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Oyster grow-out system adapted to environmental stress in tropical estuaries

Abstract – The objective of this work was to evaluate the performance and economic viability of a relocatable floating system compared with the traditional fixed system for cultivating native oysters in estuarine areas of Northeastern Brazil. Two experiments were conducted at the aquaculture park on the north coast of the state of Sergipe. In the first experiment, two farming phases (seed and juvenile) were evaluated in floating and fixed systems, with a focus on growth, survival, and the size-class distribution of the oysters. In the second experiment, the performance of the floating system was compared between shrimp ponds and estuarine areas. The oysters in the floating system exhibited a significantly superior growth and survival in both phases ($p < 0.001$), with a higher frequency in commercial-size classes. The economic analysis indicated that the floating system is financially viable, yielding a better return on investment than the fixed system. Additionally, oysters cultivated in shrimp ponds presented an improved performance ($p < 0.001$), likely due to an increased environmental stability. The obtained results suggest that adaptable floating systems are a promising strategy for resilient oyster farming, particularly in facing climatic and salinity fluctuations in tropical estuarine environments.

Index terms: *Crassostrea gasar*, climate changes, oyster culture, suspended culture.

Sistema de cultivo de ostras adaptado ao estresse ambiental em estuários tropicais

Resumo – O objetivo deste trabalho foi avaliar o desempenho e a viabilidade econômica de um sistema flutuante realocável em comparação ao sistema fixo tradicional para o cultivo de ostras nativas em áreas estuarinas do Nordeste do Brasil. Foram conduzidos dois experimentos no parque aquícola do Litoral Norte do estado de Sergipe. No primeiro experimento, duas fases de cultivo (semente e juvenil) foram avaliadas em sistemas flutuante e fixo, com foco no crescimento, na sobrevivência e na distribuição de classes de tamanho das ostras. No segundo experimento, o desempenho do sistema flutuante foi comparado entre viveiros de camarão e áreas estuarinas. As ostras no sistema flutuante exibiram crescimento e sobrevivência significativamente superiores em ambas as fases ($p < 0,001$), com maior frequência em classes de tamanho comercial. A análise econômica indicou que o sistema flutuante é financeiramente viável, gerando melhor retorno sobre o investimento que o sistema fixo. Além disso, as ostras cultivadas em viveiros de camarão apresentaram melhor desempenho ($p < 0,001$), provavelmente devido ao aumento da estabilidade ambiental. Os resultados obtidos sugerem que sistemas

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flutuantes adaptáveis são uma estratégia promissora para a criação resiliente de ostras, especialmente diante das flutuações climáticas e de salinidade em ambientes estuarinos tropicais.

Termos para indexação: *Crassostrea gasar*, mudanças climáticas, ostreicultura, cultivo suspenso.

Introduction

Aquaculture has been the fastest growing food production sector over the past three decades according to Food and Agriculture Organization of the United Nations (FAO, 2024). On the other hand, the same institution pointed out that fisheries production has not shown a significant growth since the 1990s, in such a way that farmed aquatic animals exceeded captured aquatic animals by volume in 2022. Among the farmed animals, bivalve mollusks account for 20% and 50% of total aquaculture and mariculture production, respectively (FAO, 2024).

The sustainable development of bivalve mollusk farming is a viable solution to the stagnation in fisheries production and to natural stock overexploitation, contributing as a source of income for artisanal fishermen, and to stablish native coastal populations in their traditional environment (BARG, 1992). In Brazil, shellfish production is carried out along the entire coast and has a great socioeconomic importance for coastal communities (Valenti et al., 2021). In the Northern and Northeastern regions, it is mainly based on the *Crassostrea gasar* (Syn. *Crassostrea brasiliiana* or *Crassostrea tulipa*) native oyster, raised in a mangrove estuarine environment using bottom based grow-out systems, mostly made with fixed racks with plastic bags (Litembu et al., 2023).

Estuaries are drowned valley systems that receive water, sediment, and pollutants from fluvial and marine sources, being influenced by tide, waves, fluvial processes, and rainfall regimes (Dalrymple et al., 1992; Maia et al., 2018). The interaction and balance between physicochemical and hydrobiological variables determine estuarine circulation, morphological characteristics, and biota. In this line, changes in the water parameters of estuaries, especially in salinity and temperature, affect their structure, function, and biodiversity (Costa et al., 2022; Zhang et al., 2022), explaining why these environments are among the most threatened by climate change, primarily by

sea-level rise, storms, and alterations in the rainfall regime (Leal Filho et al., 2022).

In view of the influence of salinity on estuaries, El Niño-Southern Oscillation (ENSO) can cause severe impacts on the biota of this ecosystem in the Brazilian Northern and Northeastern regions. During the ENSO warm phase (El Niño), there is a significant decrease in rainfall, and estuarine waters become more saline, while the opposite pattern occurs during the ENSO cold phase (La Niña), when an increase in rainfall patterns reduces water salinity (Valiela et al., 2012; Correia Filho et al., 2019; Costa et al., 2022).

The changes caused in environmental salinity are stressful for marine bivalves, even for species that have a wide salinity tolerance, such as *C. gasar* and *Crassostrea virginica*. For these species, the exposure to low salinities can result in elevated mortality rates, affecting natural populations and aquaculture production (Du et al., 2021; Legat et al., 2021; Tan et al., 2023).

In this scenario, the aquaculture sector must adopt innovative practices and technologies aimed at a sustainable production, taking into account climate changes (Yadav & Metya, 2024). To avoid losses in oyster production during periods of low salinity related to La Niña, in Brazil, Empresa Brasileira de Pesquisa Agropecuária, in partnership with oyster producers from the Torto village in the municipality of Araíoses, in the state of Maranhão, developed a grow-out system to be relocated in situations of environmental stress (Legat et al., 2021). This suspended rack system was shown to be efficient in avoiding mass mortalities during the La Niña period and resulted in a higher productivity than the traditional fixed system, even in years when it did not have to be relocated (Legat et al., 2021).

The objective of this work was to evaluate the performance and economic viability of a relocatable floating system compared with the traditional fixed system for cultivating native oysters in estuarine areas of Northeastern Brazil.

Materials and Methods

The oyster studied was the native species *C. gasar*. Two experiments were conducted at an oyster and shrimp farm in an estuarine area in the aquaculture park in the municipality of Brejo Grande, on the

north coast of the state of Sergipe, Brazil (10°31'58"S, 36°29'13"W). The first experiment (EXP1) was carried out between February and December 2021, and the second (EXP2) between August 2023 and February 2024. EXP1 had two phases: oysters at seed stage (EXP1-P1) and at juvenile stage (EXP1-P2). In both phases, oyster growth and survival were compared between two different grow-out systems: bottom-based fixed rack (FXR), the most common one used by oyster farmers in Brazilian tropical estuarine waters (Litembu et al., 2023); and on-surface relocatable floating rack (RFR), developed and tested between 2017 and 2019, and currently used by oyster farmers in the Torto village (Legat et al., 2021).

The FXR consisted of a rectangle built with 100 mm PVC pipes (2.3×0.7 m), fixed to four PVC poles filled with concrete. The RFR was a rectangle built with galvanized steel tubes (2.3×0.7 m), with a 50 L buoy attached at each corner, anchored with 100 mm PVC pipes filled with concrete. In both systems, plastic oyster mesh bags were tied to the long sides to be kept in a horizontal position.

EXP1-P1 was performed between February and July 2021. The experimental design was completely randomized with two treatments (grow-out systems) and four experimental units represented by oyster mesh bags. In each experimental unit, 1,000 oyster seed (20.5±4.5 mm shell height) were placed in oyster mesh bags with 100 cm of length, 50 cm of width, 5.0 cm of depth, and an initial mesh size of 6.0 mm. After 60 days of farming, the oysters were transferred to bags with a 12 mm mesh size.

EXP1-P2 was carried out between July and December 2021. The experimental design was completely randomized with two treatments (grow-out systems) and three experimental units (oyster mesh bags). A total of 240 juveniles (48.7±5.6 mm shell height) were placed in each oyster mesh bag, whose length, width, depth, and mesh size were 100 cm, 50 cm, 5.0 cm, and 21 mm, respectively. The juveniles were randomly obtained from animals farmed in EXP1-P1 that reached the size class between 40–60 mm.

In EXP2, the growth and survival of *C. gasar* raised in the RFR were compared between two farming sites: an oyster farming area/estuary (EXP2-EST) and a shrimp pond (EXP2-PND). For this, the RFR was redesigned by replacing the galvanized pipes with

40 mm PVC pipes. The shrimp pond was located about 30 m from the EXP2-EST site and was supplied with water from the estuary during high tides, with a partial renewal every 12 hours. The experimental design was completely randomized with two treatments (farming sites) and three experimental units (plastic mesh bags). A total of 900 oyster seed (19.0±4.2 mm shell height) were placed in plastic mesh bags with a length of 100 cm, a width of 50 cm, a depth of 5.0 cm, and a mesh size of 4.0 mm.

EXP1 and EXP2 followed identical procedures for structure handling, growth rate measurement, cumulative survival assessment, and water parameter analysis, differing only in data collection frequency, number of experimental units, and sample size. Handling consisted of cleaning every 15 days during the first two months after initial setup, and, thereafter, every month. Racks and plastic mesh bags were brushed, and fouling organisms were removed using a cleaver. Growth rate was quantified by measuring the increase in oyster shell height throughout the experimental period.

In EXP1, data on shell height were collected monthly by randomly sampling 50 oysters from each experimental unit using a standard manual caliper to the nearest 0.1 mm. This protocol yielded 200 and 150 oysters per month per grow-out system during EXP-P1 and EXP1-P2, respectively. In EXP2, shell height was measured bimonthly by randomly sampling 30 oysters per experimental unit, totaling 90 oysters per grow-out system at each farming site.

Survival data were recorded at: 60 (T60), 90 (T90), 120 (T120), and 150 (T150) days after the initial setup in EXP1-P1; at T30, T60, T90, T120, and T150 in EXP1-P2; and at T60, T120, and T180 in EXP2. Cumulative survival was calculated at each sampling time by subtracting the number of dead oysters from the initial number of oysters, as follows:

$$\text{Survival rate} = (N_t/N_0) \times 100$$

where N_t is the number of live oysters at the time of sampling, and N_0 is the initial number of oysters used to stock each experimental unit.

The results were then expressed as percentages relative to the initial stock at each sampling time. The mean and standard deviation of survival and shell height were calculated for each experimental unit within each grow-out system at every sampling time.

At the end of the experiments, at 150 days for each phase of EXP1 and at 180 days for EXP2, all oysters from each grow-out system were measured, classified into predefined shell-height classes (< 40, 40–50, 50–60, 60–70, 70–80, and 80–90 mm), and quantified.

In EXP1 and EXP2, water salinity and temperature, at a 20 cm depth, were recorded using manual refractometers and thermometers, respectively. Water transparency was assessed with a Secchi disk. In EXP1-P1 and EXP1-P2, these parameters were monitored monthly at the oyster farm in the estuary, whereas in EXP2-EST and EXP2-PND, data were taken bimonthly.

Farm routines were followed during biometric assessments and structural maintenance in order to record data and support information exchange. The staff tested the FXR and RFR structures in order to assess oyster growth and survival under commercial conditions, without the interference of the research team.

Sea level rising in the study area was evaluated using historical satellite imagery from Google Earth (Google, Maxar Technologies, Airbus Data SIO, NOAA, U.S. NAVY, NGA, GEBCO, c2025), while shoreline retreat was quantified in meters using the program's distance measurement tool (Figure 2). A fixed geospatial reference point was established to ensure consistency across temporal comparisons, allowing for the calculation of shoreline displacement over the years.

In EXP1, the economic viability analysis was carried out using the cash-flow method with revenues and expenses of a set of five racks per structure system. The manufacturing, installation, and operating costs of each set were estimated based on the local market prices of material and labor in December 2023. Revenue was estimated from the productivity recorded in EXP1, multiplied by the unit price of oysters sold in the region. Production costs per unit of product were obtained using the values reported by Macedo et al. (2021) for the FXR and RFR. Depreciation was calculated according to the estimated useful life (in years) of each structure system. Inflation and return over capital were set to zero. Over a ten-year horizon, the following financial indicators were calculated: net present value, representing revenues minus costs, both at the present value; internal rate of return, defined as the discount rate that equalizes total costs and total

revenues over the project's horizon; benefit-cost ratio, calculated as the ratio between expected revenues and associated costs; and payback period, representing the time required for cumulative net revenues to recover the initial investment.

The size class approach was used, as it is an effective tool for evaluating oyster growth under different experimental treatments, yielding information that is more detailed and facilitating the identification of growth patterns (Lopes et al., 2013). In fisheries biology, classifying individuals into size classes is widely used to understand growth patterns and population dynamics, complementing traditional analyses and providing insights into the structure and composition of fish communities (Boll et al., 2023).

Survival and growth data (shell height) were assessed for normality by Shapiro-Wilk's test, homogeneity of variance by Levene's test, and independence of residuals by Durbin-Watson's test. When assumptions were met, data were analyzed using the analysis of variance with pairwise comparisons of means performed using Tukey's test ($\alpha=0.05$). For nonparametric data, a two-sample t-test with permutation adjustments for multiple comparisons was applied ($\alpha=0.05$). In EXP1, frequencies of size classes, survival, and growth were compared between grow-out systems (FXR vs. RFR), whereas, in EXP2, survival and growth were compared between farming sites (EST vs. PND) over the study period. All analyses were conducted in the R, version 4.2.1, and RStudio, version 2022.07.0 Build 548, software (Posit Team, 2022).

Results and Discussion

In EXP1, mean shell height ($p<0.001$) was higher for oysters raised in the RFR than for those in the FXR in EXP1-P1, from T30 until T150, and in EXP1-P2, from T90 until T150 (Table 1). Although the farm's staff did not take any biometric measurements or calculate survival rates, they observed the same results for the tested structures.

The oysters farmed in the RFR showed a higher frequency of individuals in larger size classes than those in the FXR in EXP1-P1 and EXP1-P2 ($p<0.001$). In EXP1-P1, oysters in the size classes above 50 mm were more frequent in the RFR (56.9%) than in the FXR (20.0%). In EXP1-P2, oysters in size classes above 60 mm represented 57.8% of oysters

farmed in the RFR and only 14.6% of oysters in the FXR (Figure 1). In studies carried out in the state of Maranhão, Legat et al. (2021) also observed a higher number of individuals in larger size classes in the RFR than in the FXR. Mason et al. (1998) highlighted the importance of determining size classes due to the varying growth rate among farm-raised bivalves of the same age growing under uniform conditions, which can result in higher standard deviation values, indicating a greater dispersion of the data around the mean that may obscure actual growth patterns.

Survival rates were higher for oysters raised in the RFR ($p < 0.001$) than in the FXR in EXP1-P1, with a cumulative survival of 34.5 ± 1.8 and $16.2 \pm 0.8\%$, respectively, after 150 days (Table 2). In EXP1-P2, survival in the RFR remained consistently higher than in the FXR throughout the experiment ($p < 0.001$). At the end of the 150 day farming period, cumulative survival was $41.1 \pm 1.6\%$ for the RFR and $4.5 \pm 1.8\%$ for the FXR.

The highest survival and growth rates and the highest percentages of oysters in larger size classes observed in the RFR were attributed to two key factors: reduced exposure to air and sunlight; and prolonged maintenance in the upper water layer, where phytoplankton are mostly concentrated. While oysters in the FXR were exposed to air during the low tide, those in the RFR remained submerged throughout the entire tidal cycle, except during the lowest astronomical tides in the study area. In the RFR, oysters followed tidal movements and consistently remained 20–30 cm below the surface, precisely within the phytoplankton-enriched layer (Lucas et al., 2009). In contrast, oysters in the FXR, though submerged during high tides, only accessed this productive layer when the water

level approached the height of the culture structures. Since the phytoplankton-rich zone is typically confined to the upper portion of the water column, higher tides can submerge oysters in the FXR below this optimal feeding zone, reducing their food intake. This relationship between improved growth, longer submersion times, and increased feeding opportunities has been previously described by Roegner & Mann (1995).

Air exposure during low tides, especially under high temperature conditions, imposes an additional layer of physiological stress on oysters. Zhang et al. (2006) found that aerial exposure at elevated temperatures induces metabolic depression and compromises cellular integrity, particularly affecting lysosomal membrane stability, which is critical for immune function. According to Zhang et al. (2025), such exposure, especially during hot and dry periods, could lead to dehydration, oxidative stress, and an overall physiological strain, depending on species-specific tolerances.

When accounting for productivity gains and associated costs, including construction, installation, and operation, the RFR showed a clear economic superiority to the FXR across all evaluated indicators. In a ten-year horizon analysis, a 12.5% annual discount rate (minimum attractiveness rate) was applied, corresponding to the mean interest rate of the Brazilian economy in 2024. Under this parameter, the net present value of the FXR was estimated as R\$ 2,140.74, while that of the RFR reached R\$ 30,705.58. In effect, this implies that the RFR could yield a net income approximately 14 times greater than that of the FXR over the same period.

Table 1. Means (standard deviation) and mean test results for the shell height of the *Crassostrea gasar* oyster in six measurement events in experiment 1, in phase 1 (EXP1-P1), from February to July 2021, and in phase 2 (EXP1-P2), from July to December 2021, using the fixed rack (FXR) and relocatable floating rack (RFR) systems⁽¹⁾.

Treatment	Shell height (mm) at days after the initial setup					
	0	30	60	90	120	150
EXP1-P1 RFR	20.5 (4.5)a	32.1 (7.1)a	47.7 (9.1)a	50.0 (11.8)a	55.3 (10.5)a	50.4 (10.6)a
EXP1-P1 FXR	20.5 (4.5)a	23.7 (4.4)b	34.2 (5.4)b	37.8 (6.1)b	38.2 (8.2)b	42.6 (7.6)b
EXP1-P2 RFR	47.2 (4.1)A	51.0 (6.3)A	51.1 (6.3)A	56.7 (7.2)A	57.5 (7.7)A	60.5 (8.4)A
EXP1-P2 FXR	47.2 (4.1)A	48.2 (7.3)A	50.1 (7.3)A	51.8 (7.4)B	50.8 (6.5)B	52.8 (6.5)B

⁽¹⁾Means followed by equal letters, lowercase in phase 1 and uppercase in phase 2 in the same column, do not differ statistically from each other by Tukey's test, at 5% probability.

The RFR exhibited a positive cash flow from its first year of operation, rendering the calculation of the internal rate of return inapplicable. However, the payback period further underscored the economic

advantage of this system: capital recovery occurring in less than one year, whereas the FXR requires approximately 3.15 years to reach the same point. Therefore, the RFR is characterized by low capital

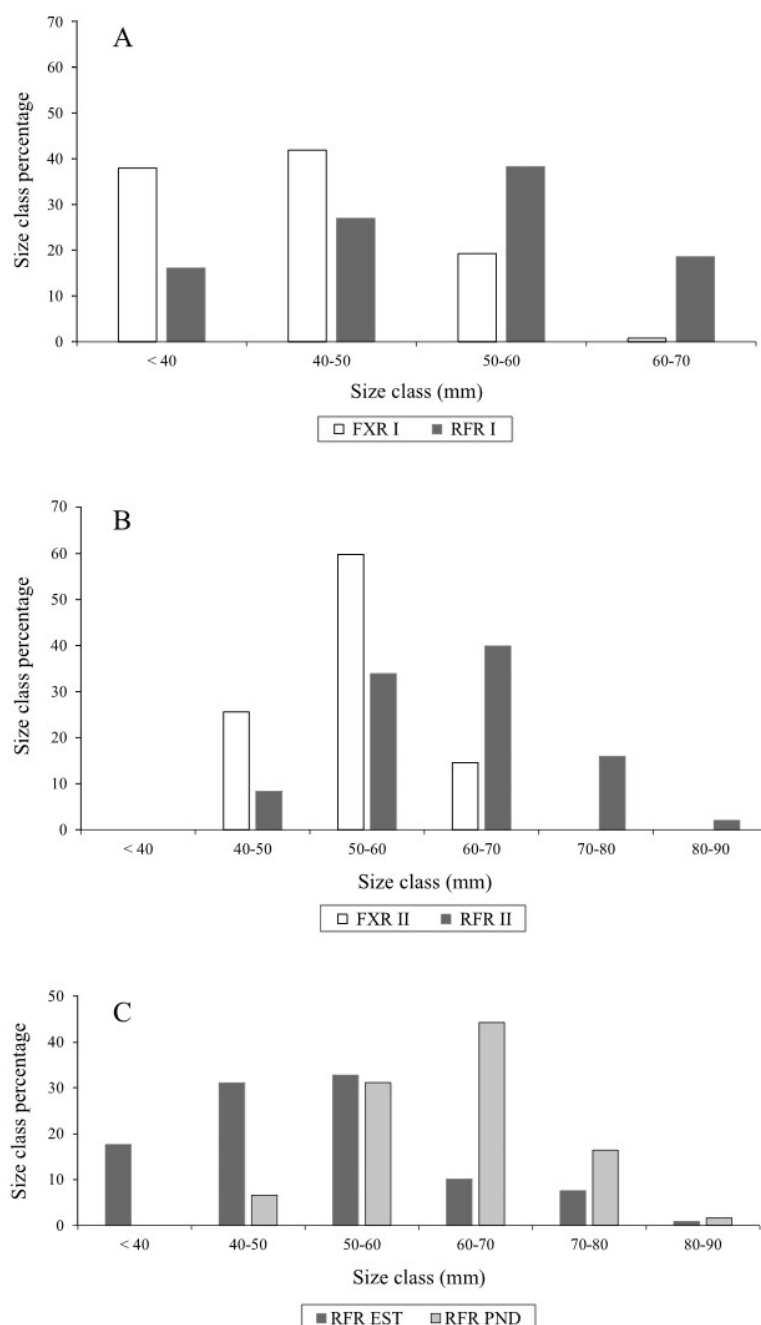


Figure 1. Percentage of the *Crassostrea gasar* oyster by size class in: A, experiment 1, phase 1, using the fixed rack (FXR I) and relocatable floating rack (RFR I) systems; B, experiment 1, phase 2, using the fixed rack (FXR II) and relocatable floating rack (RFR II) systems; and C, experiment 2, using the relocatable floating rack system in estuarine river (RFR EST) and in shrimp pond (RFR PND).

investment requirements, as well as by reduced implementation and maintenance costs, being easily replicable, structurally resilient, and capable of supporting high production yields. This integration of cost reduction and enhanced production efficiency confer to the RFR a significant potential to enhance local income generation, representing a viable alternative that integrates environmental and economic benefits for oyster farming in tropical estuarine areas, particularly in Northern and Northeastern Brazil.

In EXP2-PND, oysters raised in the RFR showed higher survival rates ($p < 0.05$), higher mean shell heights ($p < 0.001$), and higher frequencies in larger size classes ($p < 0.001$) than those raised in the RFR in EXP2-EST (Table 3 and Figure 1). The highest survival and growth rates and the highest percentages of oysters in larger size classes observed in EXP2-PND may be related to a greater stability and food availability inside the pond than in the estuarine site. At the beginning of EXP2, sea level rise breached the post-beach zone, forming an inlet that connected the ocean to the estuary. This new inlet, located

approximately 700 m from the oyster farming area, altered local hydrodynamics by enhancing tidal exchange, which promoted an intrusion that was more saline and increased water transparency.

Increased salinities and water transparencies were observed during sampling in both farming sites in 2023 (Table 4). Between February and December 2021, means of water temperature, salinity, and transparency in the study area were $28.7 \pm 1.3^\circ\text{C}$, 22.0 ± 2.7 , and 21.1 ± 4.4 cm, respectively. After inlet opening, from July 2023 to February 2024, salinity and transparency increased to the respective values of 29.2 ± 2.1 and 37.2 ± 4.6 cm. In the shrimp pond, means of water temperature, salinity, and transparency were $28.4 \pm 2.0^\circ\text{C}$, 31.8 ± 2.7 , and 19.2 ± 1.0 cm, respectively (Table 4).

The observed improvement in water clarity may be attributed to a reduction in phytoplankton biomass (James et al., 2009). Similar phenomena have been documented in previous studies. Suzuki et al. (2002), for instance, reported reductions in chlorophyll a concentration associated with changes in salinity and

Table 2. Means (standard deviation) and mean test results of survival for the *Crassostrea gasar* oyster in six measurement events in experiment 1, in phase 1 (EXP1-P1), from February to July 2021, and in phase 2 (EXP1-P2), from July to December 2021, using the fixed rack (FXR) and relocatable floating rack (RFR) systems⁽¹⁾.

Treatment	Survival (%) at days after the initial setup					
	0	30	60	90	120	150
EXP1-P1 RFR ⁽²⁾	100.0	n/a	80.0 (1.5)a	61.7 (1.8)a	57.7 (0.9)a	34.5 (1.8)a
EXP1-P1 FXR	100.0	n/a	61.0 (2.2)b	31.2 (1.4)b	19.1 (0.9)b	16.2 (0.8)b
EXP1-P2 RFR	100.0	70.8 (1.3)A	63.7 (2.7)A	60.6 (3.5)A	56.8 (3.2)A	41.1 (2.2)A
EXP1-P2 FXR	100.0	61.5 (21.1)B	60.8 (1.8)B	36.4 (1.7)B	14.2 (1.8)B	4.5 (1.5)B

⁽¹⁾Means followed by equal letters, lowercase in phase 1 and uppercase in phase 2 in the same column, do not differ statistically from each other by Tukey's test, at 5% probability. n/a, not available. ⁽²⁾Survival was not assessed at 30 days after initial setup in phase 1 due to large number of seeds in each experimental unit and the small size of the individuals, which prevented an accurate count.

Table 3. Means (standard deviation) and mean test results for shell height and survival of the *Crassostrea gasar* oyster in four measurement events in experiment 2, in estuarine river (EXP2-EST) and shrimp pond (EXP2-PND), using the relocatable floating rack system, from August 2023 to February 2024⁽¹⁾.

Trait	Treatment	Days after the initial setup			
		0	60	120	180
Shell height (mm)	EXP2-EST	19.0 (4.2)a	30.4 (7.9)a	42.5 (10.5)a	45.8 (7.2)a
	EXP2-PND	19.0 (4.2)a	37.9 (6.9)b	54.3 (11.7)b	62.6 (8.2)b
Survival (%)	EXP2-EST	100.0A	67.3 (25.6)A	57.9 (3.6)A	32.7 (11.3)A
	EXP2-PND	100.0A	83.6 (4.1)A	80.8 (2.2)B	68.2 (17.9)B

⁽¹⁾Means followed by equal letters, lowercase for shell height and uppercase for survival in the same column, do not differ statistically from each other by Tukey's test, at 5% probability. n/a, not available.

nutrient mixing during sandbar openings, while Silva et al. (2018) found that water transparency, measured with a Secchi disk, decreased in shrimp ponds as phytoplankton biomass increased. Therefore, changes in estuarine water parameters, particularly in salinity and temperature, can alter estuarine circulation and morphology (Zhang et al., 2022).

Although current velocity was not directly measured due to the high cost of equipment, qualitative observations by the research team, oyster farmers, and local fishermen suggested an increase in this parameter. Considering the inverse relationship between water transparency and phytoplankton biomass, as well as the values recorded in the estuary before and after inlet opening, the increase in salinity and in current velocity may have reduced phytoplankton availability in the estuary, limiting oyster feeding. Conversely, in the shrimp pond, the lower water transparency can reflect a higher phytoplankton concentration, while the minimal influence of currents creates a stable environment that may enhance oyster growth and survival. In this context, in order to support sustainable aquaculture, future studies should investigate the zootechnical performance of oysters and shrimp in polyculture, or in multi-trophic systems with macroalgae.

As observed in EXP2, salinity fluctuations represent a critical environmental stressor in estuarine habitats. Intense rainfall or river discharge events, such as those driven by La Niña-related climate variability in Northeastern Brazil, can drastically reduce salinity levels, whereas extended droughts and pronounced saline intrusions associated with sea level rise can lead to hypersaline conditions. Both extremes may cause a high mortality in oyster populations. Du et al. (2021) documented mass oyster die-offs in Galveston Bay following a prolonged low-salinity exposure. On the other hand, in the present study, routine farm operations revealed a gradual increase in oyster mortality after inlet opening, ranging from 4–10% per mesh bag between March 2021 and June 2023 and from 80–90% by December 2024, indicating mortality associated with an abrupt salinity increase. This pattern is consistent with the physiological effects reported by Tan et al. (2023), who concluded that sudden salinity changes impair osmoregulation and cellular stability in marine bivalves, ultimately affecting their growth and survival. Such osmotic fluctuations under hypo- or hypersaline conditions can destabilize membrane integrity by altering ion gradients and fluidity, disrupting key physiological

Table 4. Seawater temperature, transparency, and salinity for experiment 1 (EXP1) in an estuarine river, from February to December 2021, and for experiment 2 (EXP2) in an estuary (EST) and shrimp pond (PND), from July 2023 to February 2024.

Experiment	Date	Temperature (°C)		Transparency (mm)		Salinity	
EXP1	Feb. 2021	30.0		-		20.0	
	Mar. 2021	30.5		27.0		28.0	
	Apr. 2021	29.7		20.0		25.0	
	May 2021	27.5		18.0		21.0	
	June 2021	28.9		20.0		18.5	
	July 2021	26.4		13.0		20.0	
	Aug. 2021	27.5		27.0		22.0	
	Sept. 2021	27.5		25.0		22.0	
	Oct. 2021	28.7		23.0		24.0	
	Nov. 2021	29.4		18.0		22.5	
	Dec. 2021	28.3		20.0		20.0	
EXP2	Date	EST	PND	EST	PND	EST	PND
	July 2023	25	26	30	18	27	29
	Aug. 2023	26	27	38	20	27	29
	Oct. 2023	27	28	36	20	30	32
	Dec. 2023	29	31	42	18	32	35
	Feb. 2024	28	30	40	20	30	34

processes, including respiration, nutrient absorption, and cell signaling (Parrish, 2013). Therefore, salinity is a key factor influencing the survival and population dynamics of wild and farmed oysters.

Laboratory database records and routine farm observations consistently showed that salinity levels in the shrimp pond are 1.0–2.0 ppm higher than in the estuarine site likely due to water evaporation. Despite this salinity difference, oyster growth and survival rates were higher in the pond than in the estuary. This finding underscores the complexity of environmental factors influencing oyster performance, as well as the need for continuous monitoring of hydrodynamics and water parameters. However, in the Northern and Northeastern regions of Brazil, most farms are small-scale and located in areas of difficult access, making the deployment of in situ instruments for remote data acquisition unfeasible due to the high costs of importing specialized instruments and to the limited availability of suitable devices in the domestic market. This situation restricts the quantity and resolution of research data, requiring the establishment of programs in environmental monitoring, estuarine dynamics, climatic variability, and anthropogenic pressures for

sustainable management, coastal governance, and the planning of aquaculture activities.

The satellite image analysis revealed a steady sea level rise in the study area, with the distance to a fixed reference point decreasing from 396.6 m in 1970 to 287.5 m in 2010, 182.1 m in 2020, and 147.9 m in 2025 (Figure 2). If this trend continues, it may lead to the formation of new inlets, posing a risk to oyster farming and other economic activities developed in the region.

The obtained results show how estuarine ecosystems are highly vulnerable to climate change, including altered precipitation, rising temperatures, acidification, sea-level rise, and increasing salinity (Leal Filho et al., 2022). The intensification of the El Niño and La Niña events is expected, increasing evaporation and reducing freshwater input, with a consequent promotion of hypersalinity in tropical estuaries (Cai et al., 2022). These conditions challenge oyster farming, particularly when using the FXR, which seems to be less suitable for this ecosystem. The use of the RFR may be preferable, as it can be adjusted to tidal regimes and relocated in response to stressors such as hypersalinity or poor water quality, allowing producers to operate in areas that are more favorable. Therefore, to mitigate problems

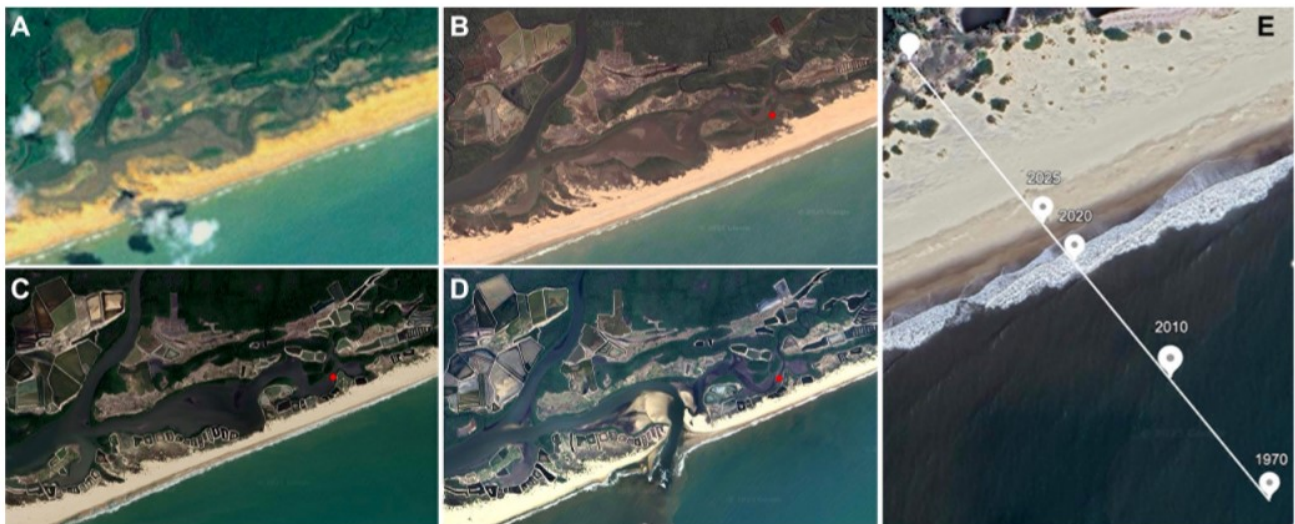


Figure 2. Google Earth's images showing: sea level rising in 1970 (A), 2010 (B), 2020 (C), and 2025 (D) in the coastline of an estuarine area in the municipality of Brejo Grande, in the north coast of the state of Sergipe, Brazil, as well as a perpendicular line from a fixed reference point in the coast to the highest tide lines of previous years (E). The red dot (images B, C, and D) indicates where the study was conducted ($10^{\circ}31'58''\text{S}$, $36^{\circ}29'13''\text{W}$). Source: Map data: Google, Maxar Technologies, Airbus Data SIO, NOAA, U.S. Navy, NGA, GEBCO.

caused by environmental variability, site selection should be optimized and continuous water quality and hydrodynamics monitoring programs should be implemented.

Conclusions

1. The relocatable floating rack (RFR) system for oyster farming proved to be economically viable in tropical estuaries, with low costs, a high productivity, and ease of implementation and replicate.

2. The mobility of the RFR enhances resilience to climate change, supporting stable oyster production in estuarine areas.

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Data availability statement

The data supporting the findings of this study are available in the article. Should any raw data be needed, they will be provided by the corresponding author upon reasonable request.

Declaration of use of AI technologies

During the preparation of this work, the author(s) used ChatGPT (version GPT-4, OpenAI) in order to assist with the revision of the English translation of the text. After this use, the author(s) reviewed and edited the content as needed and take(s) full responsibility for it.

Conflict of interest statement

The authors declare no conflicts of interest.

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