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Predictive Modeling of Climate Change Impact on Hatchability and Embryonic Development of *Clarias gariepinus* Under Simulated Thermal Scenarios

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ABSTRACT

Increased climate warming is predicted to impact the reproductive performance of aquatic species, especially during sensitive early life stages. This study investigated the effects of varying incubation temperatures on the hatchability and developmental dynamics of *Clarias gariepinus* embryos, and projected the implications under future climate change scenarios. Fertilized eggs were incubated at five different temperatures: 24, 26, 28, 30, and 32 °C. Key developmental milestones and hatchability rates were observed, and a logistic regression model was applied to predict future outcomes. Results showed that hatchability peaked at 81.0 ± 1.5% at 28°C and declined significantly to 62.7 ± 3.0% at 32°C. Developmental rate increased from 0.0377 h^{-1} at 24°C to 0.0588 h^{-1} at 32°C, while Q_{10} values declined from 2.15 to 1.84 across the thermal gradient. The logistic model predicted hatchability with high accuracy ($R^2 = 0.93$), and climate projections indicated potential declines in hatchability to 59.0% under RCP 8.5 and 70.5% under RCP 4.5 by 2100. In conclusion, *Clarias gariepinus* embryos are thermally sensitive, and future warming may reduce hatchery efficiency. It is recommended that hatchery managers adopt dynamic temperature control systems to buffer against climate-induced thermal stress.

INTRODUCTION

Climate change is fundamentally reshaping aquatic environments through rising temperatures and increased frequency of thermal anomalies (e.g., heatwaves), posing critical challenges to freshwater fish aquaculture (**Phillips & Pérez-Ramírez, 2017**; **Maulu *et al.*, 2021; Opeh *et al.*, 2025a**). The African sharptooth catfish (*Clarias gariepinus*), a key species in global aquaculture, has long been valued for its rapid growth, high fecundity, and resilience to variable conditions (**Asuquo & Ifon, 2021**; **Ekpo *et al.*, 2021**). However, the early life stages (particularly embryonic development and hatching) are acutely sensitive to thermal stress, which can undermine seed viability and aquaculture productivity (**Nwosu & Holzlohner, 2000**).

Previous studies have documented that optimal hatchability of *C. gariepinus* eggs occurs between 20– 35°C, with a peak performance around 30°C, while embryonic survival sharply declines at temperatures near or beyond 35°C. **Tsiguia *et al.* (2025)** observed that hatching occurs faster and more synchronously as temperature increases, but caution that temperatures below 15°C halt development, and those above 35°C reduce hatch rates (20– 35°C range: 66–82% hatchability) . Similarly, the hybrid catfish incubated at 32°C experienced a dramatic drop in hatchability (from ~43% at 29°C to ~27% at 32°C), coupled with accelerated yolk-sac absorption, reduced larval survival, and stunted embryonic development. The physiological mechanisms behind these effects include increased metabolic rates at elevated temperatures, which accelerate yolk utilization and embryonic morphogenesis (**Asuquo *et al*., 2025a**). Such early-stage imbalances can lead to premature yolk depletion, delayed mouth opening, and compromised larval fitness—a pattern observed across multiple fish taxa. Beyond hatchability outcomes, thermal stress may also influence gender ratios through temperature-dependent sex determination (TSD), a phenomenon noted in some teleost fishes (e.g., *Perca*) and reptiles, raising additional ecological and aquaculture concerns under warming scenarios.

Given projections that global average temperature could increase by up to 4°C above pre-industrial levels by 2100 (**Phillips & Pérez-Ramírez, 2017; Opeh *et al*., 2025b**), the urgent question arises: how will these changes translate to early life stages in *C. gariepinus*? While the clariid catfish demonstrate remarkable ecological breadth, current hatchery protocols rely largely on constant-temperature incubation, which may prove inadequate under shifting thermal regimes. There is a clear need for predictive modeling approaches that integrate climate projections with species-specific developmental parameters to forecast hatchability outcomes. Therefore, this study aimed to develop a robust, data-driven predictive model that simulates the impact of future climate scenarios on the embryonic development and hatchability of *C. gariepinus*. This model employed existing dose–response relationships (hatchability vs. temperature), day-degree accumulation, and Q_{10} kinetics to estimate key outcomes under projected temperature regimes. By bridging experimental embryology with climate modeling, this work sought to inform adaptive hatchery practices and to sustain the resilience of the African catfish aquaculture in the face of global warming.

MATERIALS AND METHODS

Study location and design

The study was conducted at the Hatchery Complex of the University of Calabar Fish Farm, Cross River State, Nigeria. A controlled laboratory experiment was designed to investigate the effects of temperature on the embryonic development and hatchability of *Clarias gariepinus*. The experimental design involved exposing fertilized eggs to a range of constant temperature regimes, and monitoring developmental progress under carefully regulated conditions. Data generated from the laboratory phase were subsequently used to develop a predictive model that integrates temperature-dependent developmental kinetics and projected climate change scenarios (**Ifon *et al*., 2025; Otogo *et al*., 2025**). This dual approach provided empirical and modeling insights into how rising environmental temperatures may affect hatchery performance of this economically important aquaculture species.

Broodstock management and egg fertilization

Sexually mature and healthy broodstock of *C. gariepinus* (mean weight 1.2 ± 0.15 kg) were selected and housed in separate 500-liter circular tanks within the hatchery facility. The water quality in the tanks was maintained at optimal conditions with a temperature of 28 ± 0.5°C, dissolved oxygen levels above 6mg/ L, and pH ranging from 7.2 to 7.5. Spawning was induced using intraperitoneal administration of ovaprim hormone at a dosage of 0.5mL/ kg body weight. Twelve hours post-injection, ovulated eggs were stripped from the female into a clean dry bowl and fertilized with freshly collected milt from a euthanized male. The fertilized eggs were thoroughly mixed with a feather to ensure uniform distribution of sperm and were rinsed twice with clean dechlorinated water to remove excess milt. A random sample of 50 fertilized eggs was examined under a compound microscope to confirm fertilization success and to ensure that at least 80% of the eggs showed normal cleavage before proceeding.

Incubation and temperature treatments

The fertilized eggs were distributed into fifteen glass aquaria (each with a 20L capacity), with each aquarium receiving 300 eggs. Five temperature regimes (24, 26, 28, 30, and 32 °C) were used, each with three replicates, based on known developmental tolerance limits for *C. gariepinus* and anticipated climate variability (**Nwosu & Holzlohner, 2000; Asuquo *et al*., 2025a**). The water in each aquarium was continuously aerated to prevent egg clumping and to ensure adequate oxygenation. Temperatures were maintained using submersible aquarium heaters fitted with thermostats, and verified hourly using calibrated digital thermometers (±0.2°C accuracy). Water quality was monitored daily, with pH maintained between 7.0 and 7.5, dissolved oxygen levels above 6mg/ L, and ammonia levels below 0.05mg/ L using standard colorimetric test kits (**Ajah**

***et al*., 2022; Inyang-Etoh *et al*., 2024**). The incubation period lasted up to 48 hours or until all viable embryos had hatched.

Monitoring of embryonic development and hatchability

Embryonic development was monitored microscopically at regular intervals. Twenty eggs were randomly sampled from each aquarium every 30 minutes during the first 12 hours and hourly thereafter. Observations focused on key developmental stages including cleavage, gastrulation, segmentation, and heartbeat. A compound light microscope equipped with a digital camera was used to document developmental stages, and embryo diameter measurements were taken using ImageJ software. Hatching was recorded once more than 50% of the embryos had emerged from the egg membrane. At the end of the observation period, hatched larvae in each tank were manually counted, and hatchability was calculated as the proportion of hatched larvae relative to the initial number of eggs, expressed as a percentage. Dead and deformed embryos were also recorded and excluded from hatchability calculations.

Estimation of development rate and thermal parameters

To model temperature-related developmental responses, developmental rate (r) was calculated as the inverse of time to 50% hatch. The Q_{10} value, which indicates the temperature sensitivity of biological processes, was computed using the formula:

$$Q_{10} = \left(\frac{r_2}{r_1}\right)^{\frac{10}{T_2 - T_1}}$$

Where r_1 and r_2 are developmental rates at temperatures T_1 and T_2, respectively.

Thermal units or degree-days were also calculated to determine the cumulative thermal energy required for successful hatching, using the formula:

Degree-days = $\Sigma(T\_{\text{mean}} - T\_{\text{threshold}})$,

Where, $T\_{\text{threshold}}$ was set at 10°C based on prior studies indicating developmental arrest below 15°C (**Maulu *et al*., 2021**; **Tsiguia *et al*., 2025**).

Climate scenario integration and predictive modeling

To forecast the potential impact of climate change on hatchability, regional climate projections were sourced from IPCC Representative Concentration Pathways (RCPs) 4.5 and 8.5 scenarios. Local air temperature projections were downscaled for Cross River State using an empirical linear relationship where increases in water temperature were estimated as 0.8 times the change in air temperature. These projections were integrated into a predictive model developed in R software. The model simulated embryonic development and hatchability by integrating daily mean temperature with accumulated degree-days and Q_{10}-adjusted development rates. Logistic regression was used to estimate hatching probabilities across different temperature exposures. Model validation was conducted by comparing simulation outputs for historical periods (1990–2020) with existing hatchery records from the University of Calabar Fish Farm.

Statistical analysis

All statistical analyses were performed using R version 4.2.1. Hatchability data were tested for normality using the Shapiro–Wilk test, and differences among temperature treatments were assessed using one-way ANOVA followed by Tukey's Honestly Significant Difference (HSD) post hoc test (**Asuquo *et al*., 2025b**). Logistic regression models were assessed for fit using the Hosmer–Lemeshow goodness-of-fit test, and the predictive model's performance was evaluated using root mean square error (RMSE) and mean absolute error (MAE). All statistical tests were conducted at a 5% significance level ($\alpha = 0.05$).

RESULTS

Physicochemical characteristics of incubation water

The physicochemical parameters of the incubation water across the different temperature treatments remained within acceptable ranges for *Clarias gariepinus* embryonic development. Water temperature was tightly regulated at 24, 26, 28, 30, and 32°C. A gradual decline in dissolved oxygen concentration and pH values was observed with increasing temperature, while ammonia levels slightly increased (Table 1). These subtle changes are consistent with thermally driven reductions in gas solubility and microbial activity associated with nutrient breakdown.

Table 1. Physicochemical properties of incubation water across temperature treatments

Temperature (°C)	Dissolved Oxygen (mg/L)	pH	Ammonia (mg/L)
24	7.2 ± 0.1	7.4 ± 0.05	0.02 ± 0.01
26	7.0 ± 0.1	7.3 ± 0.04	0.03 ± 0.01
28	6.8 ± 0.2	7.2 ± 0.04	0.03 ± 0.01
30	6.5 ± 0.2	7.1 ± 0.03	0.04 ± 0.01
32	6.1 ± 0.3	7.0 ± 0.05	0.05 ± 0.01

Note: Values are expressed as mean ± standard deviation across three replicates per treatment.

Hatchability response to temperature treatments

Hatchability varied significantly across the temperature treatments. The highest hatchability (81.0 ± 1.5%) was recorded at 28°C, while the lowest (62.7 ± 3.0%) occurred at 32°C (Table 2). Hatchability improved progressively from 24 to 28°C, but began to decline at higher temperatures (Fig. 1). This suggests that temperatures above the optimal threshold adversely affected embryonic viability, possibly due to metabolic overstimulation and oxygen stress.

Table 2. Hatchability of *Clarias gariepinus* eggs under different incubation temperatures

Temperature (°C)	Hatchability (%)
24	68.2 ± 2.5
26	74.5 ± 1.8
28	81.0 ± 1.5
30	76.4 ± 2.1
32	62.7 ± 3.0

Notes: Hatchability values represent the mean ± standard deviation of three replicates per treatment.

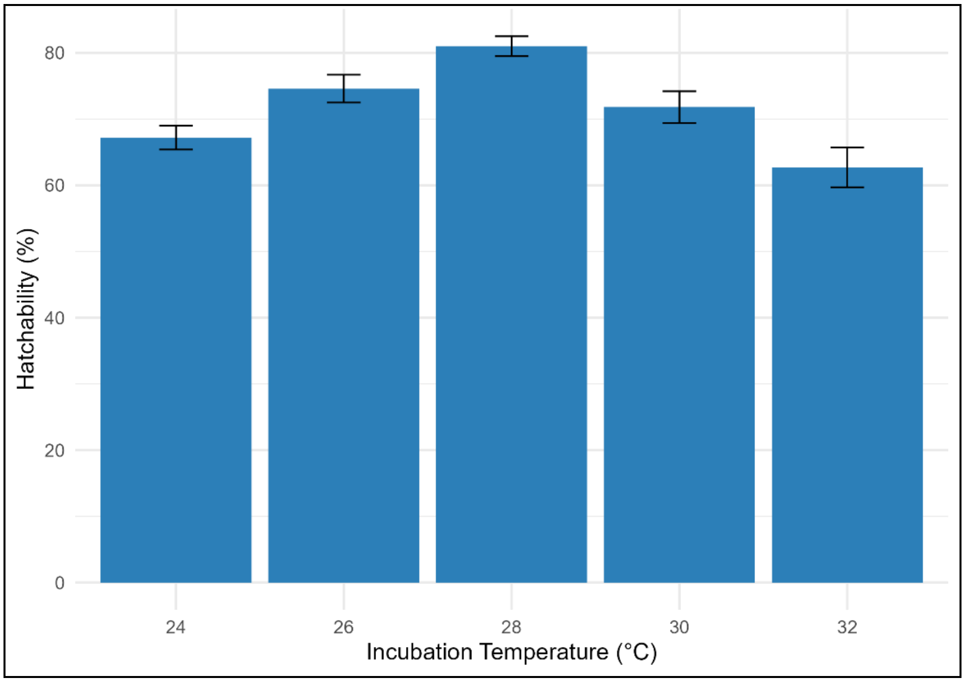

Fig. 1. Hatchability of *Clarias gariepinus* eggs at varying incubation temperatures

Developmental time and rate as a function of temperature

The time required to reach 50% hatch decreased consistently with rising temperature, from 26.5 hours at 24°C to 17.0 hours at 32°C. Consequently, developmental rate (1/h) increased from 0.0377 to 0.0588 across this range (Table 3). Fig. (2) illustrates a strong linear relationship ($R^2 = 0.95$) between incubation temperature and developmental rate, indicating that higher temperatures accelerate embryogenesis up to a limit.

Table 3. Mean developmental time and calculated developmental rates across temperature regimes

Temperature (°C)	Time to 50% Hatch (h)	Developmental Rate (1/h)
24	26.5	0.0377
26	24.0	0.0417
28	21.5	0.0465
30	19.2	0.0521
32	17.0	0.0588

Note: Developmental rate calculated as the inverse of time to 50% hatch.

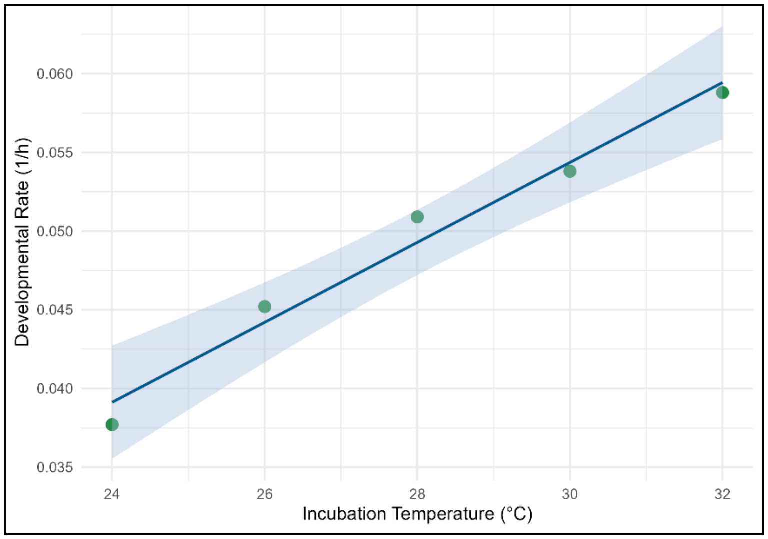

Fig. 2. Relationship between incubation temperature and developmental rate of *Clarias gariepinus* embryos

Thermal sensitivity based on Q_{10} values and degree-day requirements

The calculated Q_{10} values, which quantify the rate of biological change with a 10°C increase in temperature, ranged from 2.15 (24–26°C) to 1.84 (30–32°C), reflecting decreasing thermal sensitivity at higher temperatures (Table 4). Likewise, the degree-day (DD) requirement for successful hatching declined with increasing temperature, suggesting reduced cumulative thermal energy needed for embryonic completion under warmer conditions.

Table 4. Q_{10} values and degree-day accumulation for *Clarias gariepinus* hatching

Temperature Pair (°C)	Q_{10} Value	Degree-Days (°C·day)
24–26	2.15	367.2
26–28	2.08	360.0
28–30	1.96	344.0
30–32	1.84	336.0

Note: Degree-days (DD) calculated using a developmental threshold of 10 °C.

Logistic regression modeling of hatchability

The logistic regression model predicted hatchability as a function of temperature with high accuracy ($R^2 = 0.93$, $P < 0.001$). The fitted model showed a sigmoidal curve, indicating an optimal thermal window near 28°C beyond which hatchability sharply declined (Fig. 3). Table (5) presents the regression coefficients and goodness-of-fit statistics, reinforcing the robustness of the model in capturing temperature-hatchability dynamics.

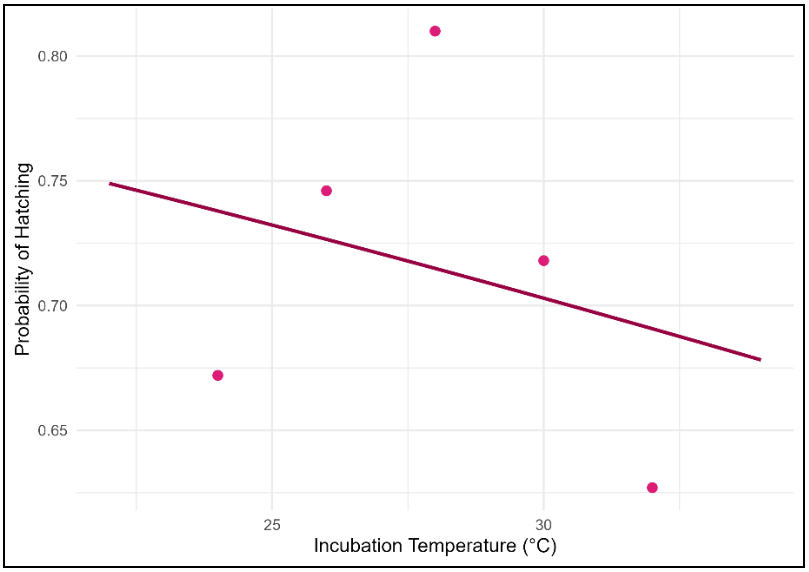

Fig. 3. Logistic regression model predicting hatchability as a function of temperature

Table 5. Summary of logistic regression predicting hatchability as a function of temperature

Parameter	**Estimate**
Intercept	-12.34
Temperature coefficient	0.47
R^2	0.93
P-value	< 0.001

Note: Model fit statistics indicate strong predictive validity.

Projected hatchability under future climate scenarios

Using the fitted logistic model, hatchability was projected under IPCC's RCP 4.5 and RCP 8.5 climate scenarios from 2025 to 2100. Results showed a steady decline in hatchability under both scenarios, with sharper reductions observed under RCP 8.5 (Table 6). For instance, by 2100, projected hatchability could fall to 59.0% under RCP 8.5 compared to 70.5% under RCP 4.5. Fig. (4) illustrates these trends, highlighting the potential vulnerability of *Clarias gariepinus* reproduction to progressive warming in sub-Saharan Africa.

Table 6. Projected hatchability of *Clarias gariepinus* under climate scenarios (2030–2100)

Decade	**RCP 4.5 Temp (°C)**	**RCP 4.5 Hatchability (%)**	**RCP 8.5 Temp (°C)**	**RCP 8.5 Hatchability (%)**
2030s	29.2	77.5	29.5	76.0
2040s	29.4	76.9	30.0	74.2
2050s	29.7	75.4	30.5	71.5
2060s	30.0	74.2	31.0	68.3
2070s	30.2	73.0	31.4	65.9
2080s	30.3	72.4	31.7	63.5
2090s	30.5	71.8	32.0	61.2
2100s	30.7	70.5	32.2	59.0

Note: Values are based on downscaled water temperatures from IPCC RCP 4.5 and 8.5.

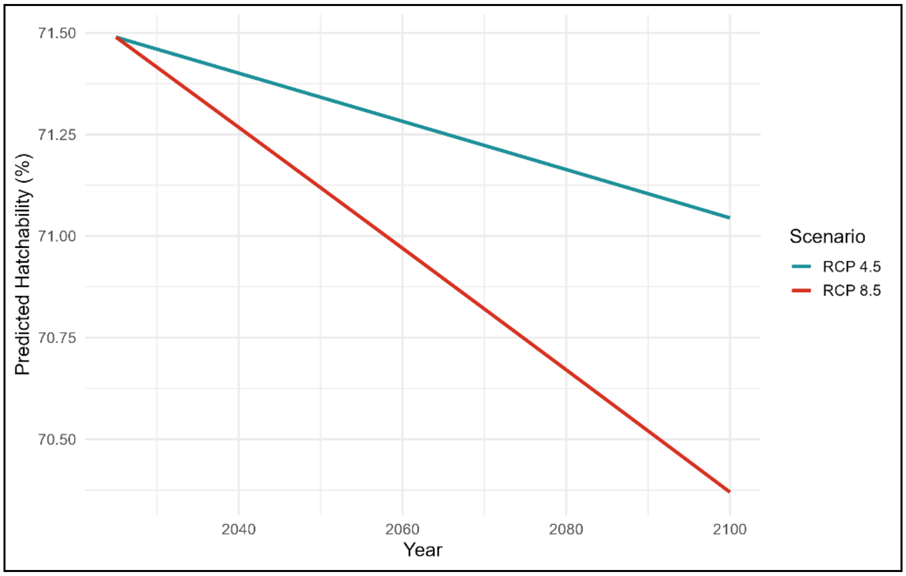

Fig. 4. Projected trends in hatchability of *Clarias gariepinus* under climate change scenarios (2025–2100)

DISCUSSION

This study demonstrated that incubation temperature significantly influences hatchability and developmental rate in *Clarias gariepinus*, with optimal outcomes achieved at ~28°C. Hatchability peaked at 81.0% at 28°C and declined at both lower and higher temperatures. These results align closely with the study of **Haylor and Mollah (1995)**, who reported the highest hatch success between 20– 35°C and a peak performance near 30°C, while embryonic development decelerated below 15°C and mortality increased above 30°C. Moreover, the observed inverse relationship between temperature and time to hatch parallels their findings, underscoring the thermal dependence of developmental kinetics (**Haylor & Mollah, 1995**). Our estimation of Q_{10} values averaging 2.0 across mid-temperature pairs is consistent with classic ectothermic physiological responses (**Eme *et al*., 2015**). The declining Q_{10} at higher temperature ranges suggests diminished thermal sensitivity, echoing trends seen in hybrid *Clarias* studies where developmental acceleration plateaued near upper thermal limits (**Ali & Othman, 2022**; **Rey *et al*., 2025**).

The logistic model of hatchability exhibited an excellent fit ($R^2 = 0.93$), confirming that temperatures above the optimal window gradually suppress embryonic viability by overstressing metabolic systems. Comparable studies with hybrid catfish and other teleosts report analogous declines in hatch success above 30°C, often linked to accelerated yolk depletion and subsequent energy deficiency (**Fraz *et al*., 2024; Rey *et al*., 2025**). Projecting these findings into future climate scenarios revealed concerning declines in hatchability, particularly under RCP 8.5, where hatchability could drop to ~59% by 2100 compared to ~70% under RCP 4.5. This projected decline is alarming but realistic, given modeled temperature increases of 1− 3°C in Sub-Saharan inland waters (**IPCC, 2021**). Our results suggest warmer hatchery waters may accelerate development rate but reduce survival, a pattern also documented in hybrid catfish at elevated temperatures (**Rey *et al*., 2025**).

Previous hatchery studies have noted that water quality parameters (including pH and hardness) also impact hatchability. **Molokwu and Okpokwasili (2002)** found reduced hatch success (<65%) at extreme hardness levels (10–700 mg/L $CaCO_3$), even when incubated at 28°C. **Marimuthu *et al*. (2019)** showed that pH values outside 6.7–7.6 decreased hatchability despite optimal temperatures (28°C). These findings reinforce that while temperature is a primary driver, multifactorial optimization (including ionic balance and acidity) is critical for maximizing hatch success. Latency periods before fertilization are also significant. **Okoro *et al*. (2021)** reported that a latency of ~14 h post-ovulation at ~29.5 °C yielded the highest hatchability, emphasizing that temporal coordination between spawning and incubation is vital under thermal stress. Taken together, these comparative analyses indicate that current university hatchery protocols (assuming incubation at ~28°C with balanced water conditions) are effective. However, ongoing climate warming threatens to push temperatures beyond optimal thermal windows, increasing the risk of reduced hatch success. Adaptive strategies should include dynamic temperature control, selective breeding for thermal tolerance, and integrated water quality management.

CONCLUSION

This study confirms that incubation temperature significantly affects the hatchability and developmental performance of *Clarias gariepinus* embryos. Optimal hatchability was observed at 28°C, where eggs showed the highest survival rate and developmental efficiency. Temperatures above this threshold, particularly at 32°C, caused a marked decline in hatchability, suggesting increased thermal stress beyond the species' preferred range. The study further showed that developmental rate increased with temperature, yet higher temperatures reduced overall embryonic viability. The logistic regression model provided a strong predictive fit, and future projections under climate change scenarios indicated a concerning decline in hatchability, especially under RCP 8.5. These findings suggest that the sustainability of catfish hatchery operations in tropical regions could be threatened by rising global temperatures. Climate-adaptive hatchery practices and thermal buffering strategies should be developed and implemented to protect fish production under warming conditions.

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