	3.33	3.30	31.34	−3.85	C4-S1	S-SP	SU	R
	T4	4.00	3.02	31.98	−6.91	C4-S1	S-SP	SU	R
	T5	5.00	2.94	28.74	−8.65	C4-S1	S-SP	SU	R

Source: Adapted from Richards (1954), Drechsel et al. (2023), El-Amier et al. (2021), and Eaton (1950)

T1—100% FW; T2—75% FW + 25% AE; T3—50% FW + 50% AE; T4—25% FW + 75% AE; and T5—100% AE; EC—Electrical conductivity; MH—Magnesium hazard; SAR—Sodium adsorption ratio; RSC—Residual sodium carbonate; C1—Low salinity risk; C2—Medium salinity risk; C3—High salinity risk; C4—Very high salinity risk; S1—Low sodium concentration; S2—Medium sodium concentration; S3—High sodium content; S4—Very high sodium content; N – No salinity risk; M – Moderate salinity risk; S – Severe salinity risk; SP – No sodicity problems; PC – Increasing sodicity problems; SU – Suitable; UN – Unsuitable; R – Recommended; PR – Not highly recommended; NR – Not recommended

promising dilution from the standpoint of balancing nutrient contribution and manageable salinity. T3 represented an intermediate condition but already with marked salinity restriction. T4 and T5 showed the highest limitations, mainly because of their salinity and chloride load. Therefore, the feasibility of using these waters for irrigation depends on crop salt tolerance, soil drainage, irrigation method, and long-term salinity management rather than on water chemistry alone.

3.3 Multivariate Analysis of Aquaculture Effluent Dilutions

3.3.1 Correlation Matrix

After descriptive statistics, Pearson's correlation matrix was constructed (Fig. 4), from which the variables hardness, MH, and RSC were removed due to multicollinearity, defined as the presence of a high degree of correlation among independent variables

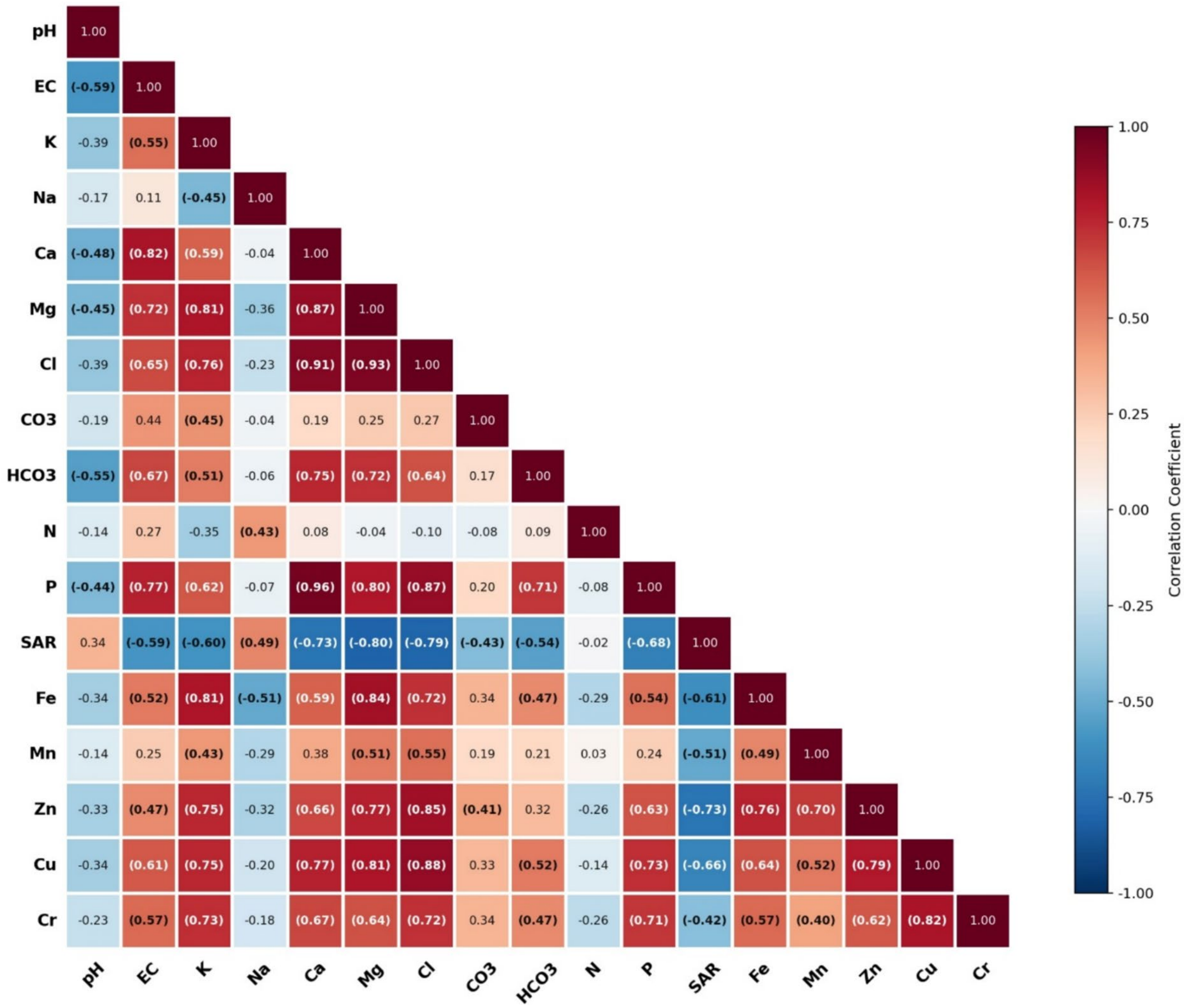


Fig. 4 Pearson correlation heatmap of the physicochemical attributes of aquaculture effluent dilutions. Colors indicate the direction and magnitude of the correlations

(Freund et al., 2006), as they presented correlations above 0.98 in absolute value. The variables lead, cadmium, and nickel were also removed because their values were mostly zero or very close to zero.

In the correlation matrix for the physicochemical attributes of the irrigation water dilutions used for irrigation, strong positive correlations were observed between Ca^{2+} and the variables P, Cl^-, Mg^{2+}, Cu^{2+}, and HCO_3^-, as well as a significant negative correlation with SAR. Mg^{2+} similarly showed strong positive correlations with Cl^-, Fe, Cu^{2+}, P, Zn^{2+}, and HCO_3^-, and a negative correlation with SAR.

The EC variable showed significant positive correlations with Ca^{2+}, P, and Mg^{2+}. K^+ correlated positively with Mg^{2+}, Fe, Cl^-, Cu^{2+}, Zn^{2+}, and Cr. Cl^- presented positive correlations with P, Cu^{2+}, Zn^{2+}, Fe, and Cr, and a negative correlation with SAR. HCO_3^- showed a significant positive correlation with P. P also correlated positively with Cu^{2+} and Cr. All significant correlations involving SAR were negative, including one with Zn^{2+}.

Among micronutrients and metals, positive correlations were identified between Fe and Zn^{2+}, between Mn and Zn^{2+}, between Zn^{2+} and Cu^{2+}, and between Cu^{2+} and Cr (all significant at $p < 0.05$; Fig. 4).

These correlations indicate that as SAR increases, all other variables tend to decrease, except for pH and N, which showed no significant correlation with SAR.

The biogeochemical behavior of the excluded variables (Cd, Pb, and Ni), as well as Cu^{2+} and Zn^{2+}, is known to be analogous (Maas, 1990).

As phosphorus content increases, calcium, chloride, magnesium, and bicarbonate also increase, which is consistent with the predominant ions found in irrigation water: Ca^{2+}, Mg^{2+}, Na^{+}, HCO_3^{-}, and Cl^{-} (Cordeiro, 2001).

3.3.2 Clustering

Cluster analysis identified three main groups at 20% similarity (Fig. 5): Group I should be interpreted as a baseline to transitional cluster. It included all T1 samples throughout the monitoring period, as well as the last collection of T2, T3, T4, and T5. The permanent presence of T1 in this group is consistent with its lower ionic loading, as indicated in Table 1 by the lowest mean EC (0.48 dS m^{-1}), lower Ca^{2+}, Mg^{2+}, Cl^{-}, HCO_3^{-}, and P concentrations, and by its classification as C2S1 in Table 2. The inclusion of the December 2023 samples of T2 to T5 in this same group should not be interpreted as agronomic equivalence to T1, but rather as a temporary convergence in multivariate analysis, since clustering reflects joint similarity among all 17 variables. In this group, SAR, Zn, Cu, and Cl^{-} had greater influence on sample association, suggesting a hydrochemical condition less dominated by the Ca^{2+}, Mg^{2+}, Cl^{-}, HCO_3^{-}, and P enrichment that characterized the most concentrated effluent samples (Anyango et al., 2024). From a practical viewpoint, Group I represents the portion of the dataset with the lowest or most transitional effluent imprint, in which salinity was less structurally dominant in the clustering pattern, although some samples may still require attention regarding infiltration-related constraints when SAR becomes relatively more expressive under low-salinity conditions.

Group II represents an intermediate dilution cluster, comprising T2, T3, and T4 in the first four sampling dates. This group is agronomically important because it reflects waters with a mixed nutrient–salinity condition. The role of phosphorus in group formation agrees with Table 1, where P increased markedly from T2 to T4 (3.60 to 11.75 mg L^{-1}), accompanied by substantial increases in EC, Ca^{2+}, Mg^{2+}, Cl^{-}, and HCO_3^{-}. Therefore, Group II corresponds to samples in which the addition of effluent was already sufficient to modify water chemistry consistently, but not enough to generate the extreme hydrochemical condition observed in Group III (Pivić et al., 2022). Table 2 reinforces this interpretation, since T2 was

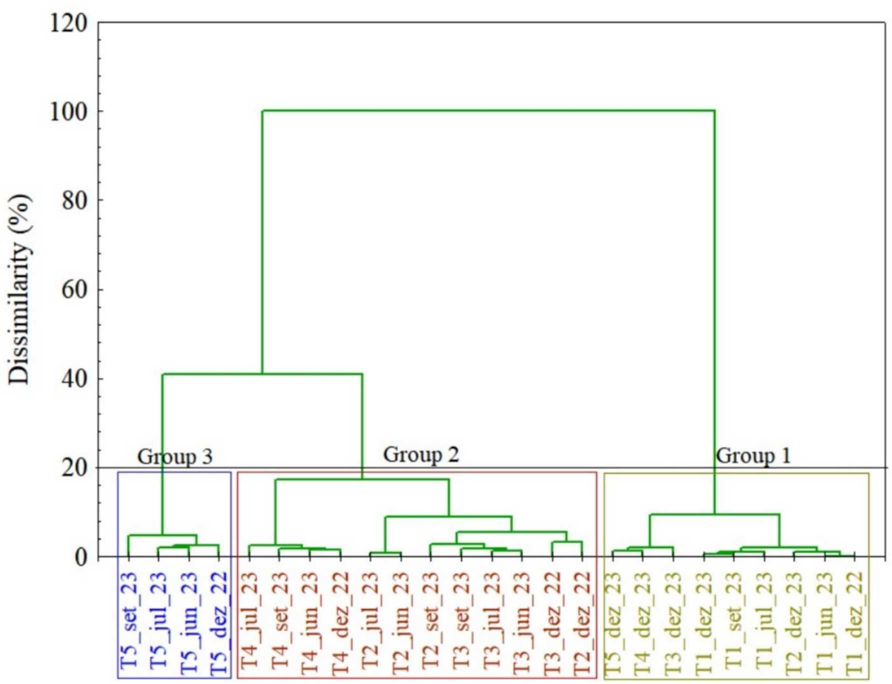


Fig. 5 Cluster analysis for the groups of physicochemical attributes of the dilutions of the treatments used for irrigation

predominantly classified as C3S1, whereas T3 and T4 were generally classified as C4S1 or as waters with moderate to severe salinity risk and no sodicity problems. Thus, the main agronomic meaning of Group II is not severe sodification, but rather progressive salinization risk associated with intermediate to high nutrient loading. This is the group that most clearly expresses the trade-off between fertigation potential and irrigation restriction: nutrient enrichment may be beneficial, but the simultaneous increase in EC and Cl^- indicates a growing need for drainage, leaching management, and salt-tolerant crops.

Group III can be defined as the saline end-member cluster, since it comprised T5 in the first four collections and was mainly influenced by Ca^{2+}, Cl^-, HCO_3-, and Cr. This grouping is fully consistent with Table 1, in which T5 showed the highest mean values of EC (4.74 dS m^{-1}), Cl^- (1081.93 mg L^{-1}), Ca^{2+} (294.27 mg L^{-1}), Mg^{2+} (215.54 mg L^{-1}), HCO_3^- (333.47 mg L^{-1}), and P (17.69 mg L^{-1}). Table 2 confirms the agronomic implication of this cluster, since T5 was predominantly classified as C4S1 and, under the Drechsel et al. (2023) approach, as presenting severe salinity risk and no sodicity problems; additionally, one sampling event was classified as unsuitable according to MH. Therefore, Group III represents the clearest expression of the undiluted effluent condition and the highest potential for soil salinization, together with greater chloride related restriction and possible long-term impacts on soil physical quality. Importantly, the separation of this group indicates that the major source of dissimilarity in the dataset was the increase in total salt concentration and divalent cations, not an increase in classic sodicity hazard, since SAR remained low and all treatments stayed within S1. This interpretation is consistent with previous multivariate irrigation-water studies showing that highly mineralized samples are often isolated into distinct clusters because EC and major ions dominate the dissimilarity structure, whereas sodicity may remain secondary when Ca^{2+} and Mg^{2+} increase simultaneously (Abdel-Fattah et al., 2020; Bradai et al., 2022).

3.3.3 Factor Analysis

According to Table 3, the eigenvalues together explained over 70% of the accumulated variance, more specifically, they explained 74.82% of the total variation in the input data. According to Vicini (2005), the principal components should be selected in order to ensure an accumulated variance close to 70%. Thus, the three principal components efficiently summarize the total variance of the sample.

Table 3 Eigenvalues and cumulative variance obtained in the principal component analysis (PCA) for physicochemical attributes of the dilutions of the treatments used for irrigation

Variables	Factor Loadings		
	Factor 1	Factor 2	Factor 3
pH	−0.66	−0.05	0.20
EC	0.86	0.25	−0.19
K^+	0.55	0.54	0.49
Na^+	0.21	−0.57	−0.54
Ca^{2+}	0.88	0.37	0.00
Mg^{2+}	0.72	0.61	0.16
Cl^-	0.72	0.59	0.18
CO_3^{2-}	0.24	0.35	0.06
HCO_3^-	0.81	0.14	−0.01
N	0.10	0.01	−0.93
P	0.89	0.24	0.17
SAR	−0.48	−0.73	−0.02
Fe	0.44	0.64	0.40
Mn	0.06	0.86	−0.10
Zn^{2+}	0.42	0.77	0.25
Cu^{2+}	0.65	0.55	0.25
Cr	0.63	0.33	0.43
Eigenvalues	9.40	2.22	1.10
Total Variance (%)	55.30	13.04	6.47
Cumulative Variance (%)	55.30	68.35	74.82

Factor axes rotated using the normalized Varimax method; factor loadings ≥ 0.70 were considered significant for interpretation purposes

Water used in agricultural irrigation has traditionally been considered only as an essential factor in crop water supply. However, studies show that its chemical composition has a direct influence on plant nutrition and soil chemical properties, expanding its role in the production system (Drechsel et al., 2023). In this context, water is now understood as an agricultural input, especially when associated with the application of nutrient-rich effluents, characterizing fertigation.

Factor 1 has an eigenvalue of 9.40 and explained 55.30% of the data variability. The variables that contributed most to the formation were: EC (0.86), Ca^{2+} (0.88), Mg^{2+} (0.72), Cl^- (0.72), HCO_3^- (0.81) and P (0.89). It is observed that part of the variability of the samples is related to chloride, calcium, and magnesium ions, which are variables associated with constituents naturally transferred from soil and rocks through solubilization and leaching processes (Chandio et al., 2015). The presence of phosphorus in water has an impact on the quality and availability of water resources in terms of eutrophication (Quevedo & Paganini, 2018).

Factor 2 had an eigenvalue of 2.22 and was explained by the variables SAR (−0.73), Mn (0.86), and Zn^{2+} (0.77), representing 13.04% of the total variation. Before applying water to the soil, it is important to assess the compatibility of the crop, SAR, and trace metal absorption, among other vegetative and percolation factors (Maas, 1990). Manganese belongs to a group of trace elements that plants cannot adequately restrict in terms of translocation and entry into the food chain, which can lead to damage to various organisms throughout this trophic chain (Silva et al., 2006). The presence of zinc in water is often associated with pollution or contamination problems due to its bioaccumulation and biomagnification properties in ecosystems (Kwon et al., 2017).

Factor 3 showed an eigenvalue of 1.10, explaining 6.47% of the total variance, formed by only the variable N (−0.93) associated load. The amount of nitrogen from aquaculture effluent is directly related to feed management and the percentage of nitrogen contained in the feed (Queiroz & Boeira, 2007).

3.3.4 Principal Component Analysis

Figure 6 indicates that Component 1 can be interpreted as a salinity–ionic enrichment gradient primarily associated with the increasing proportion of aquaculture effluent in the irrigation water.

This interpretation is supported by the positive contribution of EC, Ca^{2+}, Mg^{2+}, Cl^{-}, HCO_3^{-}, and P, which increased markedly from T1 to T5 in Table 1 and were also among the most relevant variables in Table 3. Therefore, samples with positive scores on Component 1, especially those related to T4 and T5, represent treatments with greater ionic loading and, consequently, greater potential for soil salinization. In contrast, samples with negative scores on this axis were more closely associated with T1, reflecting lower salinity and a weaker effluent signature. Component 2, in turn, represents a secondary gradient related to temporal variation and to the differential behavior of nutrients, trace elements, and sodicity-related variables. This axis helped distinguish samples influenced by N and Na^{+} in the upper right quadrant, by P and Ca^{2+} in the upper left quadrant, and by pH in T1 in the lower right quadrant, while the lower left quadrant was associated with isolated increases in Fe, K^{+}, Zn^{2+}, Cu^{2+}, and Cr.

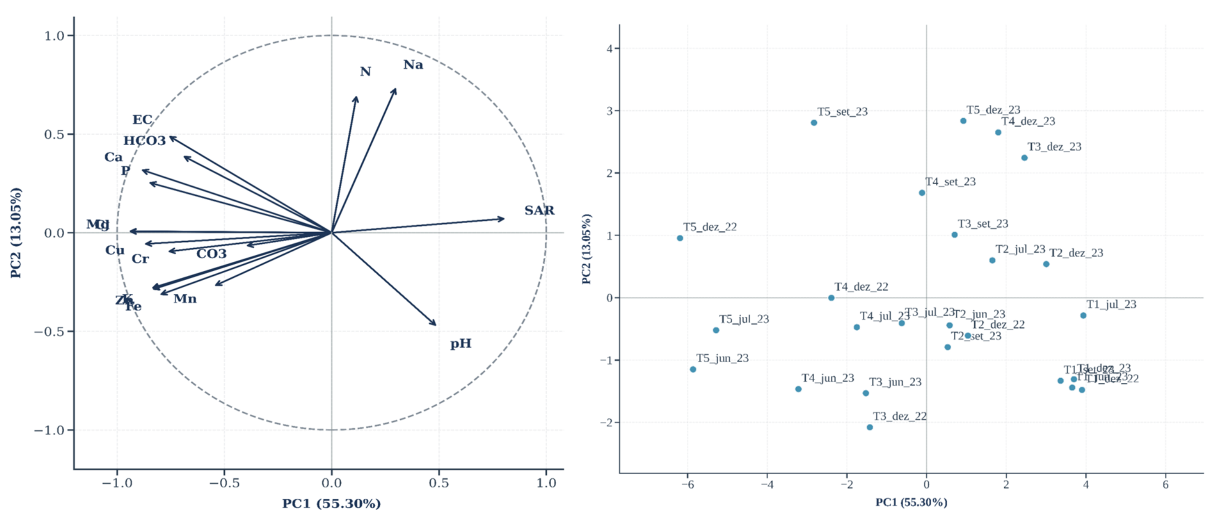


Fig. 6 Component Analysis (Component 1 and 2) for physicochemical attributes and treatments as a function of the dilution times used for irrigation

Complementing the interpretation of Fig. 6, the PCA shown in Fig. 7 reinforces that Component 1 represents the main gradient of salinity and ionic enrichment across treatments. This axis was primarily associated with EC, Ca^{2+}, Mg^{2+}, Cl^{-}, and HCO_3^{-}, which showed higher loadings and increased consistently with the proportion of aquaculture effluent, indicating that the horizontal separation of samples was mainly driven by progressive mineral enrichment of the irrigation water. In contrast, Component 3 can be interpreted as a secondary nutrient–temporal gradient, largely influenced by N, which was the most expressive variable on this axis. This component helped distinguish samples associated with higher N and pH values from those more strongly related to Na^{+}, SAR, and, in specific sampling periods, to Ca^{2+}, K^{+}, HCO_3^{-}, P, Cu^{2+}, and Cr. Therefore, while Component 1 reflects the dominant effect of effluent addition on salinity-related attributes, Component 3 captures temporal fluctuations in nutrient availability and ionic composition. Therefore, Fig. 7 confirms that the main source of variation in the dataset was the gradual increase in salinity-related constituents, whereas the third component explained a secondary but relevant pattern linked to nitrogen dynamics and seasonal changes in water quality.

Thus, the chemical composition of the water used for irrigation, especially when enriched with aquaculture effluent, demonstrates that irrigation takes on a multifunctional character, acting simultaneously on the water and nutritional supply of the crop. This integration characterizes fertigation, in which water is no longer regarded merely as a physical medium, but as a strategic component of nutrient management, contributing to the productive efficiency and sustainability of the agricultural system (Saraiva & Preto, 2023). Therefore, multivariate analysis identified EC, Ca^{2+}, Mg^{2+}, Cl^{-}, HCO_3^{-}, P, SAR, Mn, Zn^{2+}, and N as the key variables governing the behavior of aquaculture effluent dilutions, especially with respect to salinization risk and irrigation management.

4 Conclusions

This study helps to fill an important gap in the literature by integrating the preliminary physicochemical characterization of raw and diluted aquaculture effluents, the diagnosis of salinity- and sodicity related constraints, and the identification of the main drivers of water-quality variation under Brazilian semi-arid conditions.

The results showed that aquaculture effluent dilution significantly altered the physicochemical composition of the irrigation water. As the proportion of effluent increased, EC, Cl^{-}, Ca^{2+}, Mg^{2+}, K^{+}, N, and P also increased, indicating that aquaculture effluent may contribute not only to irrigation supply but

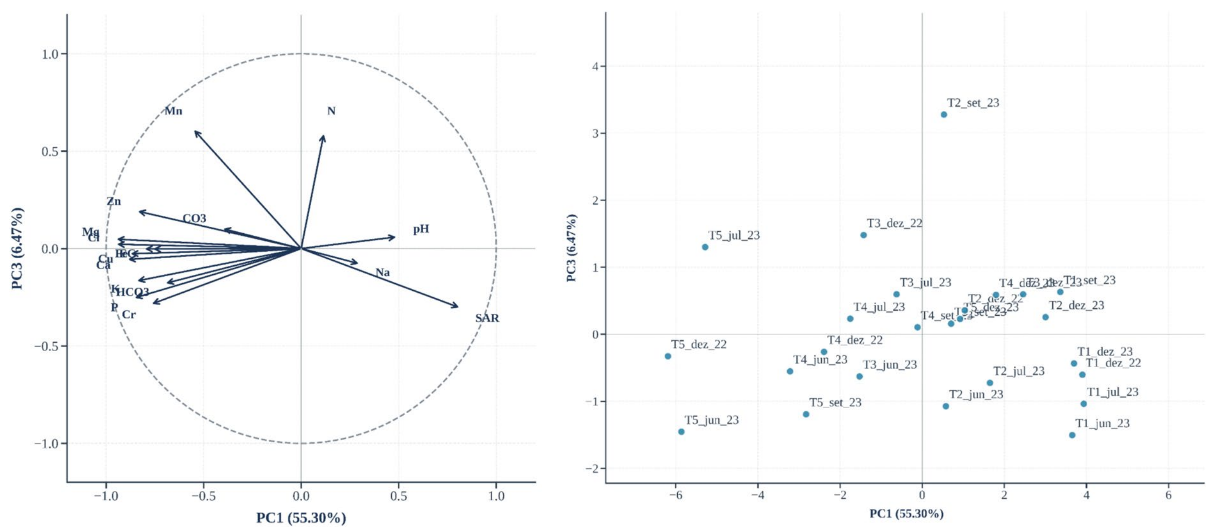


Fig. 7 Component Analysis (Component 1 and 3) for physicochemical attributes and treatments as a function of the dilution times used for irrigation

also to nutrient input. However, these potential benefits were accompanied by increasing salinity-related restrictions.

From the viewpoint of irrigation suitability, T1 was classified as C2S1, indicating medium salinity hazard and low sodicity risk; T2 was classified as C3S1; and treatments T3 to T5 were predominantly classified as C4S1, indicating increasing restrictions mainly associated with salinity. Therefore, raw and diluted aquaculture effluents cannot be considered free of limitations for irrigation reuse. Their suitability depends on appropriate management practices, including adequate drainage, irrigation control, soil salinity monitoring, and the selection of more salt-tolerant crops.

Compliance with the international limits of $SAR < 15$ and $EC < 3$ dS m^{-1} did not fully preclude the risks associated with irrigation reuse, since other evaluation criteria pointed to potential soil salinization and sodification. These findings demonstrate that the assessment of aquaculture effluents for irrigation should not rely exclusively on SAR and EC, but rather on an integrated hydrochemical approach capable of capturing restrictions relevant to long-term soil quality, especially in semi-arid environments.

Multivariate analysis showed that the differentiation among treatments was mainly driven by the effluent-enriched waters, especially T3, T4, and T5, which were more strongly associated with EC, Mg^{2+}, Cl^-, Mn, and Zn^{2+}, whereas T4 and T5 were additionally related to Ca^{2+}, HCO_3^-, and P. In contrast, T1 was more closely associated with higher pH and SAR values in specific sampling periods. Therefore, EC, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^-, P, SAR, Mn, Zn^{2+}, and N were the most relevant variables explaining water-quality variation, confirming that salinity, sodicity, and nutrient-related attributes were the main factors controlling the reuse potential of the evaluated waters.

Overall, the hypothesis of the study was partially supported. Dilution with freshwater reduced part of the restrictions associated with the raw effluent and preserved part of its nutrient load, improving its physicochemical suitability compared with the undiluted effluent. However, the dilution strategies did not fully eliminate salinity-related constraints, particularly at higher effluent proportions. Thus, aquaculture effluent use in the Brazilian semi-arid should be regarded as a promising but management-dependent strategy, requiring continuous monitoring to minimize environmental risks and support more sustainable water use, in line with SDGs 6, 12, and 14.

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Data Availability The original data for this research came from the first author's doctoral thesis and are being published in the repository of the Federal Rural University of the Semi-Arid Region and Postgraduate Program in Soil and Water Management.

Declarations

Conflicts of Interest The authors declare no competing interests.

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