



Evaluating the Adaptation of Tilapia Strains to Brackish Water Conditions for Sustainable Aquaculture in Sub-Saharan Africa

Safiatou Coulibaly ^a, N'zebo Moïse Kouamenan ^{b*},
Ekumou Valeri Akesse ^b, Amenan Marina Kouassi ^{a,c},
Bafétigué Ouattara ^{a,d} and Boua Celestin Atsé ^a

^a Department of Aquaculture, Oceanology Research Center (CRO), BP V 18 Abidjan, Côte d'Ivoire.

^b UFR of Marine Sciences, Polytechnic University of San Pedro, 01 BP 1800, San Pedro 01, Côte d'Ivoire.

^c Laboratory of Hydrobiology and Eco-Technology of Aquatic Systems, UFR of Biosciences, Félix Houphouët-Boigny University, 22 BP 582, Abidjan 22, Côte d'Ivoire.

^d Laboratory of Fundamental and Applied Physics, UFR of Sciences Fundamental Applied, Nangui Abrogoua University, Abidjan 02, Côte d'Ivoire.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

The present study aimed to compare the adaptability of the Bouaké and Brazil strains of *Oreochromis niloticus* to brackish lagoon conditions in order to identify the strain best suited to intensive lagoon aquaculture in Côte d'Ivoire and to contribute to the diversification and optimisation of national and sub-Saharan African aquaculture production. A total of 3,600 fingerlings (initial

*Corresponding author: E-mail: kouamenan.moise@usp.edu.ci;

mean weight: 5 g) were stocked equally in two 600 m² lagoon enclosures and reared for eight months (July 2024 to February 2025). Fish were fed a commercial diet, while water-quality variables and zootechnical indicators were monitored monthly. Salinity increased during the study from approximately 0.08 to 6.88‰, with similar mean values between the enclosures. The Brazil strain showed higher final body weight (603.92 ± 68.30 g vs. 429.38 ± 58.29 g), total length (28.74 ± 0.79 cm vs. 25.06 ± 1.64 cm), daily weight gain (2.50 ± 0.28 g day⁻¹ vs. 1.77 ± 0.24 g day⁻¹), and specific growth rate ($1.99 \pm 0.05\%$ day⁻¹ vs. $1.85 \pm 0.06\%$ day⁻¹) than the Bouaké strain. It also had a lower feed conversion ratio (1.67 vs. 2.47). Conversely, survival was higher in the Bouaké strain ($97.03 \pm 4.17\%$) than in the Brazil strain ($68.23 \pm 10.89\%$), and the Bouaké strain had a higher condition factor. These findings describe contrasting performance profiles under the lagoon conditions tested: the Brazil strain achieved greater growth, whereas the Bouaké strain showed higher survival. However, because the study used only one enclosure per strain and water-quality conditions were not identical between enclosures, the observed differences cannot be attributed solely to strain effects. In addition, salinity increased during the rearing period. Replicated and randomised trials are therefore needed to confirm these results and support strain selection for intensive lagoon aquaculture in Côte d'Ivoire.

Keywords: *Nile tilapia*; *Oreochromis niloticus*; brackish water; Bouaké strain; Brazil strain; lagoon aquaculture; growth performance; survival; feed conversion ratio; sub-Saharan Africa.

1. Introduction

Aquaculture is an essential and emerging strategic sector capable of meeting global food-security demands and contributing to poverty reduction, particularly in low- and middle-income countries. It contributes significantly to multiple socioeconomic and nutritional dimensions in sub-Saharan Africa (Irabor & Begho, 2026). According to the Food and Agriculture Organization (FAO, 2024), the global trade balance of aquatic animal products now exceeds USD 45 billion, surpassing that of many basic agricultural commodities and highlighting the growing economic importance of the sector.

In sub-Saharan Africa, aquaculture production has increased rapidly over the past decades; however, this growth remains uneven and constrained by technical, economic, and environmental limitations (FAO, 2022). In Côte d'Ivoire, several large-scale aquaculture development projects were implemented between 1974 and 1991, covering nearly the entire national territory (Food and Agriculture Organization-AQUASTAT [FAO-AQUASTAT], 2005; FAO, 2008; Ministère de la Production Animale et des Ressources Halieutiques [MIPARH], 2008). These initiatives benefited from an extensive hydrographic network comprising lagoons, rivers, lakes, floodplains, and wetlands, offering substantial potential for inland aquaculture (Lévêque & Paugy, 2006). Nevertheless, successive socio-political crises led to the abandonment of many aquaculture programmes and infrastructures, thereby slowing the sustainable development of the sector.

Over the past decade, the Ivorian government, through the Ministère de la Production Animale et des Ressources Halieutiques (MIRAH), has undertaken renewed efforts to revitalise aquaculture production, notably through the Strategic Development Plan for Livestock, Fisheries and Aquaculture (PSDEPA 2014–2020), followed by the Project for the Improvement of Aquaculture Inputs and Fish Production (2023–2027). Despite these initiatives, national aquaculture production remains insufficient to meet domestic demand. Annual fish consumption in Côte d'Ivoire is estimated at approximately 650,000 tonnes, of which nearly 570,000 tonnes are supplied through imports (Fréchet et al., 2022). This renewed effort underscores the urgent need to diversify local production systems, enhance their productivity, and make better use of available aquatic resources.

Among the farmed species, *Oreochromis niloticus* occupies a central position in aquaculture because of its rapid growth, high fecundity, dietary flexibility, and strong market acceptance (Huang et al., 2024; Bayir et al., 2026). However, pond culture faces increasing limitations related to land availability, rising input costs, and water-resource constraints. In this context, exploiting the adaptive capacity of *O. niloticus* to brackish environments, such as coastal and estuarine lagoons, represents a promising alternative for diversifying production systems and sustainably increasing aquaculture output. The use of these environments requires the selection of fish capable of maintaining their physiological functions and zootechnical performance under saline conditions. Exposure of *O. niloticus* to brackish water represents a major osmoregulatory challenge. Elevated salinity can induce histopathological alterations in the gills, kidneys, liver, and intestines. It can also disrupt ionic homeostasis and water-ion regulation, leading to dehydration or excessive salt accumulation and, consequently, compromising fish health and survival (Damsgaard et al., 2020; Hasan et al., 2023; Hossain et al., 2024). Nevertheless, previous studies have reported that certain tilapia strains reared in brackish water may exhibit enhanced environmental tolerance and improved growth performance (Amon et al., 2013; Gbaï et al., 2014; Moses et al., 2021; Ahmed et al., 2026). Although these studies demonstrate the technical feasibility of tilapia farming in brackish environments, their findings vary according to strain, rearing conditions, salinity levels tested, and the indicators used. Therefore, they are insufficient to identify the strain best suited to the specific ecological conditions of Ivorian lagoons.

Recent studies indicate that the performance of tilapia under saline or brackish-water culture is influenced by both husbandry conditions and genetic background. Feed management and salinity acclimation can affect growth, feed efficiency, survival, and physiological responses (Albahri et al., 2025; Monier et al., 2025; Watanabe, 1988), while strain-specific responses can contribute to differences in salinity adaptation (Nihoreye et al., 2019; Santi et al., 2023; Yu et al., 2025; Yusuf et al., 2026). Selective breeding has therefore been identified as a relevant approach for developing tilapia lines with improved suitability for brackish-water culture (Yue et al., 2024).

In Côte d'Ivoire, comparative studies evaluating the performance of available tilapia strains under lagoon conditions remain limited, particularly those comparing the local Bouaké strain with the Brazil strain. This knowledge gap represents both a scientific and an

operational constraint: without comparative assessments under lagoon conditions, the selection of broodstock and fry is based on limited evidence tailored to the local context.

Accordingly, a direct comparison of the Bouaké and Brazil strains within the Layo lagoon production setting is needed to provide locally relevant evidence for strain selection.

The present study aimed to compare the adaptability of the Bouaké and Brazil strains of *Oreochromis niloticus* to brackish lagoon conditions in order to identify the strain best suited to intensive lagoon aquaculture in Côte d'Ivoire and to contribute to the diversification and optimisation of national and sub-Saharan African aquaculture production.

2. Materials and Methods

2.1 Experimental Phase

The experiment was conducted at the Layo Experimental Aquaculture Station between July 2024 and February 2025. The station is located in the Dabou Department on the northern shore of the Ebrié Lagoon, Côte d'Ivoire. The station currently operates 23 functional lagoon enclosures, including 10 enclosures of 600 m² and 13 enclosures of 200 m², with water depths ranging from 1.20 to 1.45 m. The enclosures are constructed from 14 mm mesh netting and are installed directly within the lagoon. For the present study, two enclosures of 600 m² each were used (Fig. 1). A total of 3,600 *Oreochromis niloticus* fingerlings, with an initial mean weight of 5 g and originating from the Bouaké and Brazil strains, were stocked equally in the two enclosures.

The fish were hand-fed until apparent satiety four times per day during the fingerling stage (10% of total biomass), three times per day during the pre-grow-out phase (5% of total biomass), and twice per day during the grow-out phase (3% of total biomass) using imported commercial feed. Over eight months, temperature, pH, dissolved oxygen, salinity, electrical conductivity, and total dissolved solids (TDS) were determined monthly using a portable multiparameter probe (Hanna Instruments, HI 9828). Monthly control harvests were conducted on 30% of the total number of fish in each enclosure. Individual body weight was measured using an electronic balance (Sartorius; accuracy ± 0.01 g; capacity 1,000 g), and total length was determined using an ichthyometer.

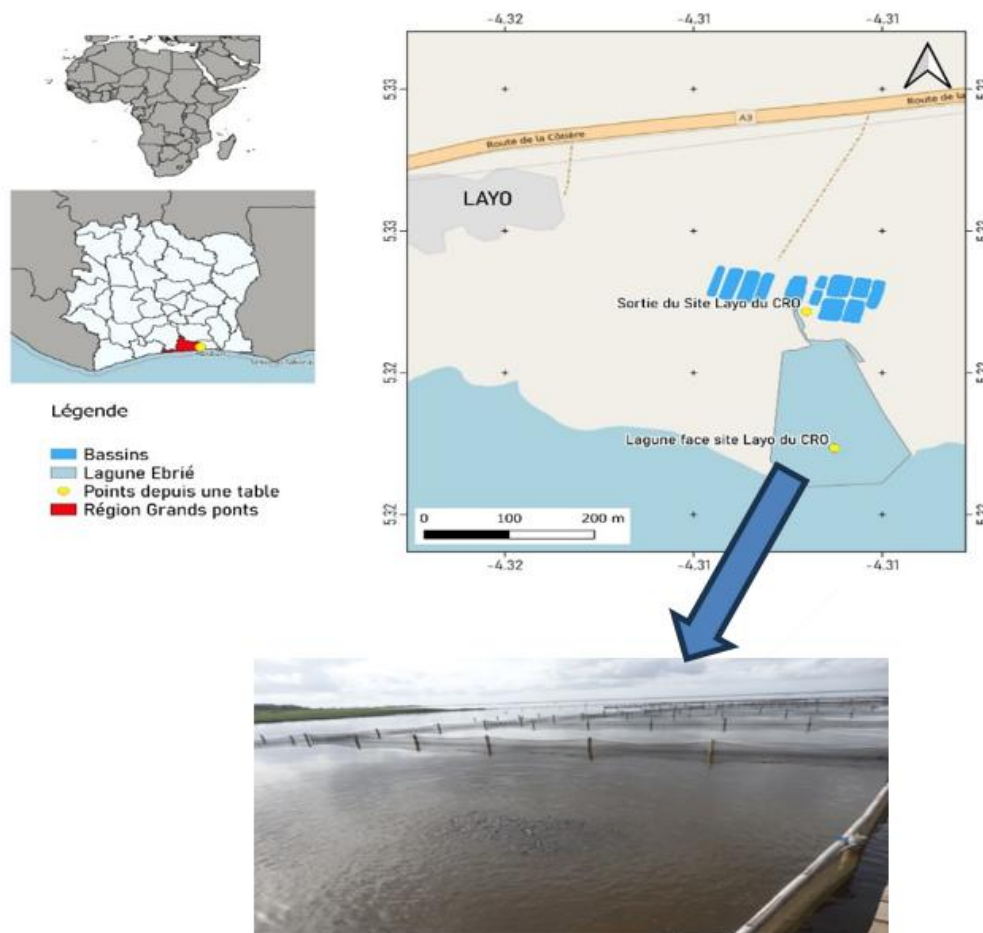


Fig. 1. Location and presentation of the lagoon enclosures at the Layo experimental aquaculture station, Côte d'Ivoire

2.2 Zootechnical Parameters Determined

The zootechnical parameters were determined as follows (Table 1): body weight (BW), average weight gain (AWG), daily weight gain (DWG), total length (TL), specific growth rate (SGR), feed conversion rate (FCR), survival rate (SR), mortality rate (MR), and condition factor (K).

Table 1. Zootechnical parameters and their formulas used to evaluate the performance of two tilapia strains

Growth parameters	Formulas
AWG (g)	[Final weight (g) – Initial weight (g)] (1)
DWG (g day⁻¹)	[Final weight (g) – Initial weight (g)]/ rearing period (in days). (2)
SR (%)	[Number of fish that survived / Total number of fish stocked] x100 (3)
MR (%)	[Number of fish that dead / Total number of fish stocked] x100 (4)
SGR (%day⁻¹)	100x [ln (Final body weight (g)) - ln (Initial body weight (g)) / Rearing period (in days)] (5)
FCR	[Total feed supplied (g) during the rearing period] / [Final weight (g) – Initial weight (g)] (6)
K	[Final weight (g)] / [Total length (cm)] ³ (7)

AWG average weight gain; DWG daily weight gain; TL total length; SGR specific growth rate; FCR feed conversion rate; SR survival rate; MR Mortality rate; K Condition factor

2.3 Statistical Analysis

A one-way analysis of variance (ANOVA) was used to test differences in zootechnical performance parameters between the two tilapia strains. Before the ANOVA, the Shapiro–Wilk normality test was performed to assess data normality. For data that did not meet the normality assumption, the Kruskal–Wallis test (a multiple-comparison test based on ranks) was applied. The significance threshold for the p-value in each test was set at $P = .05$.

Differences were considered significant at $P = .05$. Mean values of physico-chemical parameters and biometric variables, together with their standard deviations, were calculated using STATISTICA software (version 7.1).

2.4 Length–Weight Relationship

Length–weight relationships were established by linear regression analysis following logarithmic transformation of the data. The length–weight relationships of the two tilapia strains were analysed to characterise growth patterns using the power equation:

$$W = aL^b$$

where W is the total body weight (g), L is the total length (cm), a is the intercept (initial growth coefficient), and b is the allometric growth coefficient. The parameters a and b were estimated after logarithmic transformation of the equation:

$$\log W = \log a + b \log L$$

This transformation reduces variability and homogenises the two variables (P_t and L_t). The coefficient b is characteristic of the species and developmental stage (Mayrat, 1970). To determine whether the b values obtained from the linear regressions differed significantly from the isometric value ($b = 3$), the 95% confidence interval (CI) was estimated using Student's t-test (isometric if b is equal or very close to 3; allometric if b differs significantly from 3; negative allometric if $b < 3$; and positive allometric if $b > 3$).

The coefficient of determination R^2 , also derived from the regression line, represents the strength of the relationship between the two morphometric parameters considered. It is always between -1 and +1 (Randriaharimino, 2014). The regression statistics were calculated using Statistica 7.1 software.

3. Results and Discussion

The monthly values and mean concentrations of the physico-chemical parameters recorded in the lagoon enclosures containing the Bouaké and Brazil strains are presented in Table 2. Water temperature during the rearing period ranged monthly from 26.47 to 30.17 °C in both enclosures. Mean temperatures were similar between the Bouaké (28.15 ± 1.12 °C) and Brazil (28.16 ± 1.21 °C) enclosures.

The water pH values in the enclosure stocked with the Brazil strain remained slightly alkaline throughout the experiment. However, the enclosure containing the Brazil strain exhibited a higher mean pH value (7.75 ± 0.08) than the Bouaké enclosure (7.58 ± 0.20 ; $P = .05$). Dissolved oxygen concentrations ranged from 4.22 to 5.62 mg L⁻¹ in the Bouaké enclosure and from 3.12 to 5.34 mg L⁻¹ in the Brazil enclosure, with a lower mean value recorded in the latter (4.26 ± 0.95 mg L⁻¹) than in the former (5.07 ± 0.49 mg L⁻¹).

In both fish-farming enclosures, conductivity values were relatively high and ranged from 1,650 µS cm⁻¹ to 2,700 µS cm⁻¹. Total dissolved solids (TDS) and conductivity followed the same trend in the lagoon water during the culture period. Salinity progressively increased from 0.08‰ to 6.88‰ during the final months of the experiment. Mean salinity values were similar between the Bouaké (2.43 ± 2.67 ‰) and Brazil (2.48 ± 2.67 ‰) enclosures.

Table 2. Monthly values and averages of the physico-chemical parameters of the enclosures containing the Bouaké and Brazil strains

Parameters	Enc	Average	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
Temperature (°C)	Bo	28.15 ±1.12	26.52	27.42	27.87	27.41	28.25	28.45	29.12	30.12
	Br	28.16 ±1.21	26.47	27.31	27.35	27.62	28.30	28.63	29.34	30.17
pH	Bo	7.58±0.20 ^b	7.51	7.42	7.23	7.50	7.66	7.65	7.77	7.87
	Br	7.75±0.08 ^a	7.66	7.77	7.5	7.62	7.75	7.80	7.88	7.78
Dissolved Oxygen (mg/)	Bo	5.07±0.49	5.42	5.62	5.09	5.26	5.12	5.37	4.45	4.22
	Br	4.26±0.95	5.32	5.23	5.34	3.12	3.15	3.57	4.25	4.13
Conductivity (µS/Cm)	Bo	1967.13±404.72	1655	1657	1666	1769	1802	2013	2478	2697
	Br	1975.75±383.28	1651	1656	1712	1799	1836	2032	2475	2645
Salinity (‰)	Bo	2.43±2.67	0.08	0.10	0.11	0.79	2.56	3.25	5.85	6.75
	Br	2.48±2.67	0.09	0.09	0.21	0.80	2.85	3.19	5.74	6.88
TDS (mg/l)	Bo	1198.75±458.71	793	787	798	852	1250	1469	1753	1888
	Br	1213.13±460.54	790	782	833	866	1289	1477	1769	1899

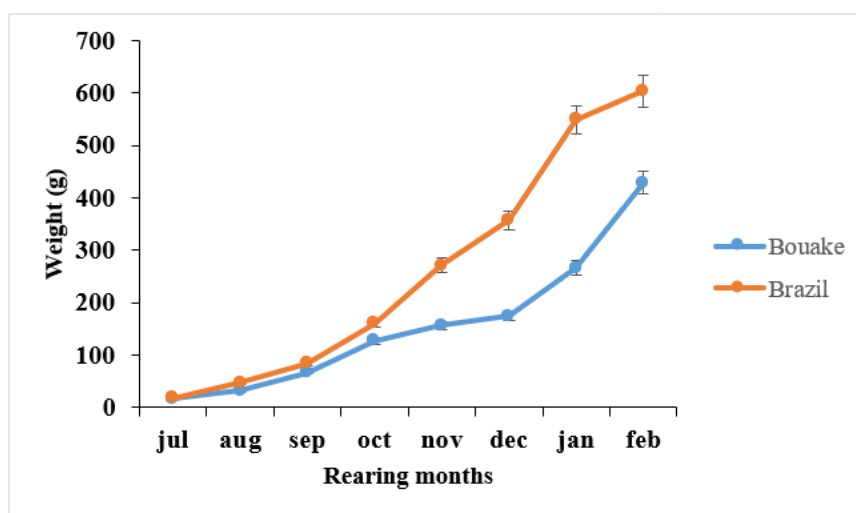
Enc Enclosure containing fish strains; Bo Bouaké strain; Br Brazil strain; jul july; aug august, sep september; oct october; nov november; dec december; jan january; feb february

This study revealed that the physico-chemical parameters recorded in the lagoon enclosures throughout the rearing period were generally within the optimal levels reported for *Oreochromis niloticus* culture. Water temperature (26.5–30.2 °C), pH (7.2–7.9), and dissolved oxygen concentrations (>3 mg L⁻¹) were appropriate for normal metabolic activity, growth, and survival of tilapia (Suresh, 2003; Lazard, 2009). These conditions indicated that the lagoon environment at Layo provided a suitable ecological setting for tilapia culture, despite seasonal fluctuations typical of coastal lagoon systems.

The progressive increase in salinity observed during the culture period reflects the growing marine influence in the Ebrié Lagoon, particularly during the dry season. Salinity values ranging from near freshwater to approximately 6–7‰ remained within the tolerance limits of *O. niloticus*, which is known for its euryhaline capacity (Azevedo *et al.*, 2015; Khanjani & Alizadeh, 2024). Moderate salinity levels may enhance osmoregulatory efficiency and feed utilisation in tilapia, thereby contributing to improved growth performance, as observed in the present study, especially for the Brazil strain. However, significant fluctuations in salinity may disrupt osmoregulatory processes and adversely affect fish health and survival. Elevated salinity levels can disrupt ionic balance, impair water–ion regulation, and lead to dehydration or excessive salt accumulation, thereby negatively affecting fish health and survival (Damsgaard *et al.*, 2020; Ahmed *et al.*, 2026).

The mean body weights of the Bouaké and Brazil strains throughout the rearing period are presented in Fig. 2. Fish of both strains grew continuously during the rearing period. However, the Brazil strain showed higher mean body weights than the Bouaké strain from the early stages of culture, with the differences increasing progressively during the grow-out phase.

Similarly, total length increased steadily in both strains during the eight-month rearing period (Fig. 3). At the end of the experiment, fish from the Brazil strain reached a higher mean total length (28.74 ± 0.79 cm) than those from the Bouaké strain (25.06 ± 1.64 cm).

**Fig. 2. Changes in weight (g) of the Bouaké and Brazil strains as a function of rearing duration (in months)**

Figs. 4 and 5 show the length–weight relationships of *Oreochromis niloticus* reared in lagoon enclosures for the Bouaké and Brazil strains. In both strains, body weight increased as a function of total length, indicating a strong positive relationship between the two

variables. The coefficients of determination were high, with R^2 values of 0.9782 for the Bouaké strain and 0.9869 for the Brazil strain.

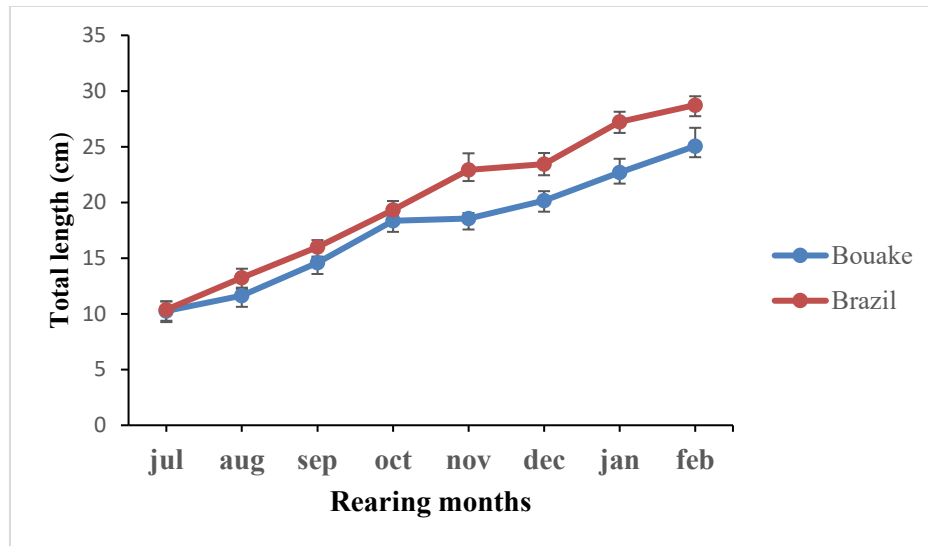


Fig. 3. Changes in total length (cm) of the Bouaké and Brazil strains as a function of rearing duration (in months)

In addition, the t-test showed that fish of both strains exhibited positive allometric growth, with $b > 3$ at $P = .05$. The t-test confirmed that b differed significantly from 3, indicating non-isometric growth patterns.

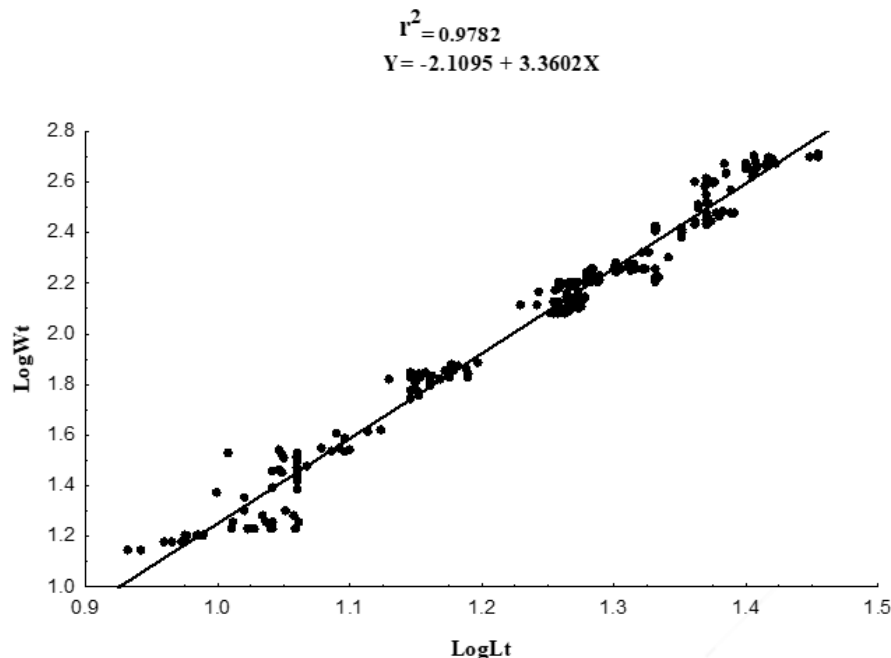


Fig. 4. Length–weight relationship of Bouaké strain

Analysis of the length–weight relationships revealed strong correlations between body length and weight in both strains, with allometric coefficients significantly different from 3, indicating non-isometric growth patterns. Positive allometric growth suggests that weight gain increased proportionally faster than length, particularly in the Brazil strain, reflecting enhanced somatic growth. Similar growth patterns have been reported for *O. niloticus* cultured in productive tropical systems (Asmamaw *et al.*, 2019), supporting the reliability of the observed growth responses. Overall, the contrasting performance profiles observed in this study highlight a clear trade-off between growth efficiency and environmental tolerance. While the Brazil strain offers superior growth and feed conversion efficiency, its lower survival under fluctuating lagoon conditions may limit its suitability in systems lacking strict environmental management. Conversely, the Bouaké strain, although less productive in terms of growth, demonstrates greater resilience and stability, making it a valuable candidate for lagoon aquaculture under less controlled conditions.

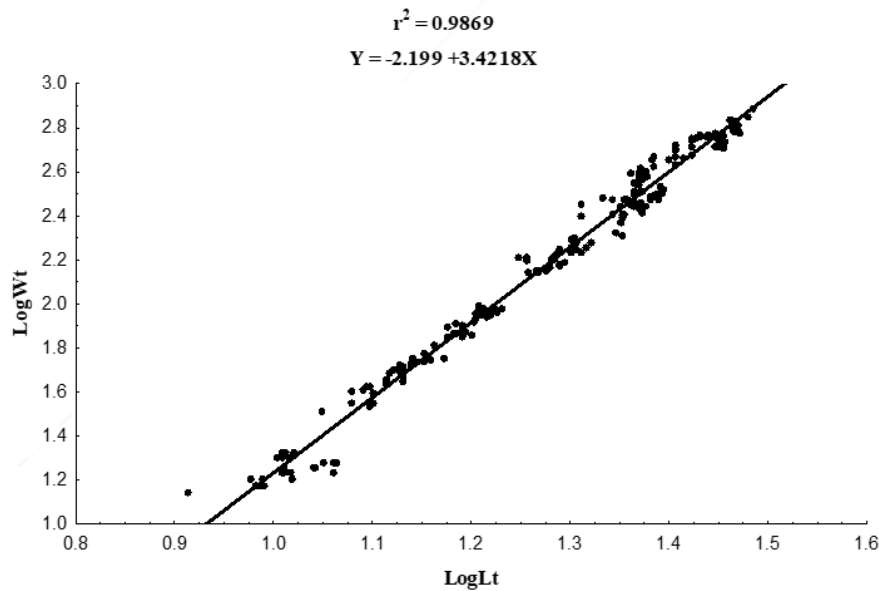


Fig. 5. Length–weight relationship of Brazil strain

The data on initial body weight, final body weight, average weight gain, daily weight gain, specific growth rate, feed conversion ratio, and survival rate are summarised in Table 3.

Table 3. Mean values of Zootechnical parameters of two tilapia strains

Parameters	Strains	
	Bouaké	Brazil
Wi (g)	5.00±0.00	5.00±0.00
Lt (cm)	25.06±1.64 ^b	28.74±0.79 ^a
Wf (g)	429.38±58.29 ^b	603.92±68.30 ^a
AWG (g)	424.38±58.29 ^b	598.92±68.30 ^a
DWG (g/day)	1.77±0.24 ^b	2.50±0.28 ^a
SGR (%/day)	1.85±0.06 ^b	1.99±0.05 ^a
K	2.73±0.30 ^a	2.54±0.19 ^b
FCR	2.47±0.00	1.67±0.00
SR (%)	97.03±4.17 ^a	68.23±10.89 ^b

Wi Initial body weight; Lt Total length; Wf final body weight; AWG Average weight gain; DWG Daily weight gain; SGR Specific growth rate; K Condition factor; FCR: Feed conversion ratio; SR Survival rate. Letters a and b in the same row show differences among strains ($P = .05$.)

Initial body weight was identical in both fish strains (5.00 g), allowing direct comparison of growth performance. Body weight increased from 5.00 g to 603.92 ± 68.30 g in the Brazil strain and from 5.00 g to 429.38 ± 58.29 g in the Bouaké strain. The Brazil strain achieved a significantly higher final body weight than the Bouaké strain ($P < 0.05$). Average weight gain and daily weight gain followed the same trend, with higher values recorded for the Brazil strain (598.92 ± 68.30 g and 2.50 ± 0.28 g/day, respectively) than for the Bouaké strain (424.38 ± 58.29 g and 1.77 ± 0.24 g/day, respectively). Specific growth rate was significantly higher in the Brazil strain (1.99 ± 0.05%/day) than in the Bouaké strain (1.85 ± 0.06%/day). The feed conversion ratio was lower in the Brazil strain (1.67) than in the Bouaké strain (2.47). In contrast, the condition factor was higher in the Bouaké strain (2.73 ± 0.30) than in the Brazil strain (2.54 ± 0.19).

Survival rate differed significantly between the strains ($P = .05$). The Bouaké strain recorded a higher survival rate (97.03 ± 4.17%) than the Brazil strain (68.23 ± 10.89%).

Fig. 6 shows the mortality rates recorded during the experimental period. The mortality rate of the Bouaké strain remained relatively stable and low, with values below the stated acceptable mortality rate of 10%. In contrast, the Brazil strain generally displayed a higher mortality rate, with a peak at the beginning of the rearing period. The mortality rate of the Brazil strain at the end of the rearing period was greater than 10%.

Clear differences in growth performance between the two strains were observed. The Brazil strain exhibited significantly higher final body weight, daily weight gain, and specific growth rate than the Bouaké strain. These results are consistent with previous studies reporting superior growth performance of genetically improved or selected tilapia strains under both freshwater and brackish-water conditions (Moses *et al.*, 2021; Tre Bi *et al.*, 2023). The enhanced growth of the Brazil strain may be attributed to

genetic selection programmes targeting growth rate and feed efficiency, which are known to improve nutrient assimilation and somatic growth.

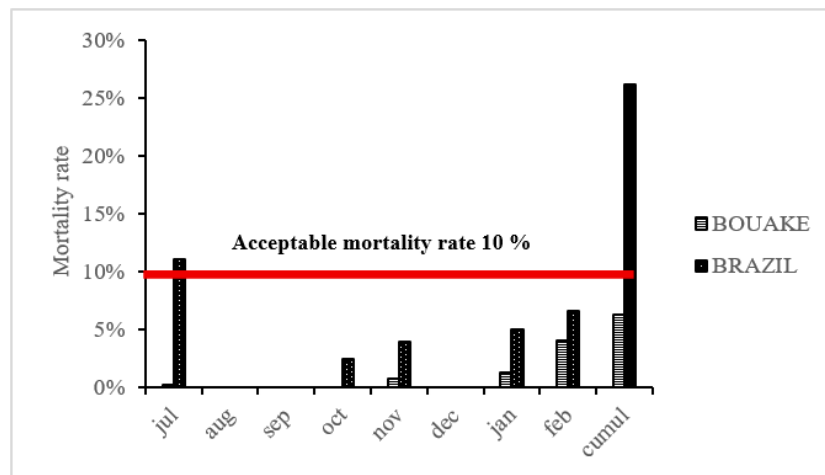


Fig. 6. Mortality rate recorded during the rearing period of *O. niloticus* Bouaké and Brazil strains

Feed conversion ratio values further support this interpretation, as the Brazil strain demonstrated more efficient feed utilisation than the Bouaké strain. Improved feed efficiency is often associated with enhanced metabolic efficiency and growth potential in selected strains (Diabagate *et al.*, 2023). In lagoon-based systems where feed represents a major production cost, such performance advantages are of considerable practical importance.

The higher condition factor observed in the Bouaké strain further supports its better physiological adaptation to lagoon conditions. A higher condition factor generally reflects greater energy reserves and improved resilience to environmental stress (Akongyuure *et al.*, 2015). Although the Bouaké strain exhibited slower growth, its robust survival and stable condition suggest that it may be more suitable for lagoon systems characterised by limited environmental control.

In contrast, survival rates differed markedly between the strains, with the Bouaké strain exhibiting significantly higher survival throughout the rearing period. The higher mortality observed in the Brazil strain may be linked to its lower tolerance to environmental stressors, particularly fluctuations in dissolved oxygen and increasing salinity during the later stages of the experiment. Similar strain-specific sensitivities to environmental variability have been reported in tilapia cultured under suboptimal or fluctuating conditions (Abd El-Hack *et al.*, 2022). The Bouaké strain, originating from local populations, appears to possess greater physiological plasticity and stress tolerance, traits commonly associated with indigenous or non-selected strains adapted to variable environments.

4. Conclusion

Under the conditions of this eight-month study in lagoon enclosures at Layo, the Brazil strain of *Oreochromis niloticus* showed higher final body weight, weight gain, daily weight gain, specific growth rate, and total length, together with a lower feed conversion ratio, than the Bouaké strain. In contrast, the Bouaké strain recorded a higher survival rate and a higher condition factor. These results indicate contrasting production profiles between the two strains under the environmental conditions observed during the study, including salinities ranging from approximately 0.08 to 6.88‰. However, they do not demonstrate differences in genetic potential, physiological adaptation, or sensitivity to specific environmental factors. In particular, because only one enclosure was used per strain and environmental variables were not controlled or systematically monitored, replicated and randomised trials are needed to confirm these patterns and determine the suitability of each strain for intensive brackish-water aquaculture in sub-Saharan Africa.

5. Limitations

These results provide preliminary evidence of the zootechnical feasibility of rearing certain Nile tilapia strains in brackish water. However, optimising this production system will require randomised, replicated trials to confirm these findings and support strain selection. More frequent environmental monitoring and appropriate statistical analyses are also needed to clarify the respective effects of diet, salinity, and their interactions on growth, feed efficiency, condition factor, and survival.

Ethical Statement

All experimental procedures were conducted in accordance with the animal welfare principles of the Oceanographic Research Center (CRO) and international recommendations for the use of fish in scientific research. To minimize handling-related stress, monitoring catches were performed monthly, and handling time was kept to an absolute minimum. All procedures were carried out in a manner designed to minimize stress, injury, and suffering in the fish.

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Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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