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Morphometry, Evidence of Head-Body Length Allometry in Broodstock from Lake Kivu, and Physicochemical Dynamics of Rearing Environments for Optimizing Larval Survival in the African Catfish (*Clarias gariepinus*)

Elie Namegabe Bacirheba[1], Désiré Akonkwa Balagizi[2], Jean-Berckmans Bahananga Muhigwa[2*], Guillain Andanga Machumu[1], Gabriel Mukabo Okito[3]

[1]Kivu Fish Corporation (KFC), Bukavu, Democratic Republic of the Congo
[2]Université Officielle de Bukavu (UOB), Bukavu, Democratic Republic of the Congo
[3]Centre de Recherche et d'enseignement en Hydrobiologie, Pêche-Aquaculture et Toxicologie Environnementale (CREHYPATE) de l'institut Supérieur de Pêche de Goma (ISPÊ-GOMA), Goma, Democratic Republic of the Congo
Email: elienamegabe1996@gmail.com, *jeanbahananga61@gmail.com, guillainmachumu1987@gmail.com, mgokito@gmail.com, akonkwadesire@gmail.com

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Abstract

This study examines broodstock morphometry and hatchery water quality to improve larval performance in *Clarias gariepinus*. It combines morphometric measurements, short-term broodstock conditioning, and physicochemical monitoring during incubation and larval rearing. Sexual dimorphism in broodstock and stable rearing conditions are reported, and it is argued that these factors support better larval survival. Morphometric analyses revealed marked sexual dimorphism: females were heavier and longer (616.67 g; 40.28 cm) than males (582.17 g; 37.72 cm), with a strong correlation between female weight and fecundity. Negative head allometry was observed in males, while females exhibited positive head allometry, suggesting direct implications for growth and broodstock selection. Physicochemical monitoring of the water in the hatchery revealed good stability: an average temperature of 27.3˚C, neutral pH (6.95), high dissolved oxygen (6.42 mg/L), and near-zero levels of ammonia and nitrites. These conditions reduced larval mortality risk, which is often linked to thermal and chemical fluctuations. Statistical correlations confirmed the inverse relationship between temperature and dissolved oxygen, confirming effective control of the rearing system. The results demonstrate that the combination of rigorous morphometric selection of broodstock and strict control of water quality constitutes an effective approach to improving larval survival

and strengthening *Clarias gariepinus* aquaculture.

Keywords

Clarias gariepinus, Morphometry, Allometry, Broodstock, Water Quality, Larval Survival

1. Introduction

In sub-Saharan Africa, rapid population growth is exacerbating food insecurity and animal protein deficits, necessitating a shift to intensive inland aquaculture due to stagnating capture fisheries [1]. In the Democratic Republic of the Congo, specifically in the eastern part of the country, anthropogenic pressures on Lake Kivu necessitate the development of controlled production systems, such as floating cage culture or above-ground tank culture [2]. Among the local fish fauna, the African catfish *Clarias gariepinus* is highly valued commercially in Bukavu and Goma markets [3].

This species possesses major zootechnical advantages: high phenotypic plasticity, broad ecological tolerance, and the ability to survive in hypoxic conditions thanks to an accessory air-breathing organ [4] [5]. However, the expansion of this industry remains hampered by a bottleneck: unpredictable larval mortality in hatcheries, often exceeding 70% during the early stages of development [6] [7].

The success of artificial reproduction depends primarily on the viability of the gametes obtained after hormonal induction [8]. In *Clarias gariepinus*, numerous studies demonstrate that spawning performance (absolute fertility, semen volume, and quality) is closely correlated with the macroscopic morphometric attributes of broodstock, such as body weight, standard length, or condition index [9]. Wild populations inhabiting Lake Kivu and its coastal areas exhibit sexual maturation cycles and phenotypic characteristics shaped by the high-altitude ecosystem [10] [11]. Nevertheless, there is currently no standardized morphometric assessment framework adapted to these local ecotypes. Fish farmers select broodstock based purely on visual and empirical criteria, which results in pronounced and unstable heterogeneity in spawning yields at hatcheries [3].

After hatching, the critical transition phase between yolk sac resorption and the first exogenous feeding is governed by the hydrochemical environment [12]. Mountain streams and rivers in the Lake Kivu basin are characterized by marked temperature gradients and physical variations [13]. The direct use of these waters by artisanal hatcheries in South Kivu, without prior regulation, exposes the larvae to severe microenvironmental instabilities [3]. Water temperature acts as a metabolic switch: relatively cold temperatures slow the rate of yolk assimilation [14], while pH fluctuations alter the toxicity of non-ionized ammonia [7] [15]. These thermal and chemical stresses weaken the larvae, causing them to lose the hydrodynamic energy required to overcome water surface tension or capture moving prey [16], triggering waves of sudden mortality.

The relationship between the morphological traits of wild broodstock from Lake Kivu and their offspring's tolerance to microenvironmental variations remains unexplored. Modeling these functional relationships will help optimize broodstock selection and stabilize fry production in the Democratic Republic of the Congo.

The overall objective of this study was to contribute to food security through the promotion of aquaculture. Specifically, it aimed to 1) determine the morphometric parameters during the growth of broodstock used as donors of pituitary glands, sperm, and oocytes in *Clarias gariepinus*; 2) To evaluate the impact of the physicochemical parameters of the rearing water on the growth and survival of *Clarias gariepinus* larvae.

2. Materials and Methods

Broodstock Sampling

Broodstock sampling was conducted in the coastal areas of the Bukavu Basin on Lake Kivu, among the region's primary artisanal fishing sites. These sites have a natural abundance of adult catfish and offer favorable conditions for their capture and live transfer to the hatchery [13]. This study showed that these coastal habitats, consisting of grassy areas, are particularly conducive to the presence of *Clarias gariepinus*, thereby confirming their strategic role in supplying broodstock for artificial reproduction.

The experimental work was conducted at the hatchery of Kivu Fish Corporation (KFC), located in the Kadutu commune on the grounds of Lycée Wima, at the following geographic coordinates: 20˚30'17.73684"S latitude, longitude E 28˚50'52.23048", and an elevation of 1583 m above sea level. This site was chosen due to its proximity to the fishing areas of Lake Kivu, ensuring the availability of broodstock, and the presence of established infrastructure for artificial reproduction and fish farming.

The experimental trials took place over a three-month period, from January to April 2026, corresponding to part of the rainy season in South Kivu, which is favorable for the natural reproduction of *Clarias* in tropical environments and for the availability of facilities to serve as hatcheries.

2.1. Materials

Biological Materials and Products

Clarias gariepinus fish (males and females) were sourced from Lake Kivu. A 0.9% w/v NaCl physiological saline solution (500 ml) from Shijiazhuang No. 4 Pharmaceutical was used. Cloves, used as an anesthetic prior to surgery, were purchased at the local market. The feed used for the fish (broodstock and larvae) was the Koudijs brand (44% crude protein) with a particle size of 4.0 mm (floating extrudates) for optimal ingestion (Koudijs Animal Nutrition, 2022) and Skretting Perla Larva Pro (62% protein), with the particle size (0.2 mm then 0.3 mm) adapted to the mouth opening of the larvae [17]. Incubation of the fertilized eggs was carried out in circular polyvinyl chloride (PVC) tanks with a capacity of 50 liters. These incubators were equipped with a continuous water exchange system (closed system with physical and biological filtration) to maintain an optimal level of dissolved oxygen. The bottoms of the tanks were fitted with drainage pipes and overflow control valves. A UV lamp was installed on these incubators to ensure that the water was free of microorganisms. The plastic tanks held 200 liters of water for rearing the broodstock. The rearing tanks for *Clarias gariepinus* larvae were made of polyvinyl chloride (PVC) and had a capacity of 20 liters. Equipment included a mini oxygenator for aeration pumps, a siphon hose for removing impurities and dead larvae, nets for collecting broodstock and larvae, microtest tubes for measuring ammonia and nitrite levels, and an OHAUS electronic scale, model: Pioneer PX4201, with an accuracy of 0.1 g for weighing broodstock, feed, and larvae of *Clarias gariepinus.* The incubation rack was used to arrange the eggs in the incubator. A clean towel was used to restrain the *Clarias gariepinus* females before stripping to prevent the mucous membrane from slipping and to avoid handling accidents. Small tanks were available for collecting eggs prior to fertilization.

2.2. Methods

Thirty catfishes were sourced from Lake Kivu on February 21, 2026. Upon arrival, morphometric measurements were taken on the twelve females and eighteen males.

Broodstock Rearing and Water Quality

The broodstock were fed for fourteen days with Koudijs brand feed intended for *Clarias gariepinus* broodstock to promote the development of their oocytes and testes prior to artificial spawning. The feed was distributed three times a day (in the morning at 7:00 a.m., at noon, and in the evening at 6:00 p.m.). Individual identification of the broodstock was achieved by notching the caudal fin using a sterile scalpel. To differentiate between experimental groups, the slit was made either on the upper lobe or on the lower lobe of the caudal fin, using different shapes. This rapid, non-lethal technique enabled precise tracking of live specimens throughout the study [18].

Water quality was rigorously monitored during four key phases: 24 hours before incubation, during the 48-hour incubation period, at hatching (after removal of the chorions), and during the 72-hour period of yolk sac resorption. In accordance with standard protocols for Siluriformes hatcheries [19], the parameters (temperature, pH, dissolved oxygen, and conductivity) were measured three times a day (8:00 a.m., 1:00 p.m., and 6:00 p.m.) before incubation and after hatching. During the critical 48-hour incubation phase, the measurement frequency was increased to six times per day (every 4 hours) to detect any temperature fluctuations or drops in oxygen levels that could affect embryogenesis, in accordance with Haylor's (1991) [20] recommendations on intensive monitoring of early developmental stages in Siluriformes. Electronic devices for in situ hatchery measurements: a multi-parameter meter was used to simultaneously record temperature, pH, and electrical conductivity (EC). At the same time, a digital oximeter was used to measure dissolved oxygen (DO) concentration. Measurements were taken at mid-depth, away from aeration points, to ensure representative data.

Chemical Analyses (Nitrogen): Total ammonia nitrogen was determined using the indophenol method (2-minute reaction time), while nitrate nitrogen was measured via the Griess diazotization reaction (8-minute reaction time). The protocol involved pipetting 5 mL of water for each test, followed by a colorimetric reading using a color chart.

This methodology, combining electronic precision and chemical rigor, complies with international standards for monitoring water quality in aquaculture [15] [21].

Larval Rearing Conditions

The Perla Skretting brand was applied to 50 larvae per 20-liter tank according to the protocol of El-Sayed (2006) [22], characterized by six daily meals during the first fifteen days, then three meals until weaning at 30 days post-hatching. Water monitoring, based on the standards of Boyd (1990) [15] and APHA (2023) [21], was carried out twice daily (07:00 and 18:00) during the 30 days following yolk sac resorption in order to capture thermal and oxygen extremes without stressing the stock. Electronic parameters such as temperature (27.3˚C ± 0.45˚C), pH 6.9 ± 0.18), conductivity (312.4 ± 85.20 $\mu S \cdot cm^{-1}$), and dissolved oxygen (6.4 ± 0.55 $mg \cdot l^{-1}$) were measured using probes at mid-depth, while chemical analyses of nitrogen compounds were performed by colorimetry on 5 ml of water using the indophenol method in two minutes for ammonia (<0.2 $mg \cdot l^{-1}$) and the Griess method in eight minutes for nitrites (0.02 ± 0.01 $mg \cdot l^{-1}$).

Measurement of Morphometric Parameters

Upon the arrival of the fish from their natural habitat, Lake Kivu, on February 21, 2026, morphometric measurements were taken on the twelve females and eighteen males. Subsequently, the males were measured a second time after two weeks—or fourteen days—of rearing, on March 6, 2026, using an ichtyometer. The measurement schedule of broodstock for both sexes before and after conditioning is described here. Zootechnical monitoring and growth evaluation during the nutritional conditioning phase were based on a protocol of exhaustive individual measurements applied to all selected broodstock (18 males and 12 females, *i.e.*, N = 30 individuals). The first morphometric measurements were carried out on February 21, 2026, upon the arrival of broodstock from the natural environment, Lake Kivu. The second measurements were taken on March 6, 2026, *i.e.*, after exactly 14 days of rearing under controlled feeding with Koudijs commercial feed. At each of these two time points, each fish was weighed (total body mass, using an OHAUS precision electronic balance) and measured (total length (TL), standard length (SL), head length (HL), and body height). Growth comparisons before and after 14 days of conditioning were constructed by individual pairing of the historical data of each subject. The specific growth rate was calculated. Temporal variations of morphometric parameters and Fulton's condition factor (K) between February 21 and March 6, 2026 were statistically compared for each sex using the non-parametric Wilcoxon test for paired samples. This rigorous statistical treatment ensures that no repeated temporal measurement was confused with an independent repetition, in perfect accordance with the criteria for body condition assessment defined by Froese (2006) [23] and the maturation dynamics monitored in Clariidae by Viveen *et al.* (1985) [24].

The following parameters were recorded: Standard length (SL): from the tip of the snout to the tip of the caudal peduncle, excluding the caudal fin; Total length (TL): from the tip of the snout to the tip of the caudal fin; Head length (HL): from the tip of the snout to the operculum (the bony plate covering the gills); Maximum body height: the vertical distance between the back and the belly at the widest point; Body weight (W): This is the total mass of the animal, expressed in kilograms (kg) or grams (g). This data was collected periodically using a precision scale to track weight changes; Relative Growth Rate (RGR): This indicator assesses weight gain relative to initial weight over a given period. It reflects the animal's ability to increase its initial mass; Specific Growth Rate (SGR): Represents the percentage increase in weight per day. According to the methodology of [25], it is generally calculated using the following logarithmic formula:

$$\text{SGR} = \frac{\ln\left(W_f\right) - \ln\left(W_i\right)}{t} \times 100,$$

where W_f is the final weight, W_i is the initial weight, and t is the duration of the experiment in days.

Estimation of Absolute Fecundity

Three subsamples of 1 gram (w = 1 g) were taken homogeneously within the mass of eggs collected, then counted to allow calculation of the average. For each individual spawn obtained by gentle abdominal stripping, the total mass of oocytes was weighed using an OHAUS precision electronic balance. Absolute fecundity was estimated by extrapolation via the standardized gravimetric method, following the protocol adapted from [26].

3. Data Analysis

Statistical analyses were performed using R software version 4.5.0. A one-way ANOVA was used to compare survival and growth. Means were compared using Tukey's HSD test ($p < 0.05$). When the data did not follow a normal distribution, a nonparametric Wilcoxon signed-rank test was used. Mann-Kendall trend test was used to evaluate the pattern of chemical changes. The relationship between survival and growth was explored using linear regression models. A Pearson correlation matrix was generated to quantify the relationships between growth parameters (SGR, TCR), condition indices (K), and initial morphometric measurements. PCA was computed to evaluate head-to-body relationships. Weight, TL, SL, HL, and BH (body height) were included to compare allometry in males and in females.

4. Results

Physicochemical Properties of Larval Rearing Water Over 30 Days

The stability of the aquatic environment during the 30-day experiment was monitored through daily measurements of physicochemical parameters, as shown in Table 1.

Table 1. Physicochemical parameters of the water (Day 1 - Day 30; n = 360).

Physicochemical Parameters	Mean ± SD	Optimal values (Clarias)	CV (%)	Target CV (Hatchery)
Temperature (˚C)	27.32 ± 0.45	25 - 30	1.65%	<3%
pH	6.95 ± 0.18	6.5 - 8.5	2.59%	<5%
Dissolved oxygen (mg/L)	6.42 ± 0.55	>5	8.57%	<15%
Total ammonia (mg/L)	<0.2 ± 0.00	<0.5	0.00%	<30%
Nitrites (mg/L)	0.02 ± 0.01	<0.1	50.00%	<50%
Conductivity (μS/cm)	312.4 ± 85.2	150 - 600	27.27%	<15%

Table 1 shows daily monitoring of water parameters during the 30-day fry rearing period and reveals a remarkably stable aquatic environment, perfectly aligned with the physiological requirements of *Clarias gariepinus*. The reliability of these results is based on intensive sampling of 360 individual measurements, ensuring high statistical representativeness. The average temperature (27.32˚C ± 0.45˚C) and pH (6.95 ± 0.18) remained constant and within the optimal growth ranges, thereby preventing any thermal or osmotic stress on the larvae. The maintenance of high dissolved oxygen concentrations (6.42 ± 0.55 mg/L) and near-zero nitrite levels (0.02 ± 0.01 mg/L) indicates good tank hygiene management and effective water exchange. This chemical stability was maintained despite daily feeding with nutrient-rich commercial feed (Perla-Skretting). Total ammonia consistently remained below the detection limit (<0.2 ± 0.00), proving that waste removal and water changes were adequate. Finally, the conductivity (312.4 ± 85.2 uS/cm) confirms a stable mineral balance throughout the experiment.

Physicochemical Properties of Post-Surgery Rearing Water (Days 1 - 10)

Environmental parameters were monitored daily during the post-surgical recovery phase. Table 2 presents the average water quality values, ensuring optimal conditions for the survival of the operated broodstock.

Table 2. Monitoring of physicochemical water parameters (D1 - D10) n = 6.

Parameters	Mean ± SD
Temperature (˚C)	25.75 ± 0.40
pH	7.41 ± 0.39
Conductivity (μS/cm)	187.30 ± 53.71
Nitrites (mg/L)	0.04 ± 0.06
Dissolved oxygen (mg/L)	7.10 ± 0.60

NH_3 levels remained below 0.2 mg/L throughout the 10-day period.

Table 2 shows the monitoring of physicochemical parameters during the ten days following orchidectomy, revealing a remarkably stable aquatic environment. The average temperature of 25.75˚C ± 0.40˚C and the pH close to neutral (7.41 ± 0.39) fall perfectly within the biological comfort zone of the African catfish, thereby limiting any thermal or chemical stress during the critical convalescence phase.

The success of stabilization relies primarily on the excellent oxygenation of the tanks, with an average dissolved oxygen level of 7.10 ± 0.60 mg/L. This high level is a key factor in postoperative survival, as it promotes rapid tissue healing and helps the fish overcome the stress associated with anesthesia and surgery.

Finally, effective control of the organic load is confirmed by extremely low nitrite levels (0.04 ± 0.06 mg/L) and an ammonia level maintained below the threshold of 0.2 mg/L. This water quality, as evidenced by very low standard deviations, demonstrates that the broodstock benefited from a healthy, non-toxic environment, thereby ensuring the absence of infectious complications during the ten-day follow-up period.

The temporal evolution of the physicochemical parameters during the ten-day post-operative monitoring period is presented in Figure 1; it illustrates the overall stability of the rearing environment despite the physiological variations associated with the stabilization phase.

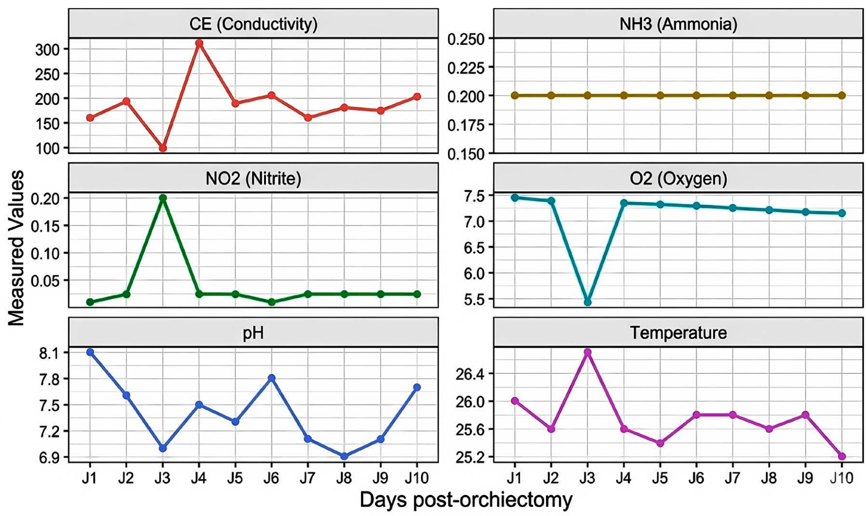

Figure 1. Kinetics of dissolved oxygen and water temperature during the postoperative stabilization phase of the broodstock (D1 - D10).

Figure 1 illustrates the temporal evolution of physicochemical parameters and confirms that the male broodstock were maintained in a stable and secure environment during the ten days following orchidectomy. The graph highlights a major biological event on the third day (D3), marked by a rise in temperature to 26.7˚C, which coincided with a drop in dissolved oxygen to 5.42 mg/L and a peak in nitrite levels at 0.2 mg/L. The responsiveness of the protocol allowed for a rapid return to optimal conditions as early as the fourth day, thereby demonstrating the resilience of the rearing system. Despite these occasional fluctuations, the pH remained within an optimal range with an average of 7.41, preventing any chemical irritation of the surgical wounds, while electrical conductivity remained below the critical threshold of 350 μS/cm. Maintaining oxygen at saturation levels for most of the period, combined with a constant, non-toxic ammonia level of 0.2 mg/L, was critical to the experiment's success. High oxygenation supported active recovery metabolism, which is essential for tissue healing and the survival of all operated individuals.

Pearson's correlation analysis was performed to assess the interdependence of water quality parameters. Figure 2 highlights the statistical relationships between physical and chemical variables, confirming the biological stability of the convalescence environment.

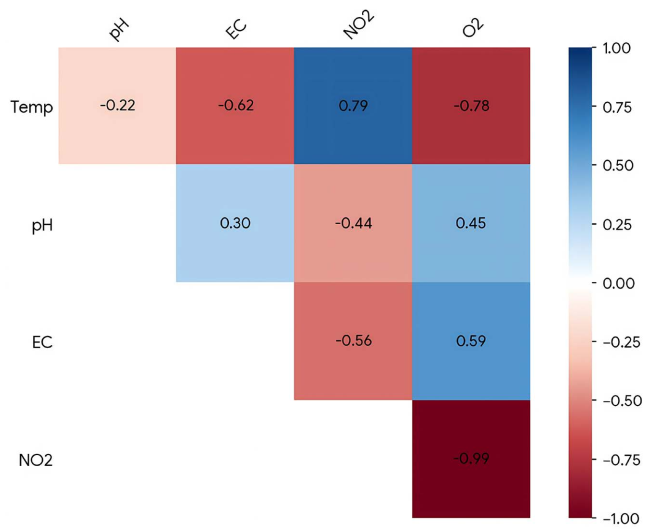

Figure 2. Post-surgery physicochemical correlation matrix.

Figure 2, based on Pearson's correlation analysis, confirms that water quality remained subject to the classical physical laws of hydrobiology during the ten-day follow-up period. In particular, a marked negative correlation is observed between temperature and dissolved oxygen ($r = -0.78$), which statistically confirms the observed drop in oxygen levels observed during the temperature peak on the third day (D3). The higher the temperature rises, the less oxygen the water can hold: this is a natural relationship that was perfectly controlled.

Furthermore, the nearly perfect negative correlation between nitrites and oxygen ($r = -0.99$) is the most significant finding: it proves that the bacteria's consumption of oxygen to break down nitrogenous waste was immediate and effective.

The relationship between water temperature and dissolved oxygen concentration was modeled using linear regression. Figure 3 illustrates the strength of this statistical link and its consistency with the principles of gas solubility in aquatic environments. Figure 3 presents the linear regression and confirms a close, mathematically proven relationship between water temperature and dissolved oxygen levels. The strong negative correlation (r = 0.78) demonstrates that demonstrates that tank oxygenation followed natural physical laws: each increase in temperature mechanically reduces the water's capacity to retain oxygen. This result is highly significant (p = 0.0083), ruling out chance.

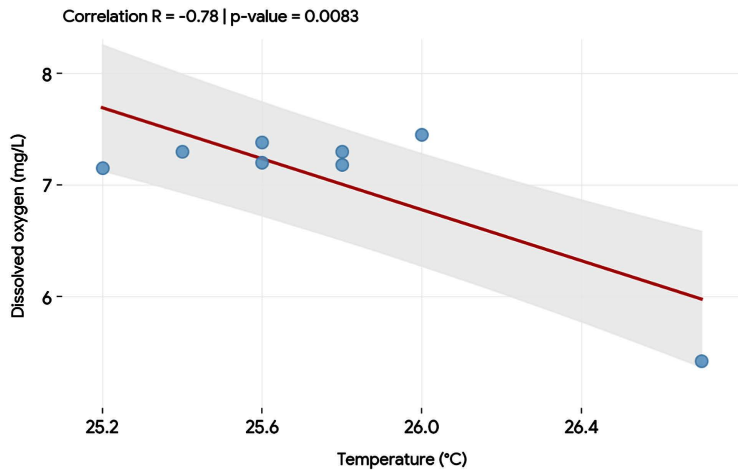

Figure 3. Linear regression (Temperature and Oxygen).

Growth of *Clarias gariepinus* Broodstock

Analysis of growth parameters reveals sexual dimorphism, with females exhibiting a significantly greater overall size and length than males. However, these results show that this difference in weight does not reflect a disparity in growth rate between the two sexes. There is a clear physical difference between the two sexes: females are generally larger than males, as detailed in Table 3.

Table 3. Comparison of broodstock for selected morphometric parameters by sex (independent samples T-test).

Parameters	Female	Male	p-value	Statistical status
TL before 14 days (cm)	39.15 ± 2.86	36.08 ± 1.59	0.0008	Highly significant
TL after 14 days (cm)	40.28 ± 2.70	37.72 ± 1.51	0.0024	Highly significant
SL before 14 days (cm)	8.23 ± 0.09	7.19 ± 0.06	<0.0001	Highly significant
SL after 14 days (cm)	8.55 ± 0.03	7.35 ± 0.03	<0.0001	Highly significant
Weight before 14 days (g)	599.83 ± 55.33	567.11 ± 61.66	0.1496	Not significant
Weight after 14 days (g)	616.67 ± 55.88	582.17 ± 61.06	0.1284	Not significant
Fulton's K index	0.96 ± 0.17	1.08 ± 0.09	0.0175	Significant

Table 3 shows that, at the end of the experiment, they reached an average weight of 616.67 ± 55.88 g and a length of 40.28 ± 2.70 cm, significantly exceeding those of the males (582.17 ± 61.06 g and 37.72 ± 1.51 cm). Females also had longer heads and taller bodies. Looking at the Specific Growth Rate (SGR), both sexes grow at nearly the same rate: 0.2%/day for females versus 0.19%/day for males. Statistically, their growth rates are therefore identical ($p = 0.6648$) for the SGR. As for body condition, the Fulton Condition Index (K) is higher in males (1.08 ± 0.09) than in females (0.96 ± 0.17).

The morphometric parameters of *Clarias gariepinus* reveal a sexual dimorphism. The results presented in **Figure 4** summarize the main variations in body size observed between male and female specimens.

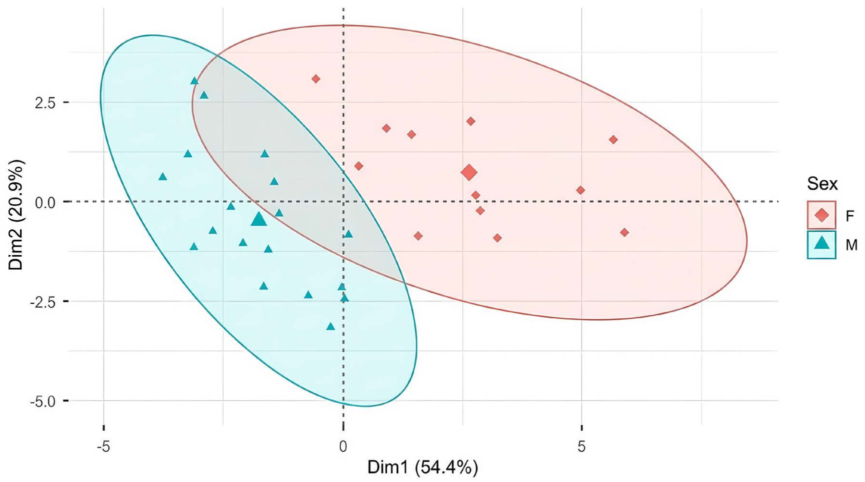

Figure 4. Principal Component Analysis (PCA) showing morphological differentiation between the sexes.

Figure 4 (PCA) visually summarizes the physical differences between male and female *Clarias gariepinus*. With more than 75% of the variability explained by the two axes, this representation accurately reflects our measurements. A separation can be observed between the red points (females) and the blue points (males), indicating marked sexual dimorphism. The horizontal axis, which accounts for 54.4% of the differences, primarily represents the overall body size of the individuals. The concentration of females on the right side of this axis confirms their larger size in terms of weight and length. In contrast, males cluster on the left, reflecting a smaller and more slender appearance.

Figure 5 shows that body size parameters are strongly correlated among females, and are captured by the first component. Growth rates (SGR and Relative) are strongly correlated in the second component and are negatively correlated with head length (LH) thereafter. Thus, growth rates were lower in individuals with longer heads. Similarly, growth rates and head length are, together, negatively correlated with weight (before and after). Furthermore, a lower growth rate is observed in longer individuals (LT and LS). This suggests that larger individuals with greater height and longer heads exhibited slower growth. This may indicate growth inhibition linked to head development or genetic/sexual variation. Pre- and post-growth weights are found in the third component, while pre- and post-height are found in the fourth component, where they are correlated with pre-head height.

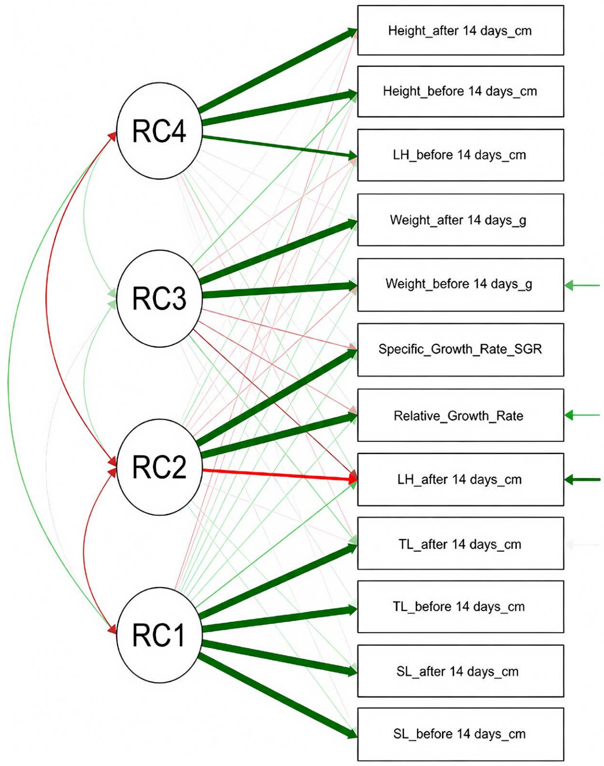

Figure 5. PCA of morphological, weight, and growth parameters in female broodstock.

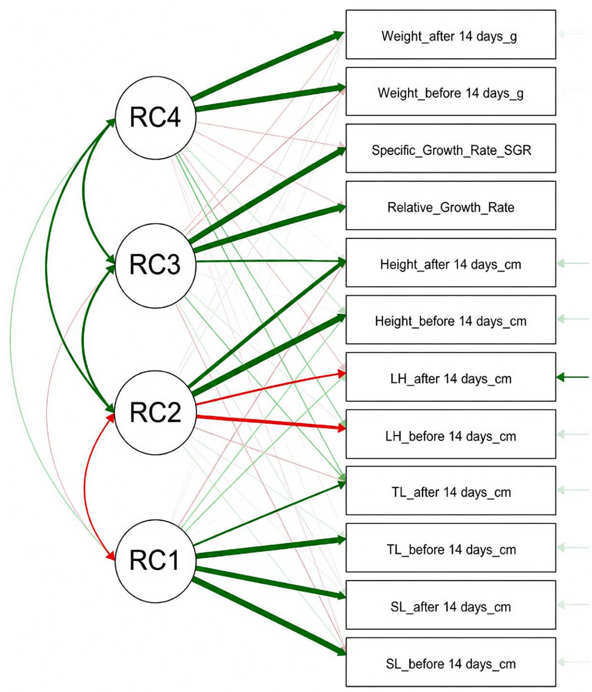

Figure 6. PCA of morphological and weight parameters and growth rates in male broodstock.

Figure 6 shows that in adult males, lengths are found in the first component.

Heights belong to the second component, where they are negatively correlated with head length. Larger males (LT) have shorter heads. A positive correlation is observed between growth rate and weight.

Influence of Female Breeders' Body Weight on Fecundity

The grey area represents the 95% confidence interval. The analysis of spawning performance shows significant variability in oocyte production depending on the size of the fish. The mathematical relationship between the body mass of broodstock and their reproductive investment is formalized and illustrated by Figure 7. The data reveal that absolute fecundity increases linearly with the body condition of females.

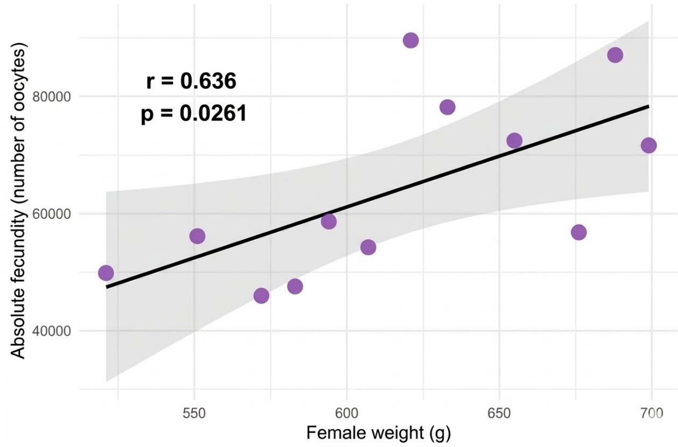

Figure 7. Linear relationship between the body weight of *Clarias gariepinus* broodstock and absolute fecundity (total number of oocytes).

Differential Growth of Broodstock

The size-weight relationship, presented in Table 4, allows us to define the type of isometry specific to our sample.

Table 4. Size-weight relationship and allometric coefficients by sex.

Sex	Coeff. (a)	Slope (b)	R^2	Growth type
F	0.0098	3.05	0.92	Isometric (b ≈ 3)
M	0.0112	2.98	0.89	Isometric (b ≈ 3)

Table 4 presents the size-weight relationship in *Clarias gariepinus* broodstock proves satisfactory growth parameters. For females, the allometric coefficient (b) is 3.05, while for males it is 2.98. These values, being extremely close to the theoretical value of 3, confirm that the studied population exhibits isometric growth.

From a biological perspective, this isometry means that the fish develops harmoniously: its shape and proportions remain constant as it grows. Weight increases in proportion to the cube of length, which indicates excellent overall health.

The robustness of this model is confirmed by the high coefficients of determination (R^2), which are 0.92 for females and 0.89 for males. This indicates that more than 90% of the variation in weight is explained by growth in length. Finally, the condition coefficients (a) obtained (between 0.0098 and 0.0112) are fully consistent with the standards for this species in tropical environments. These results suggest that the broodstock used to optimize artificial reproduction had sufficient energy reserves, a crucial factor for the success of hormonal induction and larval survival.

The interactions between morphometric variables and growth performance indices were analyzed using a correlation matrix. Figure 5 allows us to identify causal relationships or redundancies among the various parameters used to monitor the specimens.

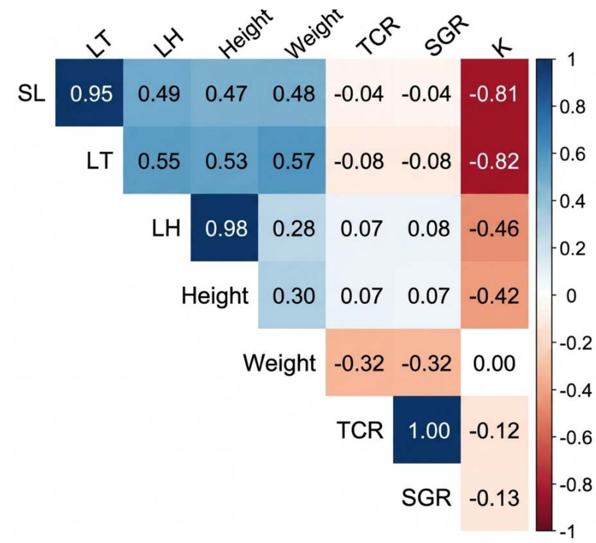

Figure 8. Relationship between morphometry and growth.

Figure 8, which presents the correlation matrix, highlights strong and contrasting relationships between the various morphological and growth parameters. A very high positive correlation (r = 0.95 to 0.98) is observed between length measurements (LS, LT) and body height, confirming consistency in the overall stature of the individuals. The relationship between weight and body dimensions is more moderate (r ≈ 0.5), suggesting variability in mass for similar sizes. A perfect correlation (r = 1.0) exists between the TCR and the SGR, demonstrating that these two indices accurately reflect the exact same growth dynamics over 14 days. Conversely, the K condition index shows marked negative correlations with length (r = −0.82), indicating that the longest fish are proportionally the thinnest. Growth performance (SGR/TCR) appears to be completely independent of the initial morphology of the broodstock, with scores close to zero

Changes in the fish's body condition over the experimental period were assessed using the Wilcoxon signed-rank test. Table 4 presents the statistical comparison of the Fulton condition index (K) between the beginning and end of the monitoring period.

Table 5. Wilcoxon test on changes in body condition.

Parameter being compared	Value of V	p	Interpretation
K Index (Before vs. After)	465	<0.001	Highly significant (***)

Table 5 illustrates the fish body condition between the beginning and end of the experiment. The Wilcoxon signed-rank test reveals a highly significant change ($V = 465$; $p < 0.001$). This very low p demonstrates that the observed change in the Fulton condition index is by no means due to chance, but results directly from the rearing conditions.

This result shows that 14 days of conditioning had a significant positive physiological impact on all of the 30 *Clarias gariepinus* broodstock. The significant increase in the K index indicates an accumulation of energy reserves and excellent adaptation of the fish to captivity following their collection from the natural environment—Lake Kivu.

The average weight gain after 14 days of conditioning was assessed for both sexes. Table 6 presents the weight gain values and the results of the statistical comparison test between males and females.

Table 6. Estimated weight gain over 14 days of broodstock conditioning.

Sex	Average weight gain (g)
Females (F)	16.83 ± 4.58
Males (M)	15.06 ± 5.55

$p = 0.3452$.

Table 6 shows that average weight gain after 14 days of conditioning increased to 16.83 ± 4.58 in females and 15.06 ± 5.55 in males. In the context of mature broodstock, this weight gain, although seemingly modest, is biologically significant.

Statistical analysis shows that the difference in weight gain between the two sexes is not significant ($p = 0.3452$). This result is crucial because it demonstrates that the housing protocol was equally effective for the entire batch: males and females responded with the same metabolic intensity to the rearing conditions.

In females, this weight gain primarily reflects the accumulation of reserves in the oocytes (vitellogenesis), whereas in males, it reflects optimal preparation for spermatogenesis. These findings confirm that the 14-day conditioning period enabled effective metabolic maintenance and adequate preparation for artificial reproduction, with weight gain serving here as a direct indicator of genital maturation.

Survival and Growth of *Clarias gariepinus* Larvae

The final step in validating the protocol is to evaluate the long-term viability of the larvae produced as shown in Figure 9. Figure 9 illustrates that the size parameters and weights of the larvae, as well as their K index are strongly positively correlated in the first component. Larval survival rates on the 10th and 20th days are correlated and are found in the 2nd component. Survival on the 30th day is found as a singleton in the third component. Furthermore, the surgical method and the K index on the 10th day are negatively correlated in the fourth component. Survival rates on days 10 and 20 and on the 30th day were relatively lower among larger individuals (weight and length).

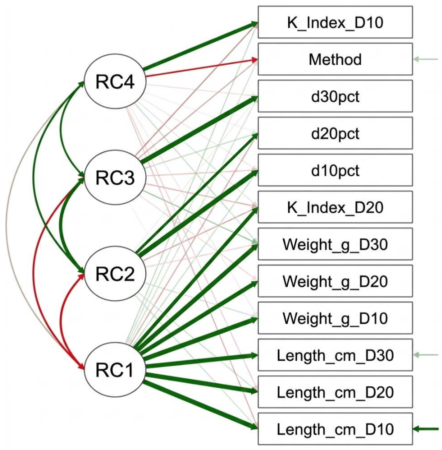

Figure 9. PCA of growth, condition (K), and survival parameters for *Clarias gariepinus* larvae.

Physicochemical Dynamics of the Water: From Incubation to Vitelline Resorption in *Clarias gariepinus* (*D*1 - *D*30)

Figure 10 illustrates good thermal and chemical stability throughout the experimental cycle. Temperature (red curve) follows an ascending linear trend. Temperature and pH during larval growth ranged from 26.58˚C to 28.20˚C, which promoted a gradual acceleration of embryonic and larval metabolism. At the same time, after an initial drop related to induction, the pH (blue curve) stabilized in a slightly acidic range around 6.9. The near absence of error bars (standard deviations) on both curves confirms the perfect homogeneity of the medium across the twelve tanks in the hatchery, ensuring identical developmental conditions for all batches.

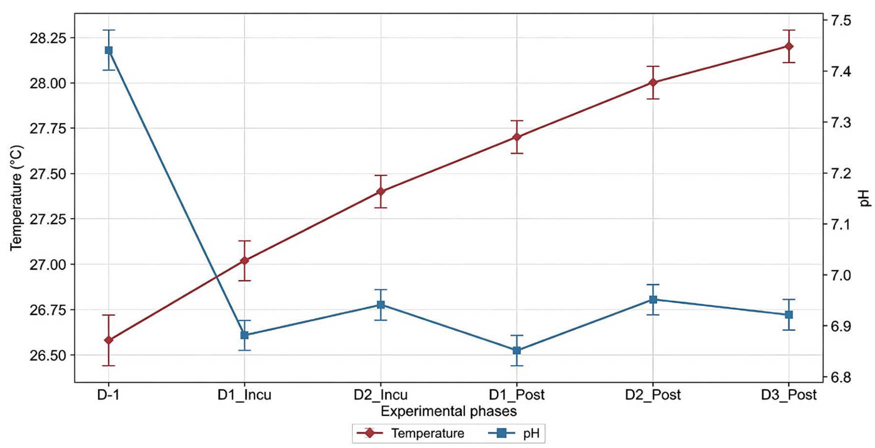

Figure 10. Physicochemical dynamics of the water.

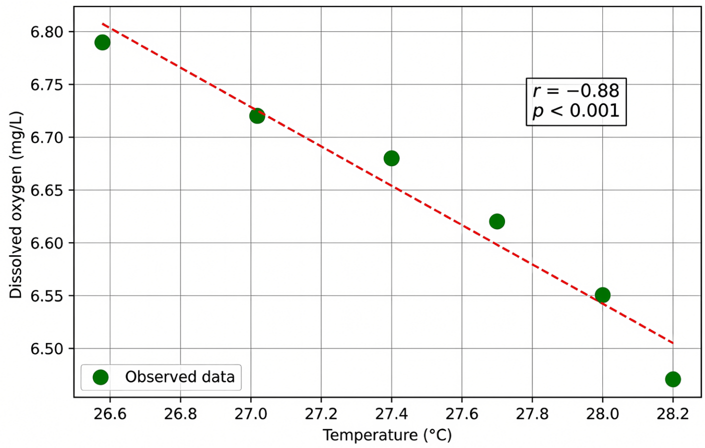

Figure 11. Relationship between temperature and oxygen levels in the incubation water.

Figure 11 highlights a highly significant inverse relationship ($r = -0.88$; $p < 0.001$) between water temperature and dissolved oxygen levels. This strong negative correlation reflects a natural physical phenomenon: as temperature rises, the water's capacity to dissolve oxygen decreases. However, despite this gradual decline caused by rising temperatures, oxygen levels remained well above the critical threshold of 4 mg/L, stabilizing at 6.47 mg/L at the end of the rearing period when the yolk sac was resorbed. These results demonstrate that the aeration system used was sufficient to compensate for the increased respiratory demand of the growing larvae.

The stability of the aquatic environment during the 30-day experiment was monitored through daily measurements of physicochemical parameters as illustrated in **Figure 12**.

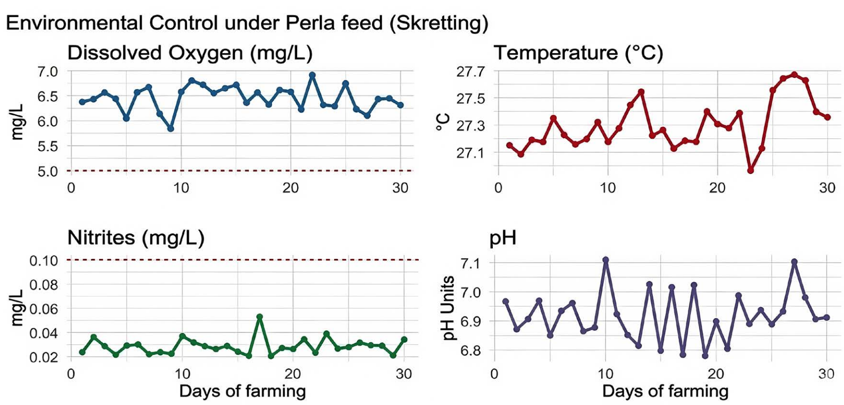

Figure 12. Temporal trends in the physicochemical parameters of the rearing environment (Day 1 - Day 30).

The time-series curves in **Figure 12** provide evidence that the rearing ecosystem was effectively controlled throughout the 30-day experiment. The physicochemical parameters exhibit good linearity, ensuring the absence of any physiological stress for the *Clarias gariepinus* larvae. Dissolved oxygen remained above the critical threshold of 5 mg/L, with values ranging between 5.8 and 6.8 mg/L, while the temperature remained stable within an optimal range of 27.1 to 27.7˚C. At the same time, nitrite concentrations remained negligible and well below the toxicity threshold of 0.1 mg/L, indicating effective management of nitrogenous waste despite the use of a nutrient-rich feed such as Skretting's Perla. The pH also remained balanced around neutral values between 6.8 and 7.1, thus providing a stable ionic environment.

Figure 13 illustrates the trends in tank B1: the temperature, which initially was 27˚C, shows a highly significant upward trend (S: 259; Z: 4.6796; p (no trend): 2.8747E−06) with a curve closely following the logistic model, where K is 28.875 on the 10th day. The steady-state phase extends from the 10th to the 25th day before rising to 29.25˚C on the 30th day. The pH also follows a significant upward trend (S: 329; Z: 5.8519; p (no trend): 4.8611E−09). Initially at 6.6, it rises until the 20th day before fluctuating between pH = 7.2 and 7.2 until the 30th day.

In contrast, oxygen levels decrease significantly in a persistent linear manner (S: −421; Z: −7.51; p (no trend): 5.9134E−14). It ranges from 5.075 to 6.75 on the 30th day. Conductivity also shows a significant upward trend (S: 166; Z: 2.9442; p (no trend): 0.0032375) with an irregular curve. It is highest between 325 and 350 from the 1st to the 7th, electrical conductivity stabilizes at 325 from the 8th to the 16th day, when it drops to a minimum of 100. Subsequently, conductivity rises to 370 on the 25th day. Between the 27th and 30th days, conductivity fluctuates between 225 and 375.

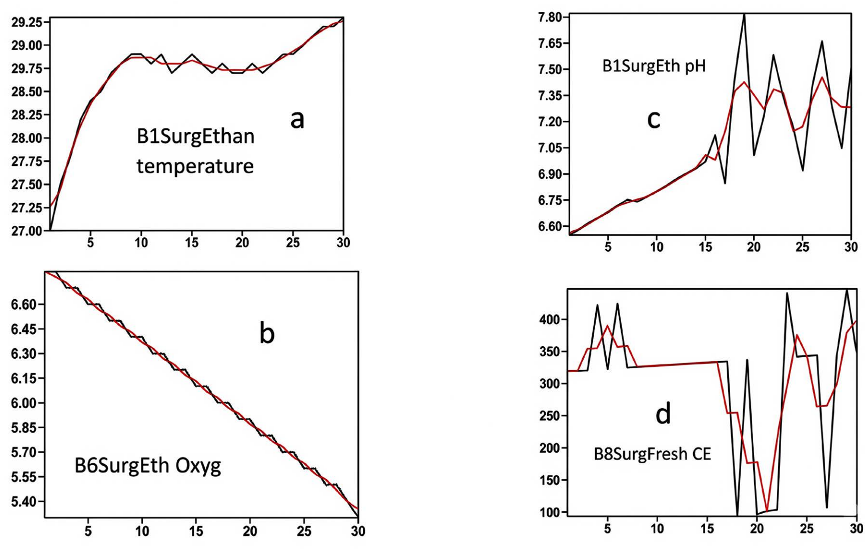

Figure 13. Temporal dynamics and modeling of physicochemical parameters in Unit B1.

Figure 14 shows that the NO_2 curve does not exhibit a significant upward trend (S: 83; Z: 1.5345; p (no trend): 0.12491). The NO_2 concentration is at its lowest from the 1st to the18th day before reaching a peak of 0.08 between the 20th and 24th days, then dropping to 0.03 from the 25th tothe 29thday; it then rises again on the 30th day.

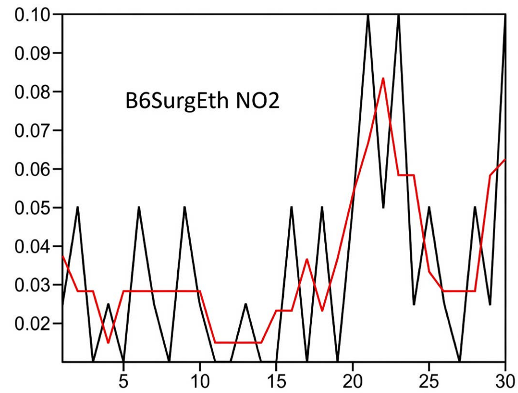

Figure 14. Trends and Stability of Nitrites (NO_2); e. g Tank B6.

Table 7. Correlations between parameters.

Factor Loadings				
	Factor 1	**Factor 2**	**Factor 3**	**Uniqueness**
B1_Chir_EthOxyg	−0.995			0.037
B1_Chir_EthpH	0.868		0.500	0.147
B1_Surgery_EthpH	0.761			0.396
B1_Surgery_EthNO₂		0.727		0.500
B1_Surgery_EthNO₂		−0.652		0.304

Table 7 shows a strong positive correlation between pH and temperature, both of which are negatively correlated with dissolved oxygen. As dissolved oxygen decreases, pH and temperature increase over time during the 30-day larval rearing period. On the other hand, NO_2 is negatively correlated with electrical conductivity, with the two varying inversely.

(a) surgery-ethanol oxygen vs. surgery-ethanol temperature; (b) surgery-ethanol NO_2 vs. surgery-ethanol EC; (c) surgery-ethanol oxygen vs. surgery-ethanol pH with raw data; (d) surgery-ethanol oxygen vs. surgery-ethanol pH with confidence intervals.

Figure 15, which shows interactions among water quality parameters within Unit B1, illustrates strongly correlated environmental dynamics. First, an inversely proportional relationship is observed between temperature and dissolved oxygen: as the temperature rises from 27.0˚C to 29.25˚C, the oxygen level drops significantly, from 6.8 mg/L to less than 5.5 mg/L. This decline in oxygenation becomes particularly pronounced above the 28.5˚C threshold, a range where gas solubility decreases while the metabolic activity of the specimens intensifies.

This drop in oxygen is also correlated with changes in pH. The transition from a slightly acidic environment (pH 6.6) to neutrality (pH 7.1) is accompanied by a rapid, linear reduction in available oxygen. Above a pH of 7.2, the system stabilizes at a low-oxygen plateau, fluctuating between 5.5 and 5.8 mg/L, indicating a phase of precarious equilibrium between biological respiration and gas exchange.

Finally, the dynamics of nitrogen compounds, illustrated by the relationship between electrical conductivity (EC) and nitrites (NO_2), show that the environment stabilizes over time.

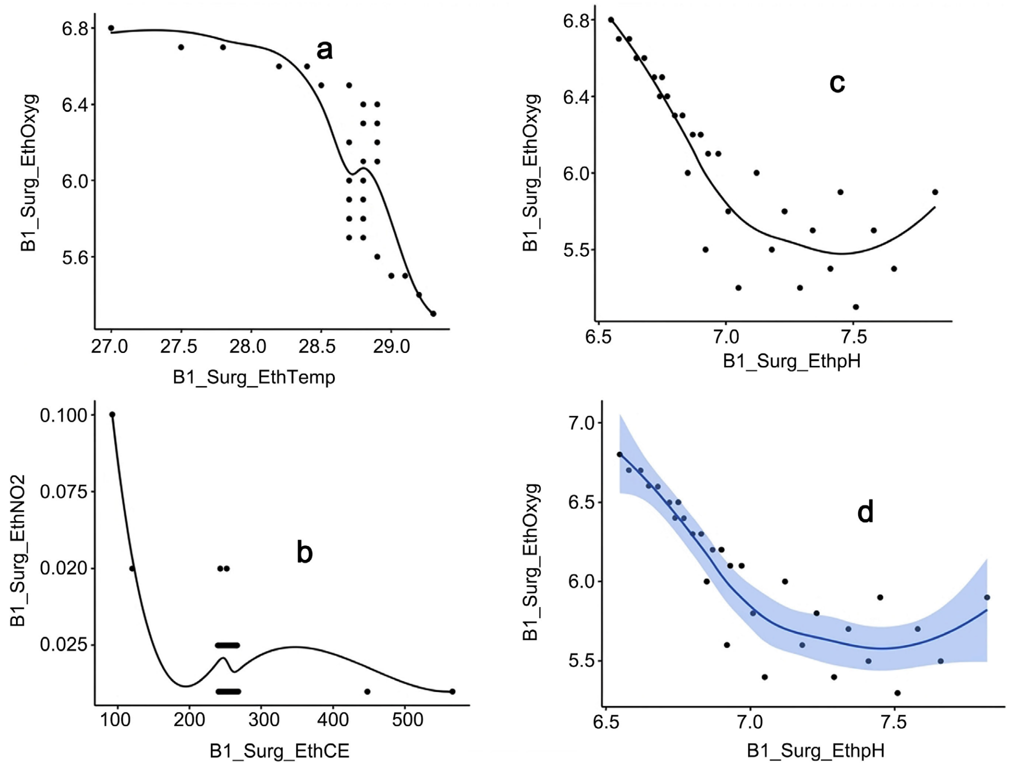

Figure 15. Dynamics of physicochemical interactions within the rearing system. E.g Tank B1.

Nitrites peaks (0.100 mg/L) are observed only during phases of low mineralization (<150 µS/cm). As conductivity increases and stabilizes between 250 and 500 µS/cm, nitrite concentrations drop below the threshold of 0.025 mg/L. This trend confirms the effectiveness of the nitrification cycle in the tank, maintaining nitrites at non-toxic levels despite the increase in mineral load.

Table 8. Inter-factor correlation matrix derived from Principal Component Analysis (PCA).

Factor Correlations			
	Factor 1	**Factor 2**	**Factor 3**
Factor 1	1.000	−0.078	−0.187
Factor 2	−0.078	1.000	0.388
Factor 3	−0.187	0.388	1.000

Table 8 shows the correlation matrix between the factors, indicating that Factor 1 is largely independent of the other dimensions ($r < 0.20$). In contrast, a moderate positive correlation ($r = 0.388$) is observed between Factor 2 and Factor 3, suggesting a slight interdependence of the biological or physicochemical processes

they represent.

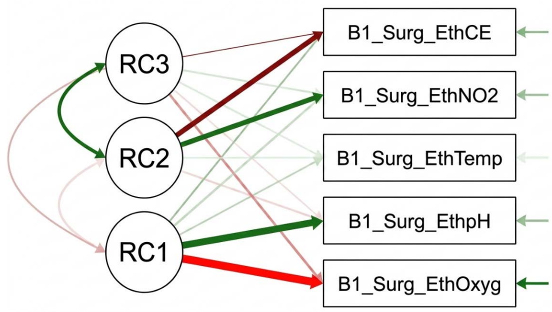

Figure 16. Factor saturation diagram (Path Diagram) of the physicochemical parameters of tank B1.

Figure 16 shows the factorial diagram that organizes the parameters into three major components. RC1 highlights the critical antagonism between environmental warming (Temperature/pH) and the availability of oxygen. RC2 characterizes the dynamics of the nitrogen cycle, highlighting the relationship between water mineralization and nitrite reduction. This framework confirms that oxygen management and the monitoring of nitrogen compounds are two distinct yet complementary pillars of aquaculture environment monitoring.

Relationships between Dissolved Oxygen and Final Weight of Fry (D30)

The interaction between the respiratory conditions of the environment and the weight gain of the larvae was explored through a correlation analysis. Figure 17 illustrates the relationship between dissolved oxygen availability and the final weight reached by the specimens at the end of the 30-day experiment.

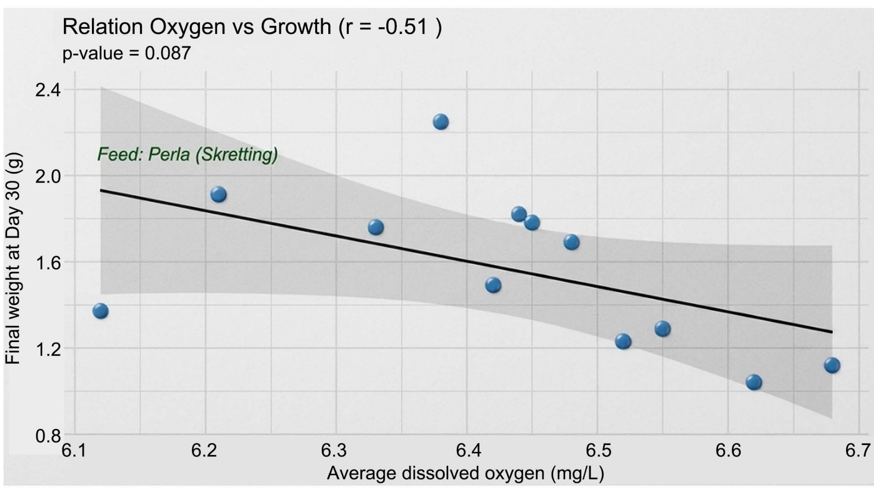

Figure 17. Correlation between the average dissolved oxygen concentration and the weight gain of *Clarias gariepinus* larvae at Day 30.

Figure 17 shows a moderate negative correlation ($r = -0.51$) between average dissolved oxygen and the final weight of the larvae at Day 30. Despite a $p = 0.087$, a metabolic phenomenon related to the use of the high-energy Perla feed (Skretting) is highlighted. The tanks with the highest individual weights (reaching 2.25 g) are those where the dissolved oxygen content is slightly lower. This result does not indicate a deficiency in the environment, since all values remain optimal (above 6.1 mg/L), but is explained by the increased oxygen consumption of the most vigorous larvae. Rapid growth leads to intense respiratory metabolism to convert feed into biomass, which tends to slightly reduce the available oxygen in the most productive tanks.

5. Discussion

Physicochemical Balance and Biosecurity

The success of a fry-rearing cycle for *Clarias gariepinus* depends on a synergy between the stability of the aquatic ecosystem and nutritional precision. Our results show that temperature (27.32˚C ± 0.45˚C) and pH (6.95 ± 0.18) were ideally centered within the optimal growth ranges. This consistency is in line with the recommendations of Boyd (2015) [27], who emphasizes that for catfish, temperature fluctuations of less than 2˚C per day are essential to prevent metabolic stress. The absence of thermal stress in our study is confirmed by the low coefficient of variation (1.65%), ensuring a safe environment for the larvae from day one.

Management of dissolved oxygen (6.42 ± 0.55 mg/L) was a key factor in biosecurity. Although we observed an expected negative correlation between temperature and oxygen ($r = -0.78$; $p = 0.0083$), oxygen levels remained consistently above the critical threshold of 5 mg/L. Maintaining this level is crucial because, as de Graaf and Janssen (1996) [6] note in the FAO technical manual, a drop in oxygen below 3 mg/L in young *Clarias gariepinus* larvae inhibits appetite and promotes the onset of opportunistic diseases. In our case, the high oxygenation levels supported an intense growth metabolism, as illustrated by an exceptional Specific Growth Rate (SGR) exceeding 21% per day.

Chemical biosecurity was characterized by rigorous control of nitrogenous waste. Nitrite levels (0.02 ± 0.01 mg/L) and ammonia levels maintained below the detection limit (<0.2 mg/L) attest to effective management of tank hygiene. This performance is linked to the high nutrient input via the Perla commercial feed (Skretting). Our observations corroborate the work of Viveen *et al.* (1985) [24], who emphasize that daily removal of uneaten feed and feces is key to larval survival in intensive systems. The nearly perfect negative correlation between nitrites and oxygen ($r = -0.99$) observed demonstrates that the bacterial nitrification process was active and immediate, preventing any toxicity. Finally, the stable conductivity (312.4 µS/cm) confirms a balanced mineral environment, which is essential for the osmoregulation of the fry.

Dynamics of Physicochemical Parameters during Incubation and the Larval Phase

The temperature in our study followed a gradual and controlled increase from 26.58˚C ± 0.14˚C to 28.2˚C ± 0.09˚C. This upward trend is fully consistent with the recommendations of Viveen *et al.* (1985) [24] and has been validated more recently by numerous studies, such as that of Marimuthu *et al.* (2019) [7], which emphasize that a stable temperature between 27˚C and 29˚C accelerates embryonic metabolism without causing any malformation. The very low coefficient of variation (CV < 0.5%) indicates a level of thermal homogeneity rarely seen in small-scale hatcheries, eliminating any stress associated with thermal shocks.

At the same time, the pH remained stable at around 6.92 ± 0.03, a value close to neutral. As noted by Ndome *et al.* (2011) [28], a pH between 6.5 and 8.0 is ideal for the survival of African catfish larvae. This stability is crucial because, as Boyd (2020) [29] explains, pH fluctuations can alter the toxicity of nitrogenous waste—a risk that was ruled out here due to the consistency of our measurements.

Dissolved oxygen showed a slight natural decline (from 6.79 to 6.47 mg/L), inversely correlated with the increase in temperature ($r = -0.88$; $p < 0.001$). Despite this decline, levels remained well above the critical threshold of 4 mg/L defined by Ndome (2011) [28]. According to Kestemont *et al.* (2015) [30], high oxygen saturation during yolk sac resorption is critical, as the larvae do not yet possess their accessory respiratory organ (labyrinth). Our results confirm that the aeration system used fully compensated for the larvae's increasing respiratory demand.

The near-total absence of ammonia ($NH_3 = 0$) and the very low nitrite content (0.03 mg/L) demonstrate the system's rigorous hygiene. These values are significantly below the toxicity thresholds (0.2 mg/L for NH_3) reported by Sipaúba-Tavares *et al.* (2017) [31]. The stability of electrical conductivity (around 254 µS/cm) corroborates this cleanliness, indicating the absence of organic salt accumulation resulting from the decomposition of unfertilized eggs—a critical issue often highlighted by Sipaúba-Tavares *et al.* (2017) [31].

Morphometric Characterization of Broodstock

Morphometric analysis of our *Clarias gariepinus* broodstock reveals marked sexual dimorphism, with females exhibiting a significantly higher overall body size (616.67 ± 55.88 g; 40.28 ± 2.70 cm) that is significantly greater than that of males (582.17 ± 61.06 g; 37.72 ± 1.51 cm). This physical dominance of females is an intrinsic characteristic of the species that has been widely documented. Our observations are consistent with the findings of Viveen *et al.* (1985) [24], who emphasize that in the Clariidae, natural selection favors larger females to maximize the abdominal space required for vitellogenesis and optimize oocyte production. The strong positive correlation ($r = 0.636$; $p = 0.026$) that we established between the weight of broodstock and their absolute fecundity confirms that size remains the most reliable predictor of hatchery productivity, a finding already validated in the scientific literature [32].

However, our results qualify this physical superiority by demonstrating that growth rate (Specific Growth Rate—SGR) is statistically identical between the two sexes (0.2%/day for females versus 0.19%/day for males; $p = 0.664$). This metabolic parity suggests that the size difference initially observed stems from a difference in age or a distinct growth history prior to capture in Lake Kivu, rather than from a higher rate of development in females during the adult phase. Conversely, body condition, as assessed by Fulton's condition index (K), was higher in males (1.08 ± 0.09) than in females (0.96 ± 0.17). As noted by Froese (2006) [23], a K index greater than 1 in males indicates robust health and the accumulation of lipid reserves necessary for spermatogenesis.

The length-weight relationship proved isometry for both sexes, with respective slopes of b = 3.05 for females and b = 2.98 for males. These values, very close to the theoretical threshold for isometry (b = 3), indicate a morphological balance maintained throughout the experimental phase.

This maintenance of isometry indicates that weight gain—including the massive development of the gonads—occurred in proportion to growth in length. Unlike situations of environmental stress or nutritional deficiency, which often induce underallometry ($b < 3$), as reported by Géoffroy *et al.* (2019) [33] in Siluriformes, our specimens benefited from a balanced energy investment. Food intake was sufficient to simultaneously support body maintenance and final maturation (reproductive effort).

The highly significant increase in the overall K condition index ($p < 0.001$) between the start and end of the 14-day experiment confirms the effectiveness of the conditioning regimen. This excellent metabolic response of *Clarias gariepinus* to controlled nutritional intake corroborates the conclusions of Nyina-wamwiza *et al.* (2007) [34], demonstrating that the fish was able to efficiently convert available energy into body and gonadal reserves without compromising its initial morphological structure.

Finally, the morphometric homogeneity of the pituitary donor batch (CV < 2%) allowed for precise standardization of hormone doses. The cephalic ratio of 19.13 ± 0.79% observed in our donors is consistent with the anatomical standards described by Idodo-Umeh (2003) [35] for Central African populations, ensuring that the size of the pituitary gland was proportional to the fish's body length—a direct relationship confirmed by the strong correlation ($r = 0.81$) between total length and cephalic area.

Larval Survival and Growth Dynamics

The larval survival and growth dynamics observed in our study represent exceptional biological performance indicators, directly correlated with the stability of the artificial ecosystem established. Our results show a Specific Growth Rate (SGR) exceeding 21% per day, a performance that aligns with the productivity standards described by de Graaf and Janssen (1996) [6] in the FAO technical manuals. This growth is the result of a synergy between precision nutrition and rigorous management of physicochemical parameters, confirming Boyd's (2015) theories on the importance of mineral balance for osmoregulation in juvenile teleosts [27].

Water quality played a decisive role in the biosecurity and survival of post-operative broodstock as well as larvae. Maintaining a high level of dissolved oxygen (6.42 ± 0.55 mg/L) was the primary safety measure. As noted by Viveen *et al.* (1985) [24], the African catfish, although equipped with an accessory respiratory organ, relies exclusively on dissolved oxygen during its early larval stages. Stable pH (6.95 ± 0.18) also limited the toxicity of non-ionized ammonia, a major risk factor identified by Marimuthu *et al.* (2019) [7] in intensive aquaculture. This environmental control explains the absence of opportunistic diseases, which are often triggered by environmental stress, as demonstrated by Noga (2010) [36] and Ndri *et al.* (2025) [37] in their studies on prophylaxis in hatcheries.

The major innovation of our study lies in the correlation between the method of semen collection and the vigor of the offspring. The 30-day survival rate, which was significantly higher for larvae from surgically collected males (90.67%) compared to those from sacrificed males (81.33%), suggests greater physiological resilience. This observation aligns with the hypotheses of Vandeputte (2003) [38] and Viveiros and Godinho (2009) [39] regarding semen quality: preserving the physiological integrity of the male parent may positively influence the epigenetic factors affecting larval survival. Furthermore, successful weaning with Perla feed [17] allowed the fish to overcome the "critical phase" of mortality, validating the protein requirements identified by Ng *et al.* (2003) [40] for this species.

Finally, overall growth dynamics were supported by an environment of "metabolic comfort." The low nitrite concentration (0.02 mg/L) indicates active nitrification, a parameter that Rouabah *et al.* (2016) consider the cornerstone of success in modern hatcheries [41].

Evidence of Allometry (Head-Body Size) in *Clarias gariepinus* in Lake Kivu

Growth rates (SGR and Relative) are strongly correlated with each other and are negatively correlated with head length (LH) after the 14-day rearing period. Thus, growth rates were lower in individuals with longer heads. Similarly, growth rates and head length are, together, negatively correlated with weight (before and after). Furthermore, a lower growth rate was observed in longer individuals (LT and LS). Specifically, larger females with greater height and longer heads exhibited slower growth. Larger males (LT) have shorter heads. Growth rates vs. head length: individuals with longer heads (LH) exhibit lower growth rates (SGR and TCR). This suggests that more energy is directed toward head development than toward weight gain. Head length and weight: head length is negatively correlated with weight (before and after). Individuals with long heads do not efficiently convert their body mass into rapid growth. Total length and growth: Longer fish (TL, LS) also show slower growth, confirming negative allometry: body size increases, but the growth rate slows down. Sexual differentiation: Larger females, with longer heads and taller bodies, exhibit slower growth. This may be related to: The diversion of energy toward ovarian maturation rather than somatic growth. A sexual dimorphism in which females prioritize reproduction at the expense of growth rate. Larger males have shorter heads, which promotes greater energy efficiency and a more stable SGR.

Thus, there appears to be inhibition due to head formation: prolonged cranial growth could slow overall growth. Sexual dimorphism: the differences observed between males and females reflect an adaptive strategy: females invest in reproduction, while males invest in body growth.

This phenomenon of negative allometry suggests that: Larger females are not necessarily the best performers in terms of growth, but they remain the best candidates for spawning. Short-headed males exhibit greater growth efficiency, which can be leveraged to optimize broodstock selection. Taking these morphometric correlations into account is essential for stabilizing fry production and avoiding selection based solely on apparent size.

Limitations of the Study

This study focused exclusively on the African catfish species *Clarias gariepinus* in the controlled environment of artificial reproduction. The morphometric parameters were measured for both male and female broodstock, whether they were donors of sperm, oocytes, or pituitary glands. The study also evaluated the early developmental stages of the larvae, specifically the growth and survival of fry, as influenced by critical water quality parameters on overall reproductive success. The study did not examine the long-term ecological impacts of these practices beyond the immediate environment of Lake Kivu for broodstock collection and the Kivu Fish Corporation (KFC) hatchery for artificial reproduction and larval rearing over a four-month period from January to April 2026. Advanced genetic manipulation techniques were not used.

6. Conclusions

This study stands out for its pragmatic approach aimed at securing local production of *Clarias gariepinus* fry in South Kivu through artificial reproduction. Our results show that rigorous morphometric selection of broodstock and stable physicochemical parameters are the two key factors for reducing larval mortality. Regarding broodstock selection, the results indicate that heavier females should be prioritized, as weight is the best indicator of fertility (number of eggs laid). In addition, a standardized morphometric selection grid (length, K index, weight) should be established to reduce variability and improve the predictability of spawning. For water quality management, the water temperature should be maintained between 26˚C and 28˚C, and sudden fluctuations that reduce dissolved oxygen should be avoided. Maintain a level > 6 mg/L through continuous aeration and regular water changes. It is essential to siphon off waste daily to keep NH_3 < 0.2 mg/L and NO_2 < 0.05 mg/L. Aim for stability between 200 - 400 μS/cm, avoiding excessive variations (>15%). Incorporate statistical models (correlations, regressions) to anticipate risks associated with thermal and chemical variations. Aim for a survival rate > 80% by combining strict hygiene, an appropriate diet, and physicochemical stability. Negative head allometry has been observed in males, in contrast to positive head allometry in females. This knowledge will enable precise adjustments to rearing practices according to growth stages.

Future research directions should include establishing standards tailored to Lake Kivu broodstock to predict fertility and reduce spawning heterogeneity, as well as verifying whether growth differences (long-headed vs. short-headed, females vs. males) reflect sexual dimorphism or ecotype-specific variations; it will be necessary to explore the impact of cranial morphology on feed efficiency, respiration, and reproduction. Models linking temperature, oxygen, and nitrite levels should be developed to anticipate critical thresholds for larval mortality. It is imperative to compare broodstock from Lake Kivu with those from other ecosystems to identify phenotypic differences useful for selection.

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Author Contributions

Conceptualization, Elie Namegabe Bacirheba and Jean-Berckmans Bahananga Muhigwa; methodology, Désiré Akonkwa Balagizi; software, Elie Namegabe Bacirheba and Jean-Berckmans Bahananga Muhigwa; investigation, Guillain Andanga Machumu and Elie Namegabe Bacirheba; resources, Désiré Akonkwa Balagizi; data curation, Jean-Berckmans Bahananga Muhigwa; writing—original draft preparation, Elie Namegabe Bacirheba; writing—review and editing, Elie Namegabe Bacirheba and Gabriel Mukabo Okito; visualization, Jean-Berckmans Bahananga Muhigwa; supervision, Désiré Akonkwa Balagizi; project administration, Elie Namegabe Bacirheba and Guillain Andanga Machumu; funding acquisition, Elie Namegabe Bacirheba and Guillain Andanga Machumu. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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