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NOTES AND INSIGHTS

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Integrated cultivation of sea asparagus, celery, and Southern black drum in saline clear waters and biofloc-based aquaponics

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Abstract

Aquaponics is an alternative agricultural practice that combines aquaculture with hydroponics. It increases productivity while treating macronutrient loads on effluents. Yet, little information is available on productivity of commercial aquaponic models using saline waters, especially with biofloc technology (BFT) systems, which are characterized by high concentrations of total suspended solids and nitrate. This experiment evaluated the productivity and nutritional quality of the halophytes celery (*Apium graveolens* var. tall Utah) and sea asparagus (*Salicornia neei*), and the growth of a coastal fish, the Southern black drum (*Pogonias courbina*) in coupled aquaponic cultivation with clear water and BFT water. No previous report was found in the literature regarding celery cultivation coupled with saline BFT. The experiment was carried out for 18 weeks with a water salinity of 10 g L^{-1}. Floating rafts with halophytes (≈20 plants m^{-2} per species) were placed inside tanks holding juvenile Southern black drums (21 ind m^{-3}). Each water-treatment type was tested in three replicate tanks (15 m^3). Both *S. neei* and *A. graveolens* produced more aboveground biomass in the BFT system than in clear-water tanks, with average shoot yields of 0.64 and 0.23 kg m^{-2} 30 $days^{-1}$, respectively. The protein content of *A. graveolens* was significantly higher in BFT system, likely due to increased nitrogen availability. *S. neei* shoots showed highest P content in clear water, suggesting that the higher alkalinity and pH in the BFT system may have reduced P uptake. The growth of *P. courbina* fry did not differ significantly between treatments. Southern black drum, celery, and sea asparagus can be successfully cocultured in a biofloc-based aquaponic system.

Abbreviations: BFT, biofloc technology; FURG, Federal University of Rio Grande; NFT, nutrient film technique; PVC, polyvinyl chloride; TSS, total suspended solids.

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Plain Language Summary

Aquaponics is a system utilizing aquaculture and hydroponics to improve crop productivity while addressing nutrient levels in effluents. In aquaculture, biofloc technology uses microbial activity to convert harmful nitrogenous waste (such as ammonia) into microbial biomass (biofloc) and nitrate, necessary for plant growth. However, high levels of biofloc in the water can block plant roots and hinder the mix of these technologies. Our study aimed to assess how salt-tolerant plants like sea asparagus and celery respond to aquaponics using saline waters from Southern black drum fish, with and without bioflocs. We discovered that both halophytes grew better in the biofloc system with minimal maintenance. Using biofloc water increased nitrogen levels in celery shoots while decreasing phosphorus content in sea asparagus biomass. The integration of biofloc technology and aquaponics is vital for enhancing productivity in limited spaces and advancing toward a more sustainable agricultural system.

1 | INTRODUCTION

Aquaponics is an ancient technology that manages a plant–aquatic organisms–bacteria ecosystem, combining hydroponics and agri-aquaculture systems. Aquaponics remedies environmental hazards associated with them, for example, water bodies' eutrophication and chemical nutrient dependency (Ibrahim et al., 2023). Defined as the recirculation of waste and nutrients from aquaculture waters into plant crops, aquaponic systems are capable of generating biomass with high added value (Goddek et al., 2019). In the case of aquaculture with saline waters, aquaponics requires plants adapted to high concentrations of Na^+ and Cl^- ions, commonly called halophytes (Fierro-Sañudo et al., 2020; Kotzen et al., 2019). Biomass of halophytes is rich in minerals and bioactive compounds, such as polyunsaturated fatty acids (e.g., ω-3 and ω-6), phenolic acids, flavonoids, and vitamins (Costa & Herrera, 2016; De Souza et al., 2018; Ventura et al., 2011). Their production associated with aquaculture systems can provide additional income for producers, as well as treat water by reducing the macronutrient load of recirculated water or effluents (Custódio et al., 2021).

Another way to manipulate nutrients in aquaculture systems is with biofloc technology (BFT). Highly regarded as a biosecure closed system based on microorganisms management. In BFT systems, the control of carbon and nitrogen ratio close to 15C:1N–20C:1N in the water provides habitat for chemoautotrophic bacteria that absorb potentially toxic nitrogen compounds (ammonia and nitrite) into less toxic forms (nitrate) and in the process generate "in situ" microbial protein provided by microbial aggregates named "bioflocs" (Emerenciano et al., 2021). These conditions allow the development of super-intensive cultures of crustaceans and fish (with hundreds of individuals per m^2 or m^3, with minimal water exchange). BFT systems can provide a nutritive environment not just for cultivation of aquatic animals, but also for plant production by directing their effluents to nourish plants in aquaponics. This integration of biofloc-based aquaculture with hydroponics can be named "flocponics" (Khanjani et al., 2024; Pinho et al., 2022). However, mature BFT systems accumulate high levels of particulate organic material (bioflocs), quantified as total suspended solids (TSS) in the water (Emerenciano et al., 2021; Goddek et al., 2019). Progressive accumulation of phosphorus in the water of BFT systems can also occur due to the degradation of animal feed and excreta (Poli et al., 2019). While high availability of nitrate and phosphorus is favorable for the growth of herbaceous plants (Doncato & Costa, 2023b), excess of suspended solids can generate high biological and chemical oxygen demands, changes in the oxidation-reduction potential and pH of the medium, affecting the availability of nutrients for plants. Suspended solids can clog the roots in hydroponic media, making it difficult to absorb nutrients and even leading to root rotting (Pinho et al., 2021; Rakocy, 2012).

Salicornia neei Lag. (Amaranthaceae) is a perennial herbaceous plant that demonstrates high productivity when irrigated with saline aquaculture waters from BFT systems (Doncato & Costa, 2023a; Gonçalves et al., 2024; Pinheiro et al., 2020). Plants of the genus *Salicornia* are commonly called sea asparagus and have a fresh value in the European market of 2.00€–3.00€ per 100 g of fresh shoots. *S. neei* is widely distributed along the Atlantic and Pacific coasts of South America (Costa & Herrera, 2016; Costa et al., 2019) and has shoot and root biomass with high nutritional value,

rich in macro- and micronutrients (Bertin et al., 2016; Doncato & Costa, 2018), as well as high levels of bioactive compounds (Bertin et al., 2014; De Souza et al., 2018). This halophyte is an important reference in the evaluation of new plant species to be cultivated in saline waters with a BFT system (Fierro-Sañudo et al., 2020).

Another vegetable with market value that can grow in saline water is celery (*Apium graveolens* L., Apiaceae). Cosmopolitan and with a large number of commercial varieties (Khalil et al., 2015), celery can be cultivated in hydroponic systems and in soil irrigated with saline waters (up to 15.7 dS m^{-1}; ≈10.6 g L^{-1}; Pardossi et al., 1999; Pascale et al., 2003). It is a plant rich in vitamin C, potassium, calcium, and magnesium, used medicinally as a diuretic, stimulant, and sedative (Sowbhagya, 2014). However, unlike *S. neei*, no report of celery cultivation with water from BFT aquaculture systems was found in the literature.

New fish species have also been introduced into saline aquaculture with BFT system and their waters used for aquaponics. Poersch et al. (2021) demonstrated the feasibility of cultivating *Sciaenops ocellatus* ("red drum"; family Sciaenidae) in a multitrophic system with BFT. In Brazil, the native black drum species (named "miragaia" or "corvina-preta") *Pogonias courbina* (Lacepède, 1803) (Sciaenidae) has potential for saline BFT cultures (Rodrigues, 2020), since it inhabits turbid estuarine waters as a juvenile and coastal waters as an adult (Haimovich et al., 2020; Urteaga & Perrota, 2001), consequently growing in a wide range of salinities. In nature, the Southern black drum can live for 55 years and reach more than 60 kg (Haimovich et al., 2020). Its reproduction and growth have been studied in laboratory conditions, aiming at the development of a program to repopulate natural populations (Benato et al., 2023), as well as to assess its productivity for mariculture in a clear water system (Kuroski et al., 2025). The assessment of *P. courbina* growth in a BFT system has not yet been carried out.

The present study aimed to evaluate the growth, production, and nutritional quality of shoot biomass of the sea asparagus *S. neei* and the celery *A. graveolens* produced in saline aquaponics with waters from *P. courbina* culture, with and without the use of the BFT system. This study also allowed testing the hypothesis that Southern black drum can present similar zootechnical performance in BFT system compared to clear water system.

2 | MATERIALS AND METHODS

2.1 | Study sites and origin of cultured organisms

The experiment was carried out at the Marine Aquaculture Station of the Federal University of Rio Grande (FURG), located on Cassino Beach (Rio Grande, Rio Grande do Sul; 32°12′19″ S, 52°10′45″ W), in the spring of 2022 (8 weeks). *A. graveolens* plants (variety Utah) were propagated from seeds purchased at a local supplier (Feltrin brand) and germinated in an incubator (Doncato & Costa, 2019). *S. neei* seedlings (BTH2 progeny; Doncato & Costa, 2019) were obtained from vegetative propagation of plants maintained in the germplasm of the Halophyte Biotechnology Laboratory (FURG), using the vegetative propagation technique by cuttings (Costa & Herrera, 2016). Juveniles of black drum *P. courbina* were provided by the Estuarine and Marine Pisciculture Laboratory (FURG), obtained from the reproduction of mature specimens (Ethics Committee of Animal Use [CEUA] of the project is 23116.006908/2017-81).

2.2 | Experimental design and systems

The development of sea asparagus and celery was evaluated in a factorial experiment with two treatments (three repetitions each): cultivated in clear water (CLEAR) and in water with BFT from Southern black drum farming. Water salinity was set to 10 g L^{-1} by diluting seawater with collected rainwater to keep salt stress inside the tolerance range of the plant species (De Souza et al., 2018; Pascale et al., 2003) and fishes (Haimovich et al., 2020). Six circular tanks of 20 m^3 (useful volume of 15 m^3) were established within an unheated greenhouse. Each tank had an aeration system via microporous hoses (aerotubes) connected to a 7.5 HP blower, and three tanks were allocated to each treatment. Each tank system was connected to a settling tank with a useful volume of 150 L, receiving water from a submerged pump via pipe and clarified water returning to fish tank by gravity. Utilizing the clarifier in the BFT and CLEAR treatments, the TSS were kept under 200 mg L^{-1} (Poersch et al., 2021) to prevent gill damage to the fish (Schumann & Brinker, 2020). Throughout the experiment for the treatment CLEAR if levels of ammonia and nitrite reached a concentration of 1 mg L^{-1}, part of the water was exchanged (Boyd & Tucker, 1998).

The duration of the *P. courbina* culture was 129 days or approximately 18 weeks. The aquaponic system was integrated at day 39 after starting the black drum juvenile culture (between weeks 5 and 6). The plants were harvested after 56 days (8 weeks) of growth, between weeks 13 and 14.

Southern black drum juveniles were stocked in the tanks (Figure 1) at a density of 0.13 kg m^{-3} (315 fish per tank). The fish were fed a dry commercial diet (38%–40% crude protein). The fish's feeding rates were adjusted biweekly based on sampling and biometric measurements taken during the study. In BFT tanks, after stocking the fish, the concentration of total ammonia nitrogen (TAN) was monitored daily until it reached 1.0 mg L^{-1}, then a source of organic carbon (sugarcane molasses) was added to maintain a carbon:nitrogen ratio

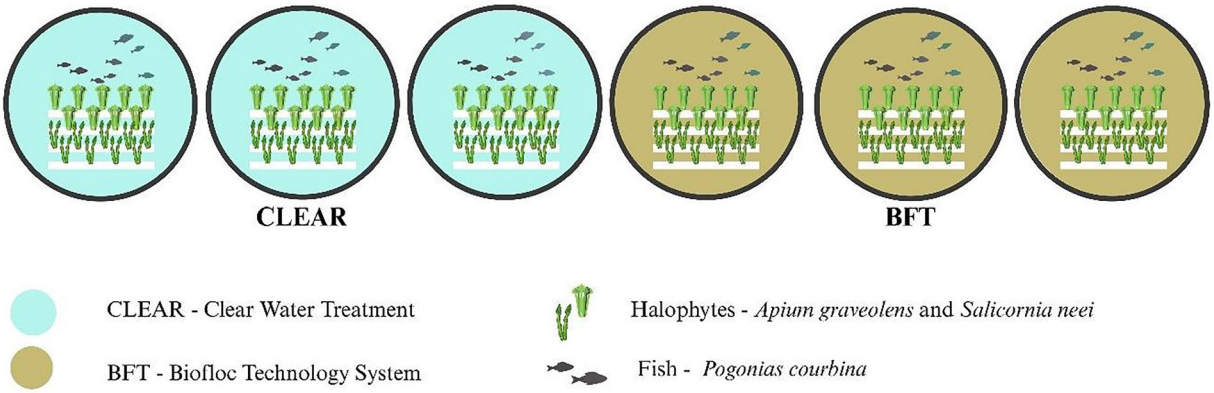


FIGURE 1 Representation of factorial experimental with three tanks with clear water (CLEAR) and three tanks with bioflocs (BFT) is shown with plants in floating rafts (halophytes *Apium graveolens* and *Salicornia neei*) and stoked with fish juveniles (*Pogonias courbina*).

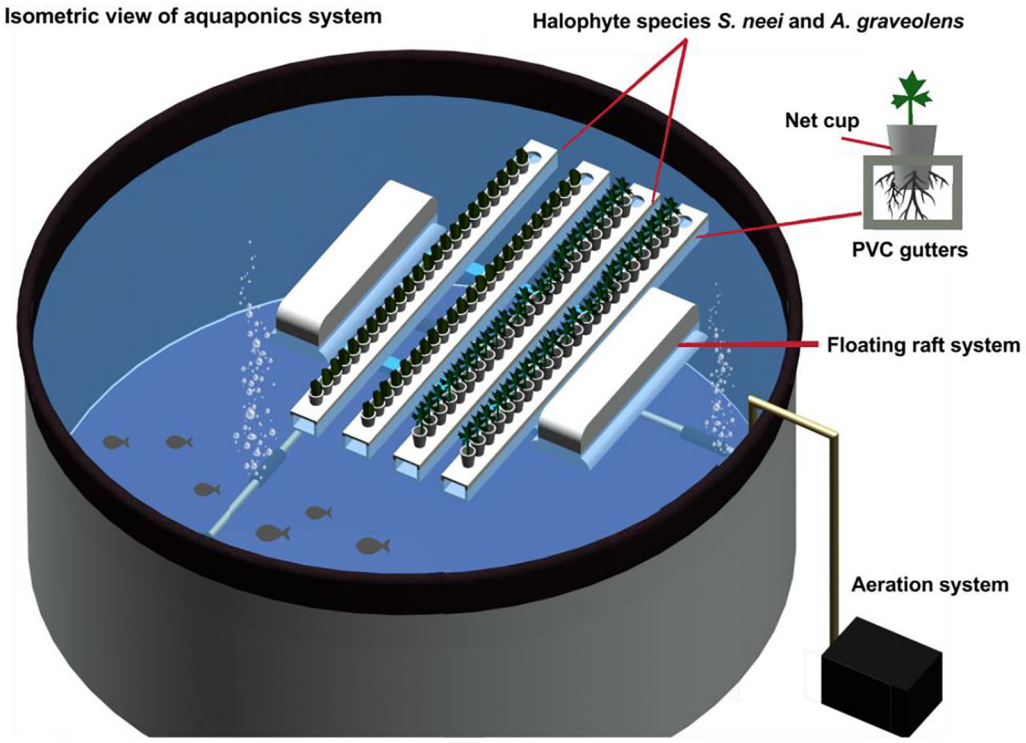


FIGURE 2 Illustration of an aquaponics system and a transversal view of the polyvinyl chloride (PVC) gutters with the plants' net cup. The aquaponic system uses two white high-density polyethylene floats connected by two metal bars to support PVC gutters that float just below the water surface. Four PVC gutters, each with open ends and holes on top holding 22 net cups with halophyte plants.

of 15:1 (Ebeling et al., 2006), stimulating bacterial biomass growth until a reduction in TAN content was observed. During the aquaponic cultivation period, the bioflocs were already in their mature phase, the carbon:nitrogen ratio was stable and there was no subsequent addition of molasses. Hydrated lime was added to each tank with bioflocs to raise the alkalinity to levels above 100 mg $CaCO_3$ L^{-1}, necessary to maintain the levels of inorganic carbon available to the chemoautotrophic bacteria in the bioflocs (Ebeling et al., 2006).

Halophytes were cultivated in a coupled aquaponic system, with floating rafts being placed inside fish tanks (Figure 2). Each tank received a raft composed of two high-density polyethylene floats, connected by a metal structure, where polyvinyl chloride (PVC) pipes (gutters) 8.5 cm in diameter and 300 cm in length hold the plants, which were kept on the surface of the water, allowing the water to flow continuously through the pipes without restrictions. Each raft contained four parallel PVC pipes spaced 10 cm apart; two pipes were

used for each halophyte species (22 plants per PVC pipe; density ≈20 plants m^{-2} per species). Each individual plant was placed in a net cup with a hollow bottom and gravel (1–2 cm) to secure the roots. Once a week, the pipes were tilted so that the particulate matter retained inside them could drain back to the tanks.

At the beginning of the aquaponic cultivation, waters of both treatments had low values (average ± standard error) of TAN (0.10 ± 0.00 and 0.09 ± 0.00 mg $N\text{-}NH_3$ L^{-1}) and nitrite (0.04 ± 0.00 and 0.11 ± 0.04 mg $N\text{-}NO_2$ L^{-1}), but nitrate concentration of BFT treatment (47.66 ± 8.19 mg $N\text{-}NO_3$ L^{-1}) was significantly higher than of CLEAR treatment (0.08 ± 0.00 mg $N\text{-}NO_3$ L^{-1}; $t = 5.80$, $p < 0.001$).

2.3 | Assessment of water physicochemical parameters

During the 8 weeks of the aquaponic cultivation, the temperature and dissolved oxygen concentration were quantified daily using a HQ40d multiparameter device (HACH Company), as well as the pH using a FEP20 pH meter (Mettler Toledo), and weekly, the salinity using a refractometer RTP-20ATC (ATC Company). Water samples (50 mL) were collected weekly from the tanks and filtered with pre-weighed Whatman GF/C filters; the retained TSS content was estimated by gravimetry (Strickland & Parsons, 1972). The filtrates were subsequently analyzed for dissolved concentrations of TAN, nitrite, and phosphate using spectrophotometry (ELx808, Biotek Instruments Inc.; Baumgarten et al., 2010). Nitrate contents were estimated using the method described by García-Robledo et al. (2014). Initial parameters of alkalinity for CLEAR and BFT were (average ± standard error) 81.66 ± 1.36 and 125 ± 3.14 mg L^{-1}, respectively. pH values (average ± standard error) were very similar, 8.27 ± 0.16 and 8.33 ± 0.02 for CLEAR and BFT, respectively. Temperature of both water treatment systems had same average (± standard error of 16.86 ± 0.12°C and 16.86 ± 0.09°C) and similar oxygen values (average ± standard error of 8.46 ± 0.15 and 8.54 ± 0.06) for CLEAR and BFT, respectively.

2.4 | Assessment of halophyte growth

At the beginning of the aquaponic cultivation, biometric measurements were performed on a random sample of 15 individuals of each plant species. *S. neei* shoots had on average (± standard error) 9.05 ± 0.25 cm of height and 19.20 ± 3.52 branches per plant, and *A. graveolens* plants showed averages of shoot height and leaf number of 3.32 ± 0.24 cm and 3.45 ± 0.13 per plant, respectively. Two weeks after taking the initial measurement for *S. neei*, all their shoots were cut at the top of the net pot (i.e., pruning 4 cm above the gravel level) to level it and later evaluate only the regrowth of this perennial halophyte. *S. neei* is able to produce biomass year-round by repeated cuttings and regrowth of its shoots (Costa & Herrera, 2016; Doncato & Costa, 2023a; Fierro-Sañudo et al., 2020). *A. graveolens* plants obtained from seedlings were cut only at the final harvest. After 8 weeks of aquaponic culture, all shoots of both species were again cut at the same height, and their biometric measurements were taken at the beginning of cultivation. The fresh shoot biomass of each plant was measured using a precision balance (± 0.01 g). The fresh biomass of the roots of each plant, which developed outside the cups, was quantified only at the conclusion of the experiment, also by weighing on a precision balance. The percentage of fresh biomass allocated to shoots was estimated by dividing shoot biomass by total biomass (shoots + roots) and multiplying by 100. Biomass production per floating raft area of each species was also calculated by summing the individual shoot biomass of all plants on the raft and subsequently dividing this value by the floating raft area occupied by the species. Additionally, the shoot biomass of each plant was dried in an oven (60°C for 48 h) and weighed on a precision balance (± 0.0001 g), allowing the estimation of the shoot dry biomass and succulence; the latter by calculating the percentage difference between the fresh and dry biomass.

2.5 | Evaluation of the Southern black drum performance

The initial mean weight was measured before fish stocking in the tank (fingerlings had approximately 18 weeks and an average ± standard error weight of 5.4 ± 0.07 g). At the end of the experiment, all remaining fish were tallied to determine survival. Final mean weight (g) was determined as the final weight of animals (g) divided by the total number of animals, and productivity of animals (kg m^{-3}) was calculated as [(final biomass {kg} − initial biomass {kg}) × 1000] divided by the useful tank volume (15 m^3).

2.6 | Proximate and mineral compositions of plant biomass

The proximate composition of the shoot biomass of both halophytes was analyzed based on dry matter according to the methodology of Bligh and Dyer (1959) for lipids, and according to the AOAC (Association of Officiating Analytical Chemists, 2005) for the determination of moisture, ash, and crude protein. For the latter parameter, the nitrogen to crude protein conversion factor of 4.06 was used for *S. neei* (Souza, unpublished data, 2025) and 4.43 for *A. graveolens* (a general factor for plant, based on the study by Yeoh and Wee

[1994]). For each species, the proximate composition analyses were performed with at least two dry samples of shoots per treatment, and each sample composed of at least two plants.

Ash represented a very significant component of the dry mass (DM) of *S. neei* plants (global average = 33.64%; see Section 3), and analyses of the mineral composition of *S. neei* shoots were performed. The biomass of two or more plants was combined to compose dry samples for each treatment, which were ground in a mortar with a pestle and subjected to nitric-perchloric and sulfuric digestion, according to the methodology described by Tedesco et al. (1995), in a TECNAL digestion block. In the extracts obtained from the digestions, nitrogen (N) was determined by distillation and titration (Tedesco et al., 1995), phosphorus (P) with a Biospectro SP-200 ultraviolet-visible spectrophotometer, potassium (K) by B462 Micronalflame photometry, and calcium (Ca) and magnesium (Mg) were determined by a Sa vantAA Atomic Absorption Spectrophotometer (GBC Scientific Equipment). All mineral analyses were performed at the Soil Chemistry Laboratory of the Eliseu Maciel School of Agronomy—Federal University of Pelotas.

2.7 | Data analysis

All data on water quality, plant growth and productivity, and Southern black drum performance were tested for the principles of normality and homoscedasticity, and were transformed when necessary. Phosphate and TAN data were transformed using the $\mathrm{Log}_{10}(100x)$ function. For *S. neei*, the shoot height variable was transformed using the $\mathrm{Log}_{10}(x)$ function, and the number of shoot branches variable was transformed using the $\sqrt{x}$ function.

Differences between the BFT and CLEAR treatments for physical–chemical parameters and nutrient levels in the water were tested using a one-way repeated-measures (weeks of collection) analysis of variance (ANOVA; fixed factor = cultivation system; Zar, 2010). The interaction factor cultivation system × weeks was considered in the adopted ANOVA model, each tank was considered a replicate (three for each cultivation system) and means of one tank were only used if the parameters were collected more than once a week (temperature, oxygen, alkalinity, pH, nitrite, and TAN), and significant differences ($p < 0.05$) between averages were assessed by Tukey's honestly significant difference (HSD) post hoc multiple comparison test at 5% significance.

For each plant species, biometric results, shoot succulence, and biomass components were compared between treatments through nested one-way ANOVA (Zar, 2010) with cultivation system treatment as the fixed factor and the cultivation tanks as the random nested factor, followed by Tukey's HSD test at 5% significance.

Differences in the proximate composition of shoot biomass (lipids, ash, moisture, and crude protein) of the two halophytes; the mineral composition of *S. neei* shoots (N, P, K, Ca, and Mg); and *P. courbina* survival, final average weight, and productivity per tank volume (m^3) between water system treatments were evaluated using the Student's *t*-test at 5% significance (Zar, 2010).

3 | RESULTS

3.1 | Environmental and water quality conditions

During the 8 weeks of the aquaponic cultivation of halophytes, the air temperature inside the greenhouse varied between 9°C and 38°C (daily average = 24.85 ± 3.50°C), and the intensity of solar radiation did not exceed 1.7 J m^{-2} s^{-1} (1668 W m^{-2}), and the daily average of solar radiation was 6.56 ± 2.87 MJ m^{-2} day^{-1}.

The averages of temperature and dissolved oxygen in the waters of the Southern black drum tanks varied significantly throughout the experiment ($p < 0.001$), associated with atmospheric heating during spring 2022, but did not present significant differences between CLEAR and BFT treatments (Table 1). The overall averages of salinity were also similar between treatments but waters of a mature and managed BFT presented higher alkalinity, TSS, dissolved nitrate, and phosphate ($p < 0.05$) than those of CLEAR tanks (Figure 3; Table 1). On the other hand, TAN content was significantly ($p < 0.05$) lower in BFT tanks than in CLEAR tanks (Table 1). Clarification was applied 52 days after the fish stocking in the CLEAR treatment due to high TSS. In "tank 5" of CLEAR treatment, a peak in TAN concentration occurred 72 days after fish stocking and 30% of the water in this tank was exchanged.

3.2 | Development and productivity of *S. neei* and *A. graveolens* in CLEAR and BFT treatments

There was no plant mortality during the experiment. The nested ANOVAs detected significant differences within BFT treatment tanks for total biomass and shoot height of *A. graveolens*, as well as all biometric parameters and biomass components of *S. neei* plants (Tables 2 and 3). In all cases, plant performance was higher in the BFT treatment tank, where the average dissolved nitrate concentration was higher (67.85 ± 10.40 mg $N\text{-}NO_3$ L^{-1}) than in the other two tanks in this treatment (40.00 ± 4.36 and 45.71 ± 5.71 mg $N\text{-}NO_3$ L^{-1}).

TABLE 1 Average (± standard error) values of the physical-chemical parameters and nutrient contents of the waters in production tanks of Southern black drum with clear waters (CLEAR) and with biofloc (BFT) during aquaponics.

Parameters	*N*	CLEAR	*N*	BFT	*F t*	*t* Sig.	*F w*	*w* Sig.	*F t* × *w*	*t* × *w* Sig.
Temperature (°C)	246	21.50 ± 1.16	246	21.10 ± 1.13	0.43	0.546	298.28	<0.001	3.35	0.010
Salinity (g L^{-1})	24	10.31 ± 0.15	24	10.14 ± 0.14	1.45	0.294	0.47	0.849	1.39	0.249
Oxygen (mg L^{-1})	246	8.00 ± 0.08	246	8.03 ± 0.06	0.01	0.922	46.17	<0.001	1.99	0.092
Ph	57	8.27 ± 0.04b	57	8.55 ± 0.02a	5.97	0.070	2.42	0.044	3.06	0.016
Alkalinity (mg L^{-1})	60	92.00 ± 1.58a	60	157.16 ± 3.25b	242.31	<0.001	27.87	<0.001	12.568	<0.001
TSS (mg L^{-1})	18	60.66 ± 8.04a	18	141.61 ± 10.45b	50.06	0.002	25.98	0.000	1.045	0.421
Nitrate (mg L^{-1})	24	0.07 ± 0.01b	24	60.62 ± 7.84a	707.68	<0.001	2.83	0.023	2.834	0.022
Nitrite (mg L^{-1})	42	0.08 ± 0.01	42	0.26 ± 0.04	2.41	0.195	1.41	0.238	1.182	0.344
TAN (mg L^{-1})[a]	48	0.16 ± 0.06b	48	0.04 ± 0.01a	9.58	0.036	2.06	0.081	1.571	0.185
Phosphate (mg L^{-1})[a]	24	1.07 ± 0.07b	24	2.77 ± 0.21a	43.91	0.002	3.610	0.006	1.687	0.152

Note: Significance values for the factors treatment (*t*), week of cultivation (*w*), and the *t* × *w* interaction, estimated by repeated-measures analysis of variance (ANOVA), are presented. Different lowercase letters in the lines indicate significantly different means between BFT treatments ($p < 0.05$) according to the Tukey test; degrees of freedom of *t*, *w*, and *t* × *w* factors are 1, 7, and 7, respectively. *F* -value indicates Fisher *F*-test statistic.

Abbreviations: TAN, total ammonia nitrogen; TSS, total suspended solids.

[a]Transformation of data in Log10(100*x*)

TABLE 2 Average (± standard error) of biometrics and fresh biomass components of *Salicornia neei* 6 weeks after pruning and regrowth in saline aquaponics with clear water (CLEAR) and with bioflocs (BFT).

Parameters	*n*	CLEAR	*n*	BFT	*F t*	Sig.	*F* nt	Sig.
Shoot height (cm)[a]	124	10.95 ± 0.27b	124	18.64 ± 0.45a	246.52	<0.001	14.24	<0.001
Branch number[b]	124	25.57 ± 0.94b	124	28.71 ± 0.85a	9.49	0.002	8.54	<0.001
Shoot biomass (g)[a]	124	8.35 ± 0.42b	124	45.94 ± 2.04a	763.74	<0.001	22.59	<0.001
Root biomass (g)	65	1.74 ± 0.22b	66	2.30 ± 0.20a	4.29	0.040	8.39	<0.001
Total biomass (g)	65	10.69 ± 0.83b	66	51.40 ± 3.03a	317.01	<0.001	32.25	<0.001
Shoot allocation (%)	65	85.05 ± 1.10b	66	95.19 ± 0.42a	86.63	<0.001	6.90	<0.001

Note: Results of nested analysis of variances (ANOVAs) are presented; degrees of freedom of the type of water (*t*) and nested tank (nt) factors were 1 and 4, respectively. ns = not significant ($p > 0.05$). Different lowercase letters in the lines indicate significantly different means between BFT treatments ($p < 0.05$) according to the Tukey test. *F* -value indicates Fisher *F*-test statistic.

[a]Log10(100*x*).

[b]$\sqrt{(x)}$.

TABLE 3 Average (± standard error) of biometrics and fresh biomass components of *Apium graveolens* after 8 weeks of growth in saline aquaponics with clear water (CLEAR) and with bioflocs (BFT).

Parameters	*n*	CLEAR	*n*	BFT	*F t*	Sig.	*F* nt	Sig.
Shoot height (cm)[a]	128	6.56 ± 0.19b	123	22.84 ± 0.34a	1999.92	<0.001	17.90	<0.001
Leaf number	128	16.47 ± 0.52b	123	59.48 ± 1.78a	952.70	<0.001	14.49	<0.001
Branch number	128	4.75 ± 0.08b	123	8.54 ± 0.17a	498.43	0.003	7.20	<0.001
Root length (cm)	128	13.41 ± 0.42	123	13.69 ± 0.41	0.32	ns	16.03	<0.001
Shoot biomass (g)	128	0.83 ± 0.06b	124	22.30 ± 0.85a	1072.53	<0.001	39.61	<0.001
Root biomass (g)	128	1.52 ± 0.13b	124	13.61 ± 0.56a	511.23	<0.001	12.29	<0.001
Total biomass (g)	128	2.35 ± 0.19b	124	35.97 ± 1.14a	932.75	<0.001	4.95	<0.001
Shoot allocation (%)	128	37.67 ± 0.6b	124	61.33 ± 1.08a	1084.00	<0.001	118.45	<0.001

Note: Results of nested analysis of variances (ANOVAs) are presented; degrees of freedom of the type of water (*t*) and nested tank (nt) were 1 and 4, respectively. ns = not significant ($p > 0.05$). Different lowercase letters in the lines indicate significantly different means between BFT treatments ($p < 0.05$) according to the Tukey test. *F* -value indicates Fisher *F*-test statistic.

[a]Log10(10*x*)

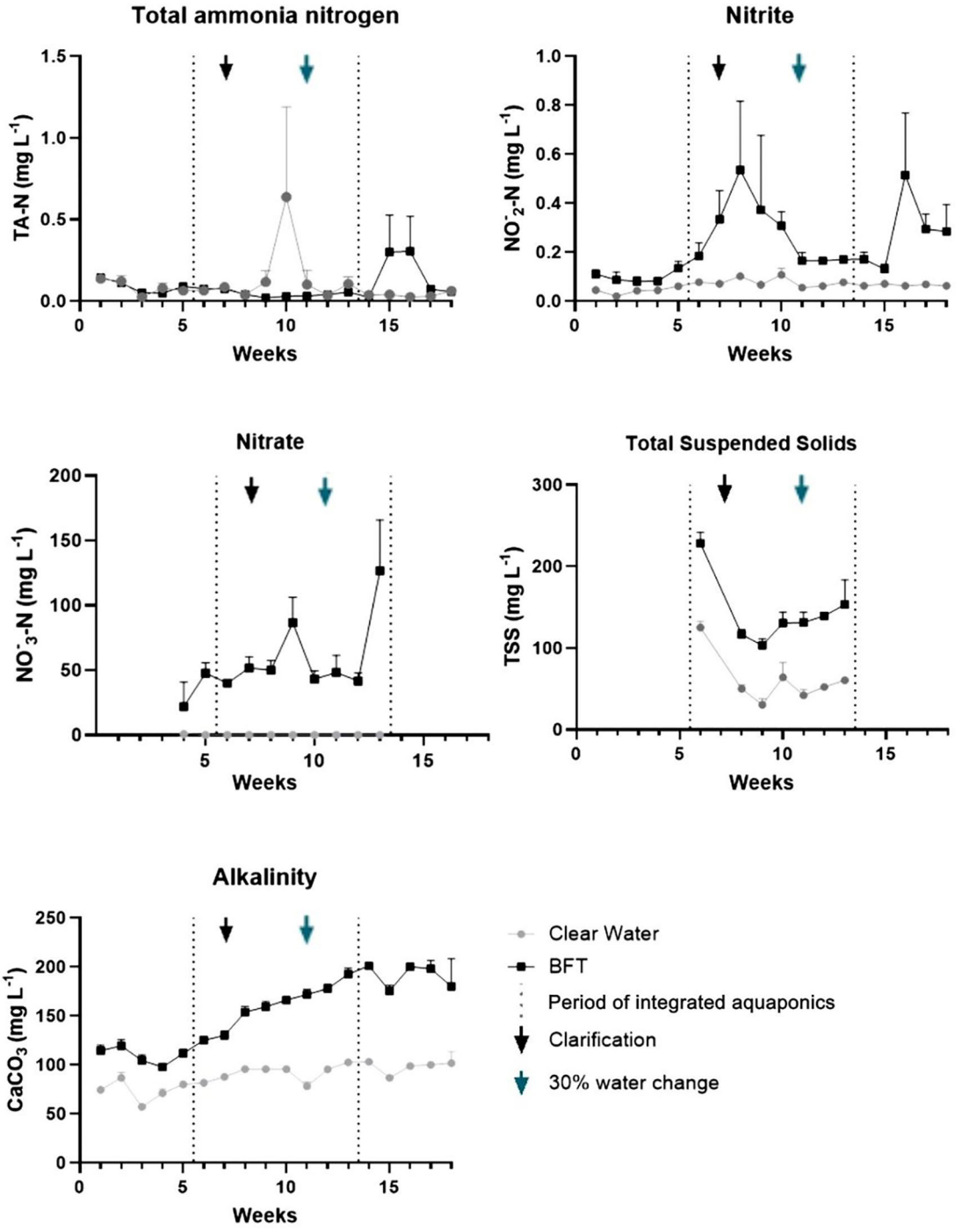


FIGURE 3 Water average (± standard error) values of total ammonia nitrogen (TAN), nitrite, nitrate, total suspended solids (TSS), and alkalinity in production tanks of black drum, the *Pogonias courbina*, with clear water (CLEAR) and with bioflocs (BFT) during ≈18 weeks of experiment. The period during which the halophytes *Salicornia neei* and *Apium graveolens* were integrated into the aquaponic system is indicated by vertical dotted lines. Dates of the clarification operation and water exchange were signed with black and blue arrows, respectively.

Except for the root length of *A. graveolens* plants (Table 3), both halophytes presented significantly ($p < 0.001$) higher biometric parameters and biomass production in *P. courbina* treatment with bioflocs (Figure 4). These differentiated growths occurred mainly through increases in shoot height. The average shoot biomass of *S. neei* and *A. graveolens* was 4.5 times and 25.9 times higher in BFT treatment than in CLEAR treatment, respectively. Furthermore, both species showed a greater allocation to shoot biomass in nutrient-rich waters of BFT tanks, where average shoot biomass *S. neei* and *A. graveolens* represented 95.2% and 61.3% of their total biomass, respectively.

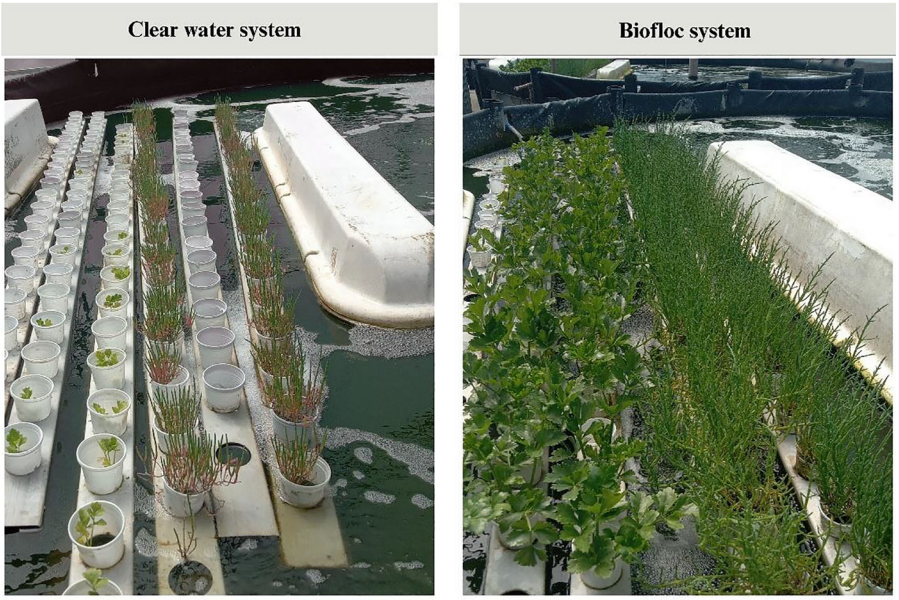


FIGURE 4 Photographs of the aquaponic systems with clear water (CLEAR) and with bioflocs (BFT) after 8 weeks of plant introduction to the system.

TABLE 4 Proximate composition of *Apium graveolens* shoots (average ± standard error) grown in saline aquaponics with clear water (CLEAR) and with bioflocs (BFT). Values on dry and fresh weight (DW and FW) basis are presented.

	CLEAR			BFT				
%	*n*	FW	DW	*n*	FW	DW	*t*-test	Sig.
Moisture	26	86.77 ± 1.82	–	26	88.16 ± 1.18	–	−3.43	<0.001
Ashes[a]	2	2.12	16.04 ± 0.14	2	2.03	17.15 ± 0.57	–	–
Crude protein[a]	2	0.94	7.79 ± 0.06	2	1.39	12.88 ± 1.35	–	–
Lipids[a]	2	0.39	2.95 ± 0.71	2	0.45	3.84 ± 1.09	–	–

[a]Due to the small sample size no statistical inference was made.

TABLE 5 Proximate composition of *Salicornia neei* shoots (average ± standard error) grown in saline aquaponics with clear water (CLEAR) and with bioflocs (BFT). Values on dry and fresh weight (DW and FW) basis are presented.

		CLEAR			BFT			
%	*n*	FW	DW	*n*	FW	DW	*t*-test	Sig.
Moisture	24	87.33 ± 4.82	–	24	87.90 ± 3.34	–	−0.50	ns
Ashes[a]	8	3.97	31.45 ± 1.2	8	4.27	35.43 ± 1.6	−5.55	<0.001
Crude protein[a]	2	0.71	5.65 ± 0.58	2	0.71	5.96 ± 0.53	–	–
Lipids[a]	2	0.30	2.44 ± 0.35	2	0.35	2.91 ± 0.75	–	–

[a]Due to the small sample size no statistical inference was made.

3.3 | Proximate and mineral compositions of plant biomass

At the end of the experiment, *A. graveolens* plants in BFT treatment showed higher ($p < 0.01$) averages moisture in their shoots than plants grown in CLEAR treatment (Table 4). *S. neei* shoots grown under the BFT treatment showed higher ash content than those grown under the CLEAR treatment (Table 5). However, shoots of this halophyte had lower ($p < 0.05$) average contents of P and K in BFT treatment (Table 6).

3.4 | Southern black drum performance cultivated in clear water (CLEAR) and BFT

The Southern black drum had survival rates greater than 86% and its zootechnical parameters showed no statistical differences between treatments (Table 7).

TABLE 6 Mineral content of *Salicornia neei* (average ± standard error; $n = 3$) grown in saline aquaponics with clear water (CLEAR) and with bioflocs (BFT).

Composition (g dry weight kg^{-1})	CLEAR	BFT	*t*-test	Sig.
P	2.25 ± 0.12	1.32 ± 0.13	5.13	0.006
K	23.70 ± 0.81	20.14 ± 0.81	3.08	0.036
Ca	6.97 ± 0.30	6.36 ± 0.52	1.00	ns
Mg	24.11 ± 2.40	25.17 ± 0.80	−0.41	ns
N	12.82 ± 0.40	18.81 ± 4.87	−1.23	ns

Note: ns, not significant ($p > 0.05$).

TABLE 7 Performance (average ± standard deviation) of black drum (*Pogonias courbina*) during 16 weeks of growth in tanks with clear water (CLEAR) and with bioflocs (BFT).

Parameters	CLEAR	BFT	*t*-test	Sig.
Survival (%)	87.9 ± 6.9	86.9 ± 8.0	0.18	ns
Initial average weight (g)	5.4 ± 0.07	5.4 ± 0.07	–	–
Final average weight (g)	26.5 ± 8.5	23.9 ± 7.3	1.75	ns
FCR	1.42 ± 0.14	1.26 ± 0.02	1.72	ns
Yield (kg m^{-3})	7.37 ± 0.82	6.54 ± 0.59	1.42	ns

Note: ns, not significant ($p > 0.05$)
Abbreviation: FCR, feed conversion rate.

4 | DISCUSSION

4.1 | Water quality of Southern black drum production

The physical-chemical and nutritional conditions of the waters used in the aquaponic crops of this study were compatible with clear water and biofloc aquaculture (Borges, 2009; Holanda et al., 2020; Rodrigues et al., 2011). The CLEAR treatment was characterized by lower nitrate and TSS levels than the BFT treatment. Plant cultivation was initiated in BFT systems when they were already in their mature phase, with high nitrate levels and maintenance of low and non-toxic concentrations of TAN and nitrite for fish (Rodrigues et al., 2007; Sampaio et al., 2010). In both systems, ammonia nitrogen and nitrite are removed through denitrification process, by ammonia-oxidizing bacteria that transform these compounds to their less toxic form: nitrate (Ebeling et al., 2006). In CLEAR treatment units, the nitrification process probably took place in biological films in more oxidized regions of the tanks, while in the BFT system, nitrifying bacteria concentrate in bioflocs (Ebeling et al., 2006).

The nitrate levels in the BFT tanks should not have posed a problem for *P. courbina* growth. A review by Camargo et al. (2005) focused on nitrate toxicity, characterized that more sensitive marine fish can present LC50 (median lethal concentration) of 573 mg N-NO_3 L^{-1}. Phosphate concentrations in both systems (3.14 ± 1.85 mg P-PO4 L^{-1}) were lower than in the culture of the red drum *S. ocellatus* in waters with bioflocs (Poersch et al., 2021) and are not associated with toxicity (Sugiura, 2018).

The other physical–chemical parameters in the waters during the experiment remained within the range tolerated by Southern black drum. Salinity, maintained at an average of 10 g salt L^{-1}, did not prove to be restrictive for the fish. Southern black drum juveniles utilize a variety of estuarine-coastal habitats (Haimovich et al., 2020; Urteaga & Perrota, 2001), and adults are commonly found in waters with salinities ranging from 9–26 g salt L^{-1} (Odell et al., 2017). The average water temperature in the experiment (≈21°C) was below the optimal growth range for Southern black drum juveniles, which, according to Kuroski et al. (2025), was stimulated by increasing the culture temperature from 23°C to 29°C. Water temperature below the optimal range for juvenile fish growth did not markedly affect fish survival. Higher pH and alkalinity values in the BFT than in the CLEAR treatment are the result of specific management (addition of lime). In these systems, pH and alkalinity levels lower than, respectively, 7.0 and 100 mg $CaCO_3$ L^{-1} can decrease the growth of bioflocs (Furtado et al., 2011). In fish, pH levels above 10 or below 5 can lead to the death of the animal due to metabolic stress (Wurts & Durborow, 1992). Dissolved oxygen levels were also not limiting for juvenile culture of black drums, as reported by Poersch et al. (2021), in which presented a weekly weight gain of 11.66 g for the BFT culture of the red drum *Sciaenops ocellatus* under average concentration of 6.24 mg O_2 L^{-1}.

4.2 | Growth and biomass production by halophytes

The physicochemical parameters observed in both cultivation systems remained within the limits of growth conditions for both halophytes (Gonçalves et al., 2024; Pascale et al., 2003; Pinheiro et al., 2020). Although the alkaline pH of the waters is outside the ideal hydroponic range of traditional cultivars, between 6.5 and 7.0 (Tyson et al., 2004), Doncato and Costa (2023b) showed that *A. graveolens* and *S. neei* do not present differences in their growth in cultures with pH values ranging from 5.0 to 7.5. Recently, Rosales-Nieblas et al. (2025) found *Salicornia europaea* very resilient across diverse pH conditions. The average TSS concentrations observed were in the range of values of waters from BFT systems used in previous cultivations of *S. neei* (104–445 mg L^{-1}; Doncato & Costa, 2021; Pinheiro et al., 2020; Poli et al., 2019), which did not show any effect on the development of this plant. On *Batis maritima*, Rafael et al. (2025) also found no difference in the yield using a settling chamber to minimize the TSS, only instability on the biofloc microbiome. No pre-

vious studies of *A. graveolens* cultivation in waters with high solids contents were found. The present experiment is the first to demonstrate the feasibility of cultivating *A. graveolens* with saline waters from BFT systems.

Regarding the plants growth between the systems, *S. neei* and *A. graveolens* achieved higher parameters in waters with bioflocs than in clear waters. It reflects growth limits due to low macronutrient contents and characterizes the tolerance of these species to suspended particulate matter in waters with bioflocs (which clogs the roots). For both species, shoot height was the biometric parameter with the greatest percentage difference between treatments CLEAR and BFT. These results are consistent with the cultivation experiment by Doncato and Costa (2023b), which demonstrated the preference of both species for nitrate as a nitrogen source (compared to ammonia nitrogen), as well as that both halophytes markedly increase their vegetative growth parameters (i.e., branch length, number of branches, shoot, and total biomass) under highly nitrifying nutritional conditions (10–50 mg $N\text{-}NO_3$ L^{-1}), analogous to those found in the current BFT treatment. For example, the highest average number of branches of *S. neei* in the BFT treatment (28.71 branches per plant) was similar to the value obtained for the same species by Doncato and Costa (2023b) of 27.50 branches per plant, in treatments with high levels of dissolved nitrate and phosphate during 28 days of laboratory cultivation. *A. graveolens* plants grown in BFT treatment showed higher shoot height values than those presented by Isnainun et al. (2021), in a 3-month nitrogen fertilization experiment with the same variety of celery (average height, number of leaves, and shoot number per plant were 22.5 cm, 39.2 leaves, and 8.9 shoots). However, growth performance of *A. graveolens* was lower, in both treatments, compared to Palomino-Arroyo (2021), who evaluated plants after 63 days of hydroponic cultivation in fresh water (average height of 58.4 cm and 15.7 shoot per plant). These responses are compatible with Pardossi et al. (1999) findings, in which chlorite ions present in saline media can interfere with nitrate absorption, decreasing ionic balance and biomass in celery plants. The high allocation of biomass to root formation (low allocation to shoots) of *S. neei* and *A. graveolens* in CLEAR treatment constituted morphological plasticity capable of increasing the uptake of limiting nutrients; *S. neei* growth is strongly limited by nitrate levels below 0.2 mg L^{-1} (Doncato & Costa, 2023b). Additionally, the variability in biometric values and biomass production observed between tanks in the BFT treatment can also be associated with differences in the nitrate levels of their water, highlighting the affinity of both species for high levels of this nitrogenous compound.

The present study was developed during the austral spring and *S. neei* reached an average shoot productivity by regrowth (after cutting) of 0.64 kg m^{-2} 30 $days^{-1}$ on floating rafts in BFT waters (0.90 kg m^{-2} after 42 days of cultivation). This value is similar to the studies by Silva et al. (2020) (0.5–0.8 kg m^{-2} 30 $days^{-1}$) and by Gonçalves et al. (2024) (0.19–0.67 kg m^{-2} 30 $days^{-1}$) with the same species in nutrient film technique (NFT) benches irrigated with BFT waters and average nitrate contents ranging between 17 and 100 mg $N\text{-}NO_3$ L^{-1}. However, the highest productivity of *S. neei* is described by Pinheiro et al. (2017) (3.41 kg m^{-2} 30 $days^{-1}$), also in NFT benches irrigated with BFT waters from *Penaeus vannamei* culture, but in a summer cultivation with high air temperatures (27°C–43°C) with an average nitrate availability of 21.4 mg $N\text{-}NO_3$ L^{-1} and high dissolved phosphate content (5.3 mg $P\text{-}PO_4$ L^{-1}). Doncato and Costa (2023b) related the low phosphate input (0.2 mg $P\text{-}PO_4$ L^{-1}) as a growth limiting factor for *S. neei* at nitrate concentrations of >10 mg $N\text{-}NO_3$ L^{-1}. Therefore, factors such as type of aquaponic system, local temperature (Costa & Herrera, 2016), and nutrient availability (Doncato & Costa, 2023b) appear to influence the productivity of *S. neei* achieved in the studies cited above.

The aboveground biomass production of *A. graveolens* in BFT waters at a salinity of 10 g L^{-1} was 0.23 kg m^{-2} 30 $days^{-1}$ (0.44 kg m^{-2} after 56 days of cultivation). This value is approximately 12%–15% of the hydroponic shoot production (on floating rafts) of the same species with fresh water by Abd-Elkaber and Alkharpotly (2016), which use high nitrate contents (waters with 90 and 180 mg $N\text{-}NO_3$ L^{-1} that produced the equivalent of 1.51 and 1.89 kg m^{-2} 30 $days^{-1}$, respectively). *A. graveolens* is a species with rapid growth in the presence of nitrogen, especially nitrate (Doncato & Costa, 2023b), and can demonstrate little loss of productivity when subjected to salinities up to 8.5–10 dS m^{-1} (≈5.7–6.7 g L^{-1}; Pardossi et al., 1999; Pascale et al., 2003). However, at high salinities such as 300 μmol (≈17.5 g NaCl L^{-1}), its growth decreases associated with lower levels of photosynthetic assimilation of CO_2 than plants irrigated with fresh water (Everard et al., 1994). Even showing lower productivity than when irrigated with freshwater, celery plants grown in saline waters (10 g L^{-1}) can be an interesting crop option for agri-aquaculture systems in saline-alkaline soils and coastal areas of Brazil, where its shoot price can reach $3.08 per kg.

Comparative studies between traditional aquaponics in clear and BFT waters are scarce in the literature and concentrated on freshwater crops. Rocha et al. (2017) did not find a significant difference in lettuce (*Lactuca sativa*) aquaponic production on floating rafts between freshwater treatments with and without BFT from catfish culture (*Rhamdia quelen*). In contrast, Pinho et al. (2017) evaluated the aquaponic production of three lettuce varieties (red, butter, and crispy) using floating rafts in freshwater from BFT (after water clarification) and clear water farming of Nile tilapia. After a 23-day cycle, these authors found higher productivity per tank area (27%–118%) for all lettuce varieties in waters with BFT. More recently, Pinho et al. (2021) quantified the production of a butter lettuce variety on a floating raft in waters of Nile tilapia and

observed 13% higher values in waters of BFT system than in clear waters, but only in their first 23-day lettuce cultivation cycle. In the second growth cycle of lettuce, already in the mature phase of biofloc development, lettuce production was lower in BFT than in clear waters. This result was associated with the accumulation of fine particulate matter (settleable solids) in the roots, as well as nutrient input by molasses, high pH and/or distinctive microbial community of the BFT system. Despite variable results in plant development, the above studies emphasized a higher nutrient load in the water and changes in the quality of plant biomass in BFT systems. Maucieri et al. (2020) also discussed the influence of microbiological processes on higher uptake of nutrients by plants in aquaponics when compared to hydroponics. The results of the present aquaponic system demonstrate the adaptability of two halophytes to the high TSS waters of BFT systems, highlighting *A. graveolens* as a novel species for growing in saline biofloc waters.

4.3 | Quality of halophyte biomass

Lower moisture (succulence) of *A. graveolens* in the CLEAR treatment may indicate greater lignification of its shoot in saline medium with low macronutrient concentrations (De Souza et al., 2018). The high succulence of the shoots of *A. graveolens* and *S. neei* (86-88%) is commonly found and constitutes a characteristic of agronomic interest (Ordoñez-Araque & Narváez-Aldáz, 2019; Pardossi et al., 1998). Additionally, average protein content in tissue was higher in *A. graveolens* plants from BFT treatment, subjected to high concentrations of nitrate. Although not inferential, this data corroborates the tendency of this species to rapidly assimilate nitrate and accumulate it in shoot cells, reflecting the concentration of the compound in the irrigation water (Abd-Elkader & Alkharpotly, 2016). Since the determination of total nitrogen by the Kjeldahl method does not discriminate against nitrogen originating from nitrate, much of the nitrogen quantified in celery and considered as crude protein was probably nitrate accumulated in the shoot. Future studies may clarify the nitrogen composition of this species' tissue.

The lipid, ash, and total protein contents of *A. graveolens* grown at 10 g L^{-1} salinity were similar to those cited by Shad et al. (2011), for plants collected in their natural saline habitat in northeastern Pakistan. However, the values of the present crop were above the value ranges cited for specimens consumed in North America, according to the U.S. Department of Agriculture (2019), 0.08%–0.26% lipids per fresh mass (FM), 0.6%–1.04% ash per FM, and 0.19%–0.62% proteins per FM. In the present study, the high ash values in celery can be explained by increased Na^+ and Cl^- ion content in their cells under saline conditions. According to Pascale et al. (2003), the tissue contents of both ions double with an increase in cultivation salinity from 4.4 to 15.7 dS m^{-1} (≈ 3.0 to 10.6 g L^{-1}).

The average lipid (0.30%–0.35% FM ≈ 2.44% and 2.91% DM) and protein (0.71% FM ≈ 5.43% DM) contents observed for *S. neei* are intermediate in relation to previous studies (Bertin et al., 2014; Pinheiro et al., 2020; Riquelme et al., 2016). The ash content of *S. neei* shoots in the tanks with BFT (35.4% DM) was similar to those cited by Riquelme et al. (2016) in Chile (35.7% DM) and Bertin et al. (2014) in Santa Catarina (24.9%–31.4% DM) for *S. neei*. Other *Salicornia* species may even present higher ash values (43%–44% DM) such as *Salicornia fruticosa* and *Salicornia ramosissima* (Custódio et al., 2021). High ash contents in *S. neei* are particularly associated with the accumulation of Na^+ ions in its tissues (Bertin et al., 2014), as a form of adaptation to survive in environments with high salinity.

The ashes of *S. neei* showed high levels of Mg and K, with the latter in greater quantity in plant shoots of the CLEAR treatment. The K, Mg, and Ca contents were similar to those cited for this same variety of *S. neei* (BTH2) cultivated by Doncato and Costa (2023a); however, these values are higher than those found by Bertin et al. (2016) for wild *S. neei* (19.0, 14.0, and 4.0 mg g^{-1}, respectively). These authors also found differences in K levels between plant shoots from marshes and those cultivated with irrigation water from shrimp farms. *S. neei* plants grown in the clear water treatment also presented higher P levels (1.7 times) in their shoots than those from tanks with BFT. The higher alkalinity in the BFT treatment (twice as high as in the clear water treatment) due to the periodic addition of hydrated lime, possibly reduced the availability of phosphorus for the plants in this medium by forming poorly soluble calcium phosphate minerals (Cerozi & Fitzsimmons, 2016). Additionally, Javid et al. (2012) found lower P and K incorporation values for *Brassica juncea* with increasing cultivation alkalinity and salinity. Ventura et al. (2011) also emphasized that differences in the mineral composition of *Salicornia* species occur according to the availability of ions in water or soil. High levels of the elements mentioned above are also observed in other species of the genus *Salicornia* found in Portugal (Custódio et al., 2021) and when supplemented in hydroponic and aquaponic systems (Rosales-Nieblas et al., 2025).

4.4 | Considerations on saline aquaponics economy

Saline aquaponic systems offer many benefits for sustainability, most notably by alleviating food scarcity in arid regions (Spradlin & Saha, 2022). On the other hand, it is a complex, understudied, and costly system (Pinho et al., 2022). The main costs of BFT can include infrastructure, fish feed, fingerlings, specialized labor, and electricity, while inputs such as

molasses and hydrated lime are minor costs (Bezerra et al., 2025; Emerenciano et al., 2025). As Pinho et al. (2021) discussed, the investment to start flocponics can be similar to that for traditional aquaponics, and operational costs will vary with the extension of the land lease. Nevertheless, lettuce production contributed 37%–56% (Pinho et al., 2021) of total revenue in feasible flocponics and aquaponics, respectively. However, Baiyin et al. (2020) reported the costs for power equipment (solar energy), overall material, and labor to surpass the sales revenue of saline aquaponics. Similar results are stated by Babatunde et al. (2023) in small-scale aquaponics, although a more plant-reliable scenario would improve profit. Certainly, the most productive system is yet to be discovered. Cultivating *S. neei* and *A. graveolens* would not be feasible on clear waters with *P. courbina* alone, since the plants did not reach marketing sizes. Cultivated in BFT, though, sea asparagus can profit 19.2€ m^{-2} 30 $days^{-1}$ with the quotation of 3€ by 100 g and celery, although around 30% smaller than the usual marketable size (30 cm; Tavares & Lana, 2020), would reach 0.6€ m^{-2} 30 $days^{-1}$ with the quotation of 2.67€ by kg. Higher productivity from flocponics has the potential to improve sustainability from an economic perspective. But further research is needed to evaluate market viability, profitability, and consumer acceptance of marine aquaponic products (Nair et al., 2025).

4.5 | Performance of Southern black drum in clear waters and with the use of the BFT system

No differences in the survival and growth of *P. courbina* were observed between the CLEAR and BFT treatments. After 18 weeks with an average water temperature of 21°C, fish weight gain was 18.5–21.1 g (≈1.0–1.1 g $week^{-1}$). This growth is similar to the one reported by Kuroski et al. (2025), where Southern black drum juveniles in recirculating waters and an average temperature of 23°C, but lower than the value found by Rossberg and Strawn (1980) of 6.93 g $week^{-1}$, in summer monoculture of *P. courbina* fry. The result of the present study demonstrates the ability of *P. courbina* to grow in waters with high TSS levels from BFT systems. The average TSS concentration in our BFT system was similar to that of the estuarine fish *Mugil liza* (142.1 mg L^{-1}; Holanda et al., 2020), but lower than that of *Oreochrimis niloticus* in freshwater (512.7 mg L^{-1}; Boitrago, 2015). Although biofloc could be added partially as an ingredient in the diet of red drum (Romano et al., 2025), no benefit from the presence of bioflocs was observed for *P. courbina*, unlike herbivorous and omnivorous fish, such as *O. niloticus*, which can use bioflocs as a complementary nutritional source, allowing for less feed use (Azim & Little, 2008; Pinho et al., 2021).

5 | CONCLUSION

The present study demonstrated the feasibility of a coupled aquaponic production of sea asparagus *S. neei* and celery *A. graveolens* in saline aquaponics with waters from black drum *P. courbina* culture. Higher productivity of halophytes was achieved in the BFT system than in clear water, which is associated with greater availability of nitrate and phosphate. Southern black drum showed similar development and productivity between the tested systems, demonstrating the applicability of production set with aquaponics either in clear waters or BFT systems. More studies are needed to approach the economic suitability of the system, especially with plants cultivated in saline BFT.

AUTHOR CONTRIBUTIONS

Larissa M. K. Britz: Data curation; formal analysis; investigation; methodology; visualization; writing—original draft. **Paola P. Guterres**: Data curation; investigation; writing—review and editing. **Isadora Kamphorst**: Data curation; investigation; writing—review and editing. **Cybele Pinheiro**: Data curation; methodology; validation. **Luis Poersch**: Funding acquisition; writing—review and editing. **Marcelo Okamoto**: Data curation; methodology; supervision. **César S. B. Costa**: Conceptualization; funding acquisition; investigation; project administration; supervision; validation; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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