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Effects of greenhouse in enhancing water quality parameters for warm water fish production in the high-altitude environments of the western Highlands of Cameroon

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Abstract
Claris gariepinus, a warm water fish exhibits limited tolerance with variations in physicochemical parameters of the environment. In other to optimize water parameters for fish farming, greenhouse was used. Six experimental tanks (three inside a greenhouse and three outside) were supplied with from nearby stream. The physicochemical parameters were measured using the standards methods. Results demonstrated that greenhouse maintained a mean daily water temperature of 25.98 °C (against 23.37 °C externally) and ambient temperature differences of 2-10 °C. Principal Component Analysis and linear regression indicated direct influence of greenhouse temperature on water temperature, subsequently affecting dissolved oxygen, alkalinity, turbidity, and nutrients concentrations. These findings underscore the greenhouse's ability to mitigate environmental fluctuations, enhancing water quality stability for aquaculture in high-altitude regions. This study recommends adopting greenhouse technology to support thermally sensitive fish species in such areas, offering practical solution to climatic constraints.

Keywords: Greenhouse, aquaculture, water quality, fish pond, temperature

1. Introduction

According to data from Worldometer, Cameroon's population is projected to surge from 29,123,744 in 2024 to over 50 million by 2050 [1, 2, 3]. This rapid demographic growth, particularly in urban centers with dense youth populations, is anticipated to escalate demand for nutrient-rich food sources, especially protein. However, natural fish production faces mounting threats from climate change, oceanic pollution, and overfishing, jeopardizing the sustainability of wild fish stocks [4, 5, 6, 7]. In response, pond aquaculture has gained prominence as a scalable and ecologically sustainable alternative [6, 8]. To optimize aquaculture productivity, integrated fish farming systems have been developed, combining aquaculture with agricultural practices such as crop cultivation [9, 10, 11, 12]. Despite these advantages, widespread adoption of fish farming remains hindered by insufficient technical knowledge, particularly regarding optimal pond design and the precise water quality parameters required for target species [13].

Water quality is a foundational determinant of aquatic ecosystem health, directly influencing the survival, growth, and physiological functions of aquatic organisms [14]. In aquaculture, maintaining optimal water conditions is critical, as deviations can impair fish development and increase susceptibility to disease [15, 16, 17, 18]. Macroclimatic conditions, shaped by geographic and topographic factors, create localized microclimates that diverge from regional trends, particularly in temperature regimes [14]. Such microclimatic variability underscores the need for adaptive management strategies in aquaculture [17, 19].

Among abiotic factors, temperature is a paramount regulator of fish physiology, influencing locomotion, metabolic rates, feeding behavior, and immune responses [20]. Temperature also modulates the solubility and bioavailability of dissolved gases, nutrients, and toxins, thereby affecting all biochemical processes in aquatic ecosystems [7, 21, 22, 23, 8, 24, 25].

Key physicochemical parameters like dissolved oxygen, pH, turbidity, ammonium, nitrate, nitrite, total phosphorus, alkalinity, and total dissolved solids (TDS) are interdependent with temperature, necessitating holistic monitoring [26, 27, 14, 18]. In this regard, understanding seasonal fluctuations in parameters such as pH, alkalinity, and dissolved oxygen is essential for optimizing primary productivity in aquaculture systems [27].

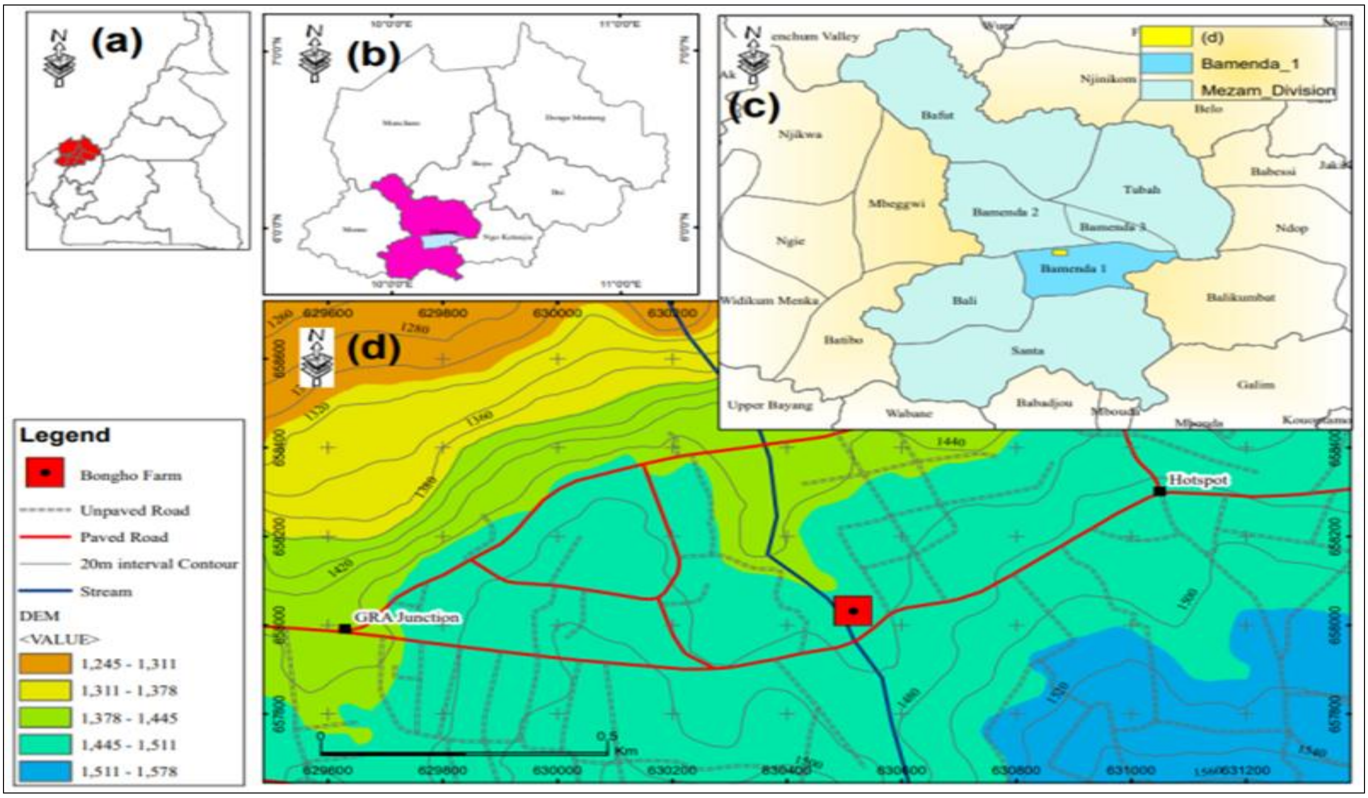
Cameroon hosts approximately 542 freshwater and brackish fish species [28, 29, 30, 31], with *C. gariepinus* ranking among the most consumed due to its hardiness and adaptability [32]. However, as a warm-water species, *C. gariepinus* exhibits limited cold tolerance, with temperatures below 12 °C proving lethal [28, 33]. This poses significant challenges in high-altitude regions like Bamenda I located at about 1,200 meters above sea level, has temperatures that range between 15 °C and 24 °C well below the species' optimal range of 25-30 °C [34]. Recent studies in Nigeria suggest that even suboptimal temperatures (20-27 °C) can support growth, but exceeding 27 °C may induce thermal stress [35]. To address these constraints, greenhouse technology offers a viable method for stabilizing water temperature and dissolved oxygen levels, mitigating physicochemical fluctuations that hinder aquaculture productivity [36].

Greenhouse (GH) fish farming is well documented practice [37, 38, 39. 40, 41, 42, 43, 44, 45, 46, 47, 36]. Greenhouses have been shown to elevate water temperatures by 3-9 °C [48], a benefit well-documented in crop production but underexplored in aquatic systems. While studies on greenhouse-enhanced plant growth abound [24], research on their application in aquaculture particularly for species like Nile tilapia remains limited [49, 50, 51, 52, 53]. Notably, no studies have investigated greenhouse technology for *C. gariepinus* production in Cameroon's North West region, where altitude-induced thermal limitations persist. This study therefore evaluates the efficacy of greenhouses in enhancing water quality parameters for fish production in high-altitude environments, addressing a critical gap in sustainable aquaculture practices. Specifically, this study evaluates the effect of air temperature on water temperature in and out the greenhouse and evaluates the level of relationship in between water parameters under the two conditions.

2 Materials and Methods

2.1 Description of the Study Area

The study was conducted at Bongho Farm, an experimental facility located in the town of Bamenda in the North West region. The site lies at geographic coordinates 5°95'19"N, 10°17'91"E and an elevation of 1,456 meters above sea level, positioning it within the Bamendankwe hills a submontane area locally referred to as "Station Hill." This region experiences a temperate highland climate characterized by moderate annual temperatures ranging between 21 °C and 24 °C. Precipitation occurs predominantly from March to November, averaging 1,800-2,200 mm annually, while December to February constitutes a drier period marked by reduced humidity and cooler nights [54]. A perennial stream, traverses the farm, serving as the primary water source for the study (Fig. 1).



Source: Geo-database of Cameroon and NASA DEM (2024)

Fig 1: Location map of Bamenda 1 Sub Division indicating BONGHO FARM, where experimental ponds are located

2.2. Experimental design

The experiment was conducted from mid-November 2023 to October 2024, encompassing a full annual cycle to account for seasonal climatic variations. The study employed a factorial design with two distinct units (Fig.2)

- **Greenhouse system:** Comprising three tanks. T1: Open tank stocked with fish (experimental), T2: Replicate open tank with fish, T3: Open control tank without fish.

- **Open-air system:** Similarly comprising three tanks. T4: Greenhouse tank stocked with fish (experimental), T5: Replicate greenhouse tank with fish, T6: Greenhouse control tank without fish.

All tanks were constructed from high-density polyethylene (HDPE) with a uniform capacity of 1 m³ (1,000 L) and dimensions of 1,200 mm (length) × 1,000 mm (width) × 1,165 mm (depth). The greenhouse structure featured a parabolic roof design covered with UV-stabilized polyethylene sheeting (200 µm thickness), optimized for solar radiation transmission while minimizing heat loss.

Fig 2: Experimental set indicating the greenhouse and open tanks

Water was sourced from the adjacent stream and delivered to the tanks via a centrifugal motor pump (0.5 HP capacity) to ensure consistent flow rates.

2.4 Water sample collection and analysis

A suite of physicochemical parameters was monitored to assess water quality dynamics in both greenhouse and open-air systems. They included: ambient temperature (°C), water temperature (°C), relative humidity (%), dissolved oxygen (DO) (% saturation), and pH were measured in situ daily between 08:00 and 10:00 AM to minimize diurnal variability. Ambient temperature and humidity were recorded using a calibrated thermo-hygrometer (Model AZ-8778, ±0.5 °C accuracy), while DO and pH were measured with a portable dissolved oxygen meter (AZ 8403, Gain Express; ±0.2 mg/L resolution) and a Wagtech multi-parameter meter (±0.01 pH unit accuracy), respectively. Measurements were taken at three predefined sampling points within each tank: the deep end (80 cm depth), shallow end (30 cm depth), and mid-pond region (60 cm depth) to capture spatial variability. For laboratory analysis, 0.5 L water samples were collected weekly from each tank using a Van Dorn sampler, preserved in acid-washed polyethylene bottles, and transported in ice packs to the AQUAFRIK Water Quality Laboratory in Yaoundé, Cameroon. Ammonia, nitrite, nitrate and total phosphorus concentrations, Turbidity and Total Dissolved Solids (TDS) and alkalinity were quantified using a Wagtech 7500 Spectrophotometer and the standard methods [55, 56].

2.5 Data Analysis

The collected data were systematically recorded in Microsoft Excel (Office 365). To evaluate significant differences between greenhouse and open-air systems, independent Student's t-tests (two-tailed) were applied (verified via Shapiro-Wilk tests). We then performed Principal Component Analysis (PCA) to identify correlations among water quality parameters. The most pertinent parameters were then computed using the Linear Regression Analysis. In all the statistics the level of 5% ($P<0.05$) of significance was used.

3. Results

3.1. Effect of the greenhouse on the ambient temperature

Throughout the seven-month experimental period (March-September), mean ambient temperatures inside the greenhouse (GH) consistently exceeded those recorded outside. The temperature differential between the two environments ranged from 1.5 °C to 10 °C, with the highest mean temperatures observed between April and June. A gradual decline in temperatures occurred from June onward, reaching the lowest values by the experiment's conclusion in September. Statistical analysis revealed a highly significant difference in daily mean temperatures between the GH and open-air systems (t-test, $p=0.0002<0.005$). The GH ponds maintained a mean daily temperature of 27.64 ± 1.9 °C, with extremes ranging from 20.5 °C (minimum) to 41.1 °C (maximum). In contrast, open-air ponds exhibited a lower mean daily temperature of 25.16 ± 2.66 °C, alongside narrower extremes of 18.8 °C (minimum) and 30.2 °C (maximum) (Fig. 3).

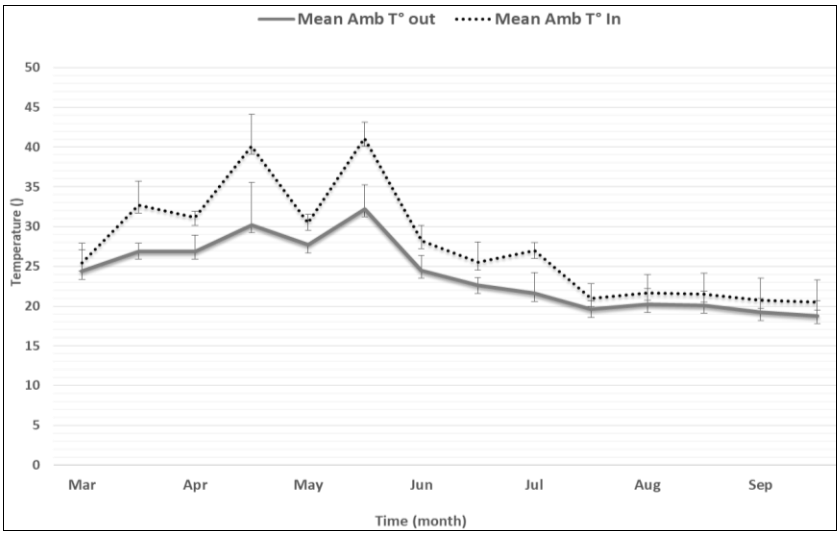


Fig 3: Evolution of the ambient temperature in and out of the Greenhouse

3.2. Effects of the greenhouse on the pond's water quality

Throughout the experimental period, the mean water temperature in greenhouse (GH) ponds consistently exceeded that of open-air ponds. The temperature differential between the two systems ranged from 1.5 °C to 3.3 °C, with the highest mean values recorded between April and June. A gradual decline in temperatures was observed from June onward, reaching the lowest values by September. Greenhouse ponds exhibited water temperatures ranging from 21.2 °C to 34.4 °C, with a mean of 25.98 ± 4.96 °C. In contrast, open-air ponds displayed a narrower range of 19.7 °C to 31.1 °C, with a lower mean of 23.37± 3.86 °C. Statistical analysis confirmed a highly significant difference in mean water temperatures between the GH and open-air systems (t-test, $p = 0.0002$) (Fig. 4).

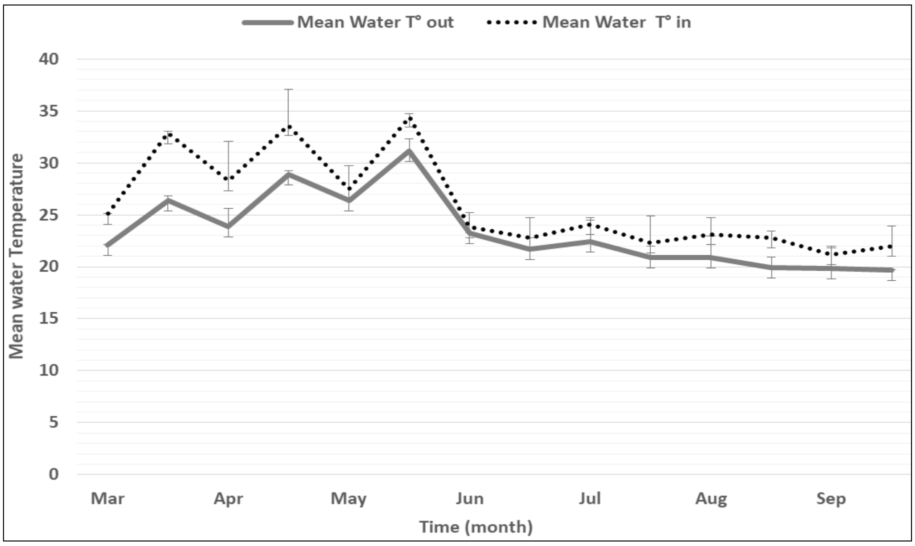


Fig 4: Evolution of the water temperature in and out the Greenhouse

Concerning dissolved oxygen concentration (DO), greenhouse (GH) ponds exhibited a slightly higher mean concentration (56.04 ± 21%) compared to open-air ponds (54.75 ± 19.67%), though this marginal difference was statistically insignificant at $p > 0.05$. this is as illustrated on Tab 1. Similarly, pH showed minimal divergence between systems (GH: 6.91 ± 0.39; open: 6.94 ± 0.36), with no significant variation ($p > 0.05$) (Tab.1). Also, ammonium (NH_4^+) and total phosphorus (TP) showed no significant variation between in the GH ponds (0.13± 0.13mg/l, 0.65± 0.28 mg/l respectively) and in open ponds (0.14 ±0.11 mg/l, 0.64± 0.45 mg/l respectively).
In contrast, alkalinity, turbidity and total dissolved solids (TDS) demonstrated marked differences. GH ponds recorded significantly lower alkalinity (58.82± 35.46 mg/l), turbidity (62.58 ± 41.87 FTU) and TDS (24.65 ± 6.87 ppm) compared to open ponds (65.96± 50.77 mg/l, 92.27 ± 91.15 FTU and 30.43 ± 23.98 ppm, respectively), with both parameters differing statistically ($p< 0.05$). Furthermore, nutrient concentrations exhibited mixed trends. nitrate (NO_3^-) levels were notably higher in GH ponds (2.08 ± 0.97 mg/L vs. 1.36 ± 1.14 mg/L; $p< 0.05$), whereas nitrite (NO_2^-) concentrations were significantly lower in GH environments (0.04 ± 0.03 mg/L vs. 0.09 ± 0.12 mg/L; $p< 0.05$) (Fig. 5).

Table 1: Summary of physicochemical parameters in greenhouse ponds and open ponds

	Greenhouse ponds			Open ponds			Desirable range
Treatment	Mean	Min	Max	Mean	Min	Max	
Ambient T° (°C)	23.5± 1.4	20.50	41.10	23.50± 1.4	18.80	30.20	
Water T° (°C)	25.98± 4.96	21. 20	34.40	23.37± 3.86	19.70	31.10	20-30
Humidity%	47.11± 17.99	24.00	74.00		-	-	
pH (U.C)	6.91± 0.39	6.53	8.13	6.94± 0.36	6.56	8.02	6.5-9
DO (%)	56.04± 21.00	23.20	81.20	54.75±19.67	21.90	79.70	39.5-65.8
Ammonium (mg/l)	0.13± 0.13	0	0.37	0.14 ±0.11	0	0.37	< 0.5 mg/L
Alkalinity (mg/l)	58.82± 35.46	5.00	150.00	65.96± 50.77	10.00	220.00	25-100
Tot Phos (mg/l)	0.65± 0.28	0.07	1.01	0.64± 0.45	0.03	1.72	0.01-3
Turbidity (FTU)	62.58± 41.87	14.00	165.00	92.27+ 91.15	14.00	250.00	5-30
Nitrates (mg/l)	2.08± 0.97	0.12	3.80	1.36± 1.14	0	3.83	0.1-4.5
Nitrites (mg/l)	0.04± 0.03	0	0.10	0.09± 0.12	0	0.38	0.02-2
TDS (ppm)	24.65± 6.87	12.00	36.00	30.43± 23.98	12.00	93.00	< 500

GhP: greenhouse ponds; OP: open ponds, Desirable ranges giving by Bhatnagar and Devi, 2019

3.3. Relationship in between air and water temperatures under the two conditions

To evaluate the level of proximity between the ambient and the water temperature, we employed a Linear Regression Test to appreciate the linkage between these two parameters both in and out of the GH. The relationship between ambient and water temperature was strongly linear in both systems, though their responsiveness differed markedly. For greenhouse (GH) tanks, the regression equation $Y = 0.698X + 6.499$ ($r = 0.935$, $p<0.0001$; Fig. 4a) indicated that water temperature rose by ~0.70 °C for every 1 °C increase in ambient temperature. In contrast, open-air systems exhibited a steeper slope (a = 0.844, r = 0.951, $p<0.0001$; Fig. 4b), with water temperature increasing by 0.84 °C per 1 °C ambient rise. While both systems showed near-perfect correlations (r > 0.93), the higher slope in open-air ponds highlights their heightened sensitivity to external temperature fluctuations.

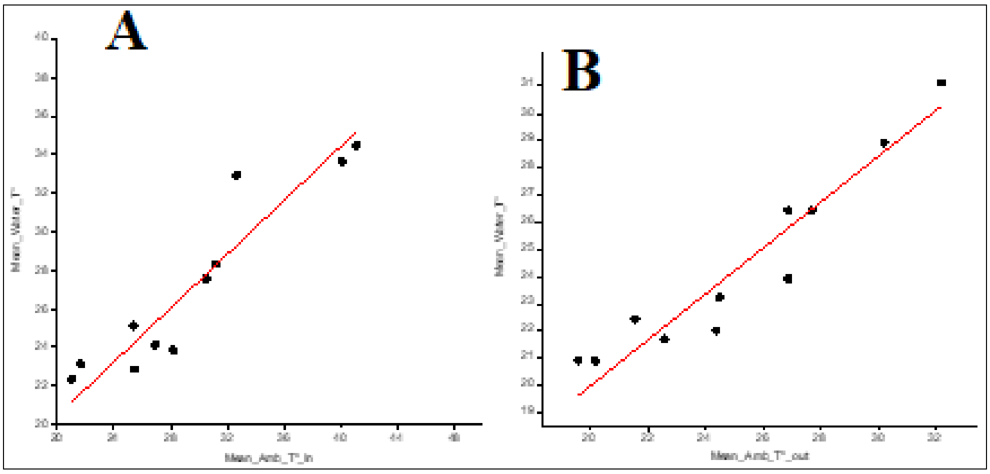


Fig 4: Regression Analysis curves indicating degree of dependence between ambient and tank water temperature in (a) and out (b) of the green house.

3.4. Relationship amount treatments and tanks water parameters

To reduce the number of parameters to those having real impact, we used the multiple variable test. The results of the Principal Component Analysis (PCA) revealed distinct drivers of variability across systems, with clear separations between experimental and control conditions. In the first place, Components 1 and 2 accounted for 98.33% of total variance (92.09% and 6.24%, respectively), dominated overwhelmingly by temperature and alkalinity. Strong correlations emerged between turbidity, pH, and nutrients concentration (NH_4^+, NO_3^-, and NO_2^-), suggesting intertwined nutrient dynamics and water clarity fluctuations (Fig. 5). Also, the levels of DO, turbidity, pH, temperature and nitrogenous waste have cumulative and interrelated effect on fish growth and health. Conversely, ambient and water temperatures clustered tightly, reinforcing their interdependence observed in prior regression analyses.

Treatment groupings further underscored system-specific influences. Experimental tanks (T1, T2, T4, and T5) clustered along alkalinity gradients, implying consistent alkalinity-driven profiles irrespective of GH or open-air conditions. In contrast, control tanks (T3, T6) grouped by dissolved oxygen (DO) levels, reflecting stable, biotic-free conditions with minimal metabolic disturbance. Notably, NH_4^+, NO_2^-, and NO_3^- exhibited minimal variation across all treatments, as evidenced by their central positioning near the PCA biplot origin, indicating negligible contribution to overall variability.

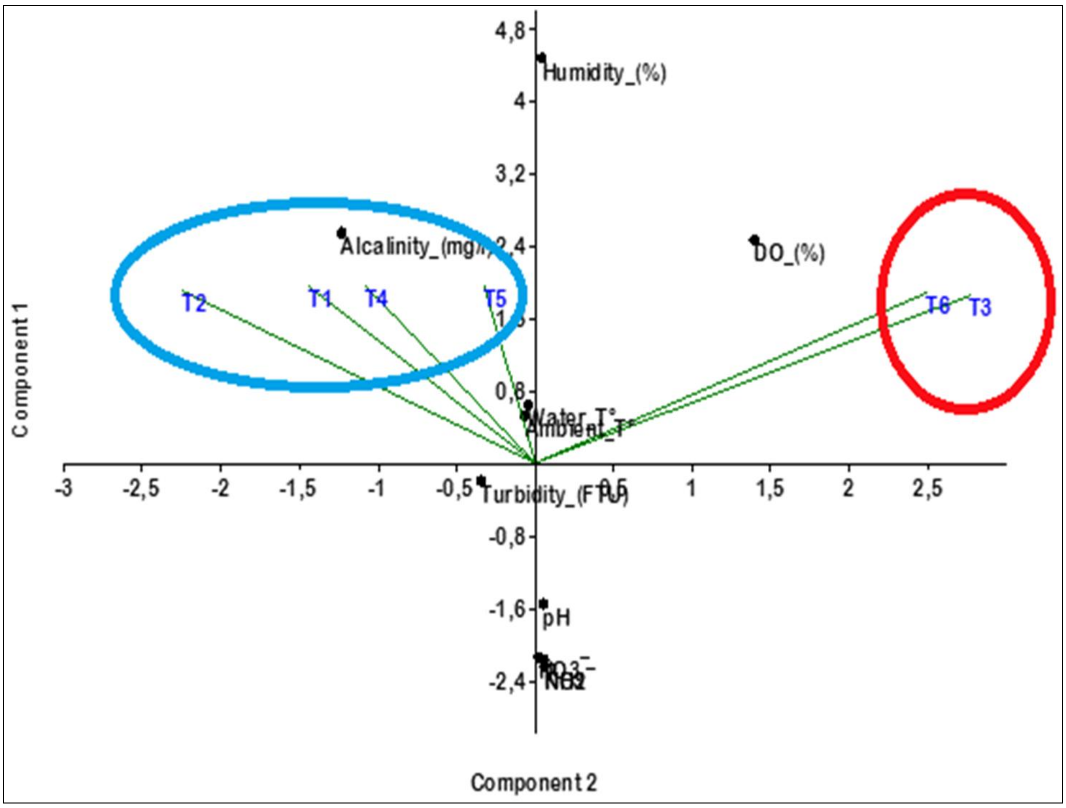


Fig 5. Graphical representation of the effect of treatments on water parameters

3.5. Effect of ambient temperature on water dissolved oxygen inside and Out of the greenhouse

The results revealed a significant positive relationship between ambient temperature and dissolved oxygen (DO) in both systems, though the strength and nature of this association differed between environments. Inside the greenhouse (Fig. 6c), the regression equation Y = 1.736X + 15.698 (r=0.618, p<0.0445) indicated that DO increase by 1.74% for every 1 °C rise in ambient temperature. In contrast, open-air systems exhibited a steeper slope (a = 2.779, r = 0.49, p< 0.05; Fig. 6d), with DO rising by 2.78% per 1 °C ambient increase. However, the moderate correlation coefficients (r<0.62) in both systems suggest ambient temperature alone explains only a portion of DO variability, leaving substantial influence to biotic and abiotic factors like photosynthesis, respiration, and nutrient dynamics. This aligns with prior findings (PCA results on Fig. 5) that highlighted biotic interactions as key modulators of water quality.

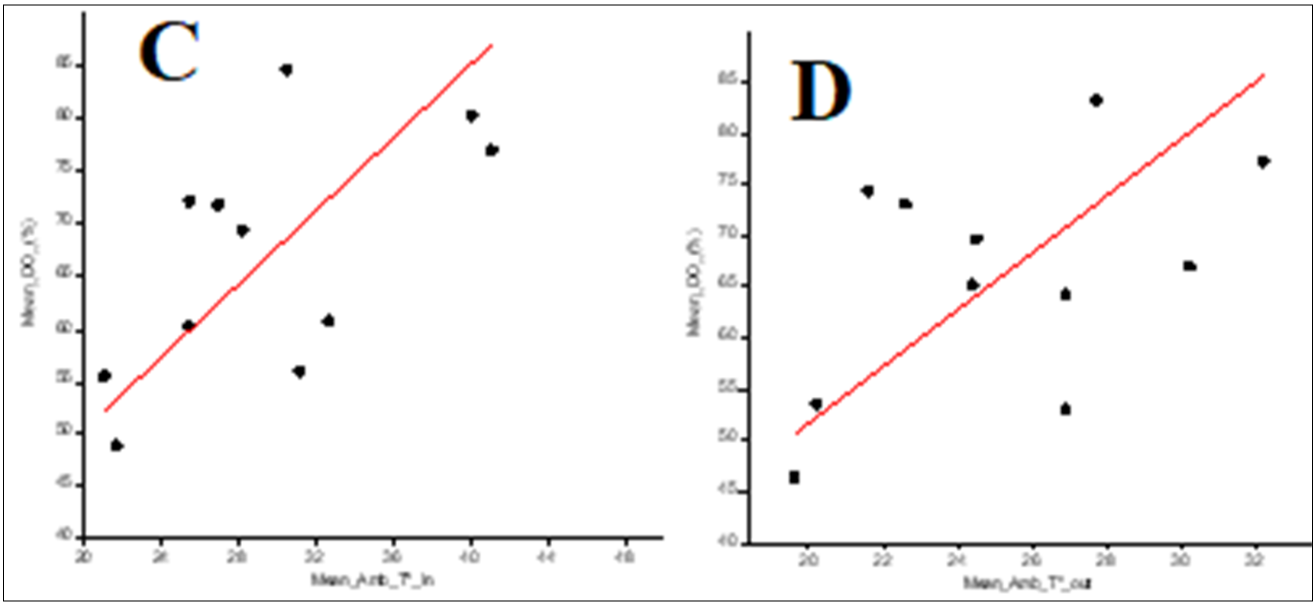


Fig 6: Regression curves indicating degree of dependence between ambient temperature and Dissolved Oxygen inside (c) and outside (d) the green house

3.6 Effect of water temperature on water quality inside and out of the greenhouse

3.6.1. Alkalinity

The relationship between water temperature and alkalinity exhibited consistent negative trends in both systems, though their statistical robustness and environmental drivers diverged significantly. Inside the greenhouse (Fig. 7e), a strong inverse correlation (r = -0.826, p = 0.011) was observed, with alkalinity declining by 6.62 mg/L per 1 °C temperature rise (Y = -6.622X + 0.525). In contrast, open-air systems (Fig. 7f) showed a weaker, non-significant trend (r = -0.586, p = 0.087), where alkalinity decreased by 4.73 mg/L per 1 °C increase (Y =-4.726X + 179.55). This baseline contrast suggests that open-air alkalinity is more strongly influenced by static external inputs, whereas greenhouse systems reflect a more isolated, temperature-dependent regime.

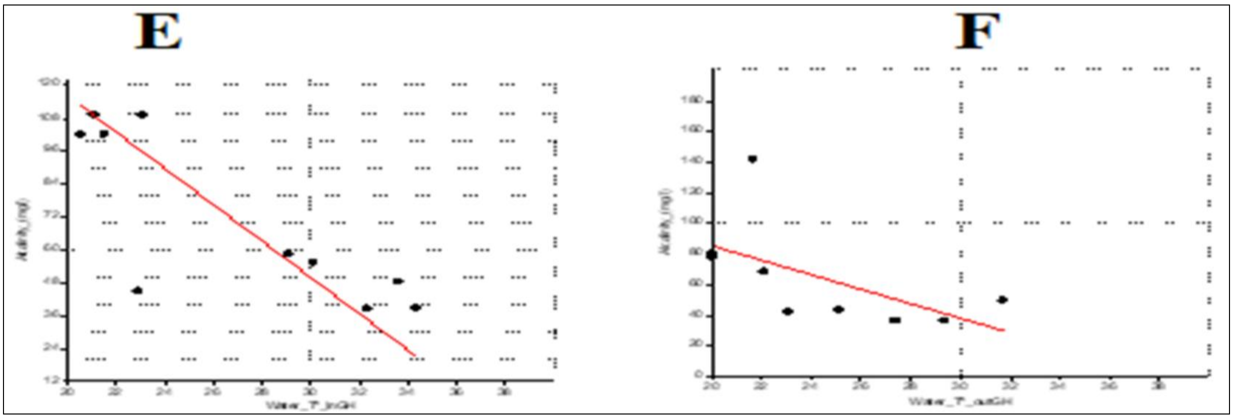


Fig 7: Linear Regression analysis indicating degree of dependence between water temperature and alkalinity in (e) and out (f) the green house

3.6.2. Ammonium concentrations

The relationship between water temperature and ammonium (NH_4^+) concentrations followed a negative trend in both systems, but its statistical validity and environmental drivers diverged sharply. Inside the greenhouse (Fig. 8g), a strong inverse correlation (r = -0.787, p=0.0093) was observed, with NH_4^+ declining by 0.012 mg/L per 1 °C temperature rise (Y = -0.0121X + 0.525). In contrast, open-air systems (Fig. 8h) exhibited a steeper but statistically insignificant slope (a =-0.0251 mg/L per °C, r =-0.625, p = 0.0764), suggesting a moderate but unstable thermal influence.

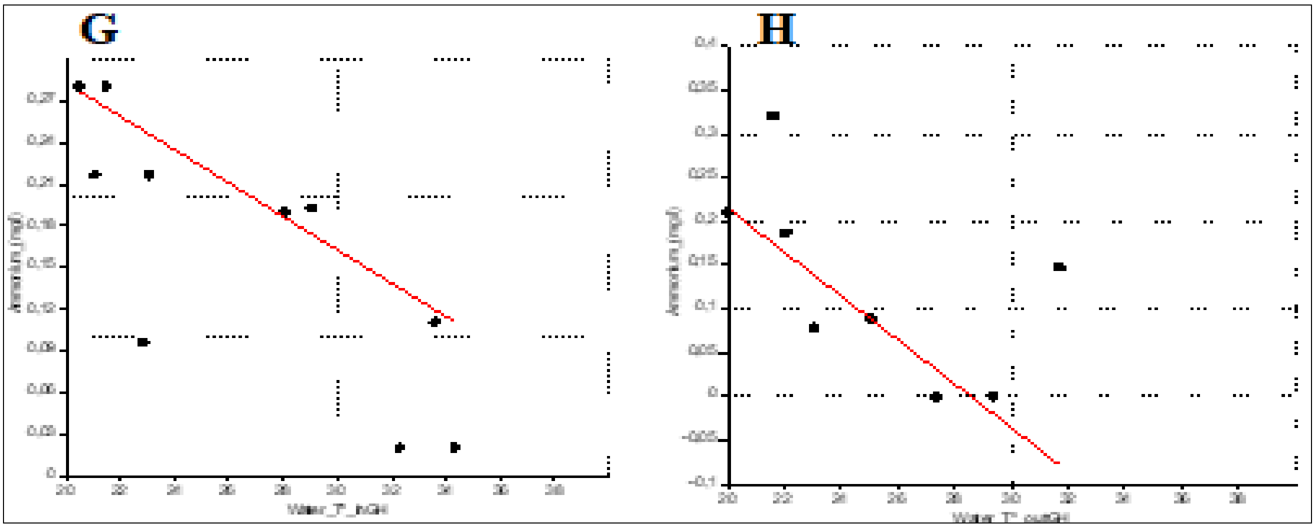


Figure 8 Regression analysis indicating degree of dependence between water temperature and ammonium concentration in (c) and out (d) the green house.

3.6.3. Turbidity

Result show that water turbidity was not related to water temperature both in and out the GH. This directly indicates that, turbidity dynamics were found to be independent of water temperature in both situations with no statistically meaningful relationship observed in either environment. Inside the greenhouse (Fig. 10e), the regression equation ($Y = -0.164X + 54.205$, $r = 0.031$, $p=0.932$) revealed a negligible slope (-0.164 NTU/ °C), indicating that turbidity remained virtually unaffected by temperature fluctuations. In stark contrast, open-air systems (Fig. 10f) exhibited a steep but statistically unreliable positive slope ($a = 78.386$ NTU/ °C, $r=0.269$, $p=0.484$), suggesting a bogus association driven by confounding variables rather than a true thermal effect. This aligns with prior analyses (PCA results), which identified turbidity as part of a nutrient-clarity cluster (with pH, NH_4^+, NO_3^-) but not directly tied to temperature. Over-all these patterns emphasizes that turbidity is governed by non-thermal drivers. In greenhouse systems, isolation from external disturbances (rainfall, wind) likely stabilized turbidity, rendering temperature irrelevant. Conversely, in open-air ponds, turbidity fluctuations are dominated by factors like sediment input.

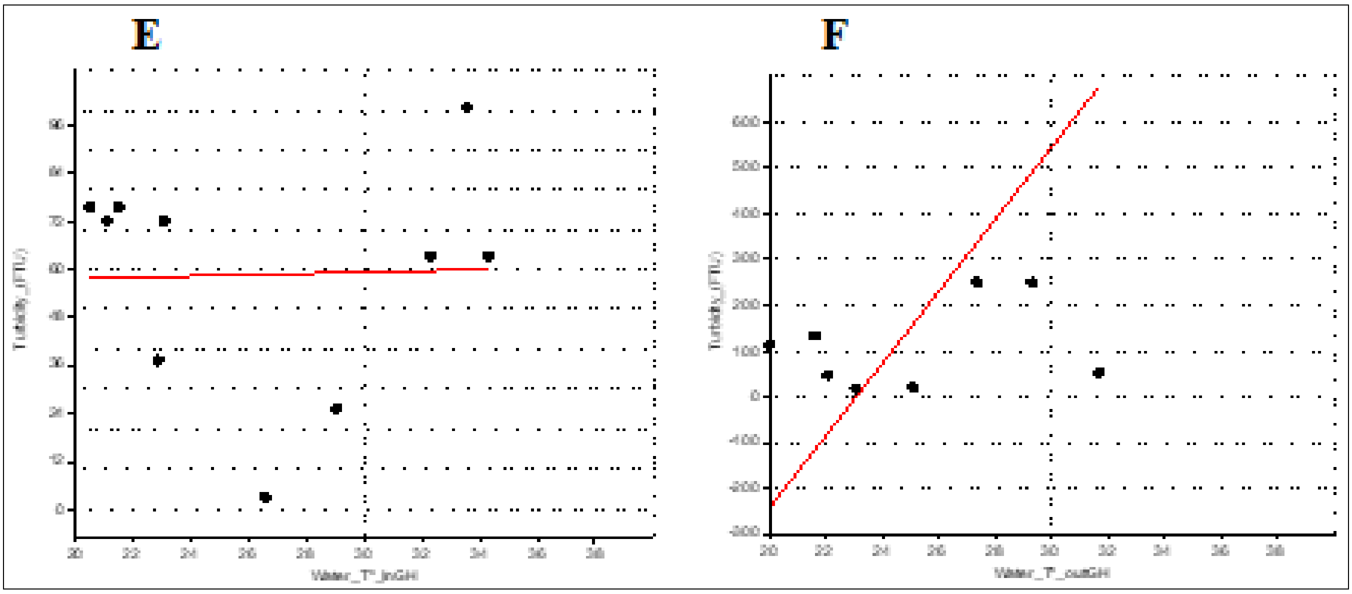


Figure 10: Regression analysis indicating degree of dependence between water temperature and turbidity in (e) and out (f) the green house.

4. Discussion

4.1. Effects of the greenhouse on the pond water quality

In this study, we have showed that, water temperatures in open ponds ranged from 19.7 °C to 31.1 °C, with a mean of 23.37 °C, while GH ponds exhibited a broader range of 21.2 °C to 34.4 °C and a higher mean of 25.98 °C. The GH system elevated the mean water temperature by 2.61 °C, creating conditions more suitable for *Clarias gariepinus*, a warm-water species whose optimal growth occurs within 25-30 °C [57, 58, 1, 59, 60, 61, 62]. The increased temperatures in the GH can be attributed to the greenhouse effect, wherein solar radiation penetrates the transparent GH structure, heats the water, and is partially trapped due to the insulating properties of the tank material. This mechanism mirrors the atmospheric greenhouse effect, where absorbed solar energy raises ambient temperatures. During daylight hours, a significant portion of incoming solar radiation is absorbed by the water, gradually elevating its temperature [60, 63, 62, 64, 65, 66]. Recent studies in Nigeria further refine these thermal thresholds, suggesting 20-27 °C as ideal for *C. gariepinus* growth, with temperatures exceeding 27 °C potentially impairing development [35]. Extreme temperatures below 12 °C or above 35 °C have been documented as lethal for this species, emphasizing the importance of thermal regulation in aquaculture [60, 61, 63, 67].

Dissolved oxygen (DO) concentrations in both GH and open ponds remained within the recommended range of 55-80% for fish growth [68], consistent with findings by [69], who observed comparable DO trends in similar systems. In this study, GH ponds exhibited DO levels ranging from 23.2% to 81.2% (mean: 56.04 ± 21%), while open ponds ranged from 21.90% to 79.70% (mean: 54.75 ± 19.67%). Contrary to [69], who reported higher DO in open systems, the GH ponds here showed marginally elevated DO concentrations (mean difference: 2%). This discrepancy may reflect differences in GH design, aeration practices, or biological activity, as photosynthetic organisms in GH systems could enhance oxygen production despite warmer temperatures typically reducing oxygen solubility. For instance, algal blooms within the GH, fueled by controlled light and nutrient availability, may offset oxygen depletion caused by higher metabolic rates in fish [70].

Additionally, during the experimental period, the ponds water remains slightly acid in and out the GH. Although pH values remain in desirable range suggested by [68]. In GH ponds, pH values ranged from 6.53 to 8.13 (mean: 6.91 ± 0.39), while open ponds exhibited a similar range of 6.56 to 8.02 (mean: 6.94 ± 0.36). This can be explain by the presence of some gases like carbon dioxide produced by organisms (plankton, fishes) that contributes to acidify the milieu. Also, this stability suggests that the GH environment did not amplify pH fluctuations, likely due to buffering effects from dissolved minerals in the water [71, 72]. Alkalinity, however, showed greater variability, with GH ponds recording lower mean values (58.82 ± 35.46 mg/L) compared to open ponds (65.96 ± 50.77 mg/L). The reduced alkalinity in GH systems may stem from accelerated microbial activity at higher temperatures, which can enhance carbonate consumption [73]. Additionally, this result shows that respiration, nitrification and sulphide oxidation were prior as chemical reaction in GH ponds. According to [74, 75] alkalinity is decreased or consumed by respiration, nitrification, and sulphide oxidation and to a lesser extent by evaporation and decomposing organic matter. Despite these variations, both systems maintained pH and alkalinity levels within ranges deemed safe for aquaculture, underscoring the GH's ability to stabilize critical water quality parameters without inducing extreme chemical shifts [76].

Nutrient concentrations remain within the normal ranges in both systems. There was an inverse correlation between water temperature and ammonium concentration, but stronger in GH ponds ($r = -0.787$, $p = 0.0093$). This shows that the increase of temperature has a negative effect on ammonium levels. Also, nitrates and nitrites concentrations were higher in the GH ponds than in the open ponds. It can be justifying by the presence of aerobic bacteria responsible of nitrification process, whose activity increase with temperature and pH [77]. Our results indicate a significant impact of GH technology through temperature on the microorganisms involve in the conversion of ammonia to nitrate (nitrification). This is similar to the findings of [24].

Results show that water turbidity was not related to water temperature both in and out the GH. Thus, turbidity and TDS levels were higher in the open ponds as compared to GH ponds. This can be justifying by the fact that open ponds were expose to rainfall (EPA 841F21007D, July 2021).

4.2. Relationship among water parameters in experimental and control tanks

The Principal Component Analysis (PCA) revealed distinct patterns in the relationships between water quality parameters and treatments, the results highlights both parameter interdependencies and treatment-specific trends. Notably, certain parameters exhibited stronger correlations with one another than with other variables. For instance, turbidity, pH, NH_4^+ (ammonium), NO_3^- (nitrate), and NO_2^- (nitrite) clustered closely along the PCA axes (Fig. 5), indicating their interrelated dynamics and limited individual influence on overall water quality variability. This is in line with the study of [78] and may be justified by the introduction of feeds and metabolic activities of fishes that contribute to the turbidity [79] but not by the influence of the GH. Similarly, ambient temperature and water temperature were positioned near each other on the biplot, reflecting their direct interdependence, as previously established in regression analyses. Temperature has a major effect on other parameters like DO, pH, TAN, nitrite-nitrogen and nitrate-nitrogen) [78]. This is more relevant in GH. These correlations underscore the interconnected nature of physicochemical processes within aquaculture systems. In parallel, the PCA delineated two distinct treatment groups. The first comprised experimental tanks (T1, T2, T4, T5), situated both inside and outside the greenhouse (GH), which clustered along the alkalinity axis due to shared biological or management practices (e.g., fish stocking, nutrient inputs). Conversely, control tanks (T3, T6) formed a separate cluster associated with stable dissolved oxygen (DO) levels, a trend attributed to the absence of fish-driven respiration or feeding activities. This can be justified with the fact that higher temperature increases the rate of bio-chemical activity of the micro biota, plant respiratory rate, and so increase in oxygen demand. It further cause decreased solubility of oxygen and also increased level of ammonia in water [68]. Water quality parameters have strong interrelationships and are interdependent; especially temperature has an important influence on other parameters [78]. Suggest that temperature with pH in predicting equation for Dissolved Oxygen, Total Ammonia-nitrogen, Nitrite-nitrogen and Nitrate- nitrogen for a high level of reliability.

4.3. Effect of ambient temperature on water dissolved oxygen

In our experimental tanks, dissolved oxygen concentrations ranged between 40% and 85%, a range attributed to the biweekly water renewal protocol. This practice ensured adequate oxygenation, aligning with the optimal dissolved oxygen (DO) levels recommended for *Clarias gariepinus* growth. According to [68], the desirable DO range for this species is 55% (5 mg/L), while [81] earlier established that DO levels ≥ 33% are sufficient for its development. In natural streams, oxygen availability is seldom limiting due to continuous water flow and atmospheric exchange, which promote aeration. However, within our experimental setup, significant DO variability was observed between control and stocked tanks. This disparity likely arose from organic matter decomposition-specifically, residual feed and fish waste-in the stocked tanks, which accelerated microbial respiration and reduced DO levels. Such findings underscore the critical balance between nutrient inputs and oxygen demand in closed aquaculture systems.

Temperature exerted a pronounced influence on water chemistry, particularly on ion solubility and alkalinity dynamics. Alkalinity, governed by bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), and hydroxide (OH^-) ions, serves as a pH buffer. Elevated temperatures reduce the solubility of carbon dioxide (CO_2), diminishing bicarbonate (HCO_3^-) concentrations and thereby lowering alkalinity. This thermal effect disrupts the chemical equilibrium among these ions, as warmer water favors the release of CO_2 into the atmosphere, destabilizing carbonate system balance. Similarly, temperature influenced ammonium (NH_4^+) dissociation: higher temperatures promoted the endothermic conversion of NH_4^+ to toxic ammonia (NH_3) and hydrogen ions (H^+), as per the reaction $NH_4^+ \rightarrow NH_3 + H^+$. This explains the observed decline in NH_4^+ concentrations in warmer conditions, a phenomenon corroborated by [82], who linked ammonia presence to fish excretory processes and thermal-driven equilibrium.

Turbidity and water color showed minimal initial variation across tanks, as all systems were sourced from the same river. However, temporal changes emerged as the experiment progressed. At the study's outset (February), the river exhibited low flow, yielding clear water. By May-August, heavy rains transformed the stream into a torrent, introducing suspended sediments. Post-filling, control tanks maintained relatively clear water, while experimental tanks developed yellowish-brown hues due to accumulated fish waste and uneaten feed. These color shifts highlighted organic loading differences between stocked and unstocked systems, though turbidity measurements remained statistically comparable, likely due to uniform sediment inputs from the shared water source.

For pH, no significant differences were observed between greenhouse (GH) and open-air systems. This stability suggests effective buffering by alkalinity components (HCO_3^-, CO_3^{2-}), which mitigated pH fluctuations despite temperature variations. The absence of divergence aligns with studies emphasizing alkalinity's role in maintaining pH equilibrium in aquatic systems, even under thermal stress.

5. Conclusion

Based on the methodology used in this study and the results obtained, it was concluded that greenhouses effectively addressee thermal limitations in high-altitude aquaculture by elevating mean water temperatures by 2.61 °C, creating optimal conditions (25-30 °C) for *Clarias gariepinus* growth while maintaining dissolved oxygen (DO) within safe ranges (55-80%). The GH environment enhanced nitrate concentrations but reduced nitrite levels, with ammonium declining due to temperature-driven dissociation into ammonia (NH_3), consistent with biochemical equilibrium. Despite temperature-induced alkalinity reductions, pH remained stable across systems, underscoring the buffering capacity of bicarbonate and carbonate ions. Turbidity showed minimal variation, though organic waste discolored experimental tanks, highlighting the need for feed management. Multivariate analysis identified temperature and alkalinity as primary variability drivers, with experimental tanks clustering by alkalinity and controls by stable DO, while nutrients like NH_4^+ and NO_3^- exhibited uniform baseline influences. It is therefore recommended that GH can be used for thermal optimization in high-altitude regions. However, ammonia levels and organic waste should be monitored to mitigate risks. Future research should explore biofiltration integration and long-term GH impacts to refine sustainable aquaculture practices in climate-vulnerable areas.

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