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Multivariate Analysis of Environmental Factors Influencing Fish Health and Productivity in Earthen Pond Aquaculture Systems in Sokoto State, Nigeria

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Abstract- Aquaculture productivity in earthen pond systems is strongly influenced by environmental conditions, particularly water quality, yet limited information exists on the combined effects of multiple environmental factors on fish health and productivity in northwestern Nigeria. This study investigated the environmental drivers influencing fish health and productivity in earthen pond aquaculture systems in Sokoto State, Nigeria, using multivariate statistical techniques. A field-based cross-sectional survey was conducted in selected earthen ponds, where water samples were collected and analyzed for temperature, pH, dissolved oxygen (DO), ammonia (NH_3), nitrite (NO_2^-), nitrate (NO_3^-), biochemical oxygen demand (BOD), and chemical oxygen demand (COD) following standard laboratory procedures. Fish productivity indicators, including survival rate, growth performance, disease incidence, and mortality rate, were also assessed. Data were analyzed using descriptive statistics, Pearson correlation, multiple linear regression, and Principal Component Analysis (PCA) at a 5% level of significance. The regression model was statistically significant ($R^2 = 0.74$, $p < 0.001$), indicating that physicochemical water quality parameters explained 74% of the variation in fish productivity. Dissolved oxygen significantly enhanced fish productivity, whereas elevated temperature, ammonia, nitrite, BOD, and COD exerted significant negative effects. Correlation analysis revealed strong positive associations between dissolved oxygen and fish survival and growth, whereas pollution-related variables exhibited significant negative relationships with productivity indicators. PCA extracted three principal components representing organic pollution, water chemistry balance, and thermal variation, accounting for 86.02% of the total variance. The study concludes that integrated water quality management is essential for enhancing sustainable aquaculture production and improving fish health in tropical earthen pond systems.

Keywords: Aquaculture, Earthen ponds, Water quality, Fish productivity.

I. INTRODUCTION

Aquaculture has emerged as one of the fastest-growing food production sectors globally, playing a pivotal role in enhancing food security, improving nutrition, and supporting the livelihoods of millions of people. According to the Food and Agriculture Organization (FAO, 2024), aquaculture now accounts for more than half of global aquatic animal production, reflecting its growing contribution to meeting the increasing demand for high-quality animal protein. Despite this remarkable growth, the intensification of aquaculture has been accompanied by significant environmental, biological, and management challenges, including deteriorating water quality, disease outbreaks, reduced production efficiency, and ecosystem degradation (Boyd & Tucker, 2019; Diana, 2009; Tacon & Metian, 2015).

Earthen pond aquaculture remains the predominant fish production system in many developing countries, including Nigeria, owing to its relatively low capital investment, ease of management, and suitability for both extensive and semi-intensive farming practices (Edwards, 2015). However, these systems are particularly susceptible to environmental fluctuations because water quality is influenced by both internal biological processes and external environmental conditions. Inadequate pond management, excessive feeding, high stocking densities, and poor water exchange often result in nutrient enrichment, organic matter accumulation, and physicochemical instability, thereby reducing fish productivity and increasing the likelihood of disease outbreaks (Bhatnagar & Singh, 2010; Bhatnagar & Devi, 2013; Stabili et al., 2022). Furthermore, agricultural runoff, domestic effluents, and other anthropogenic activities may introduce additional contaminants into pond ecosystems, further compromising water quality and fish health.

Water quality parameters—including dissolved oxygen, temperature, pH, ammonia, nitrite, nitrate, biochemical oxygen demand (BOD), chemical oxygen demand (COD), and turbidity—are widely recognized as fundamental determinants of fish growth, survival, reproduction, and overall productivity (Boyd, 2020; El-Sayed, 2020). Deviations from optimal physicochemical conditions can induce physiological stress, suppress immune responses, reduce feed utilization efficiency, and increase mortality rates (Wedemeyer, 1996; Boyd & Tucker, 2019). In particular, elevated concentrations of ammonia and nitrite have been shown to impair respiratory functions, damage gill tissues, and reduce fish growth. A recent study in Nigeria further demonstrated that deteriorating water quality was significantly associated with the occurrence of Aeromonas species in fish production systems, emphasizing the close relationship between environmental conditions and disease prevalence (Adah et al., 2025). Similarly, comparative assessments of aquaculture production systems have shown that earthen ponds generally exhibit higher microbial loads and greater physicochemical variability than more controlled systems such as tanks and recirculating aquaculture systems (Stabili et al., 2022).

Environmental variables in aquaculture systems are highly interconnected rather than operating independently. Changes in one physicochemical parameter frequently influence several others through biological, chemical, and ecological processes. For example, nutrient accumulation resulting from uneaten feed and fish excreta increases ammonia concentrations, stimulates microbial decomposition, elevates biochemical and chemical oxygen demand, and subsequently reduces dissolved oxygen availability. These interactions create complex environmental conditions that directly influence fish health and production performance (Boyd, 2020; Bhatnagar & Singh, 2010). Recent multivariate investigations have demonstrated that water quality variables exhibit strong interrelationships and can collectively explain variations in aquaculture productivity and environmental sustainability more effectively than individual parameters considered in isolation (Adah et al., 2025; Delgado-Villafuerte et al., 2026). Consequently, the application of multivariate statistical techniques provides a more comprehensive understanding of aquaculture ecosystems than traditional univariate analytical approaches.

Advances in data analytics and precision aquaculture have further highlighted the importance of integrated environmental monitoring for sustainable fish production. Multivariate statistical techniques such as Principal Component Analysis (PCA), Cluster Analysis, and Canonical Correspondence Analysis (CCA) have become valuable tools for reducing data complexity, identifying dominant environmental gradients, and explaining relationships among multiple water quality variables (Hair et al., 2019; Jolliffe, 2002). In addition, precision aquaculture technologies incorporating sensor networks, automated monitoring systems, and artificial intelligence have substantially improved the real-time assessment of environmental conditions and production efficiency (Føre et al., 2018). Recent developments in digital aquaculture have also demonstrated that fish behaviour, growth performance, and welfare can be effectively monitored through integrated sensing technologies, computer vision, and advanced analytical methods, thereby enhancing environmental management and production decision-making (Cui et al., 2025).

Despite these advances, empirical evidence regarding the combined influence of multiple environmental factors on fish health and productivity remains limited for small- and medium-scale earthen pond aquaculture systems in tropical developing countries. Most previous investigations have focused on individual water quality variables or controlled experimental environments, with relatively few studies employing comprehensive multivariate analytical approaches under practical production conditions in Nigeria (Ayinla, 2007; Delgado-Villafuerte et al., 2026). This knowledge gap is particularly evident in Sokoto State, where earthen pond aquaculture plays an important role in household income generation, food security, and rural economic development, yet scientific information on the complex interactions among environmental variables remains scarce.

Therefore, this study applies multivariate statistical analysis to investigate the environmental factors influencing fish health and productivity in earthen pond aquaculture systems in Sokoto State, Nigeria. Specifically, the study seeks to identify the key physicochemical water quality parameters affecting fish performance, examine the interrelationships among these environmental variables, and determine their combined influence on fish health and productivity. The findings are expected to provide evidence-based information that will enhance water quality management, improve fish production efficiency, and support the sustainable development of earthen pond aquaculture in tropical environments

Objectives of the Study

The study aimed to investigate the environmental factors influencing fish health and productivity in earthen pond aquaculture systems in Sokoto State, Nigeria. Specifically, the study sought to:

1. Identify the key physicochemical water quality parameters influencing fish health and productivity in earthen pond aquaculture systems.
2. Examine the relationships between selected environmental variables and fish productivity indicators in earthen pond aquaculture systems
3. Evaluate the combined influence of environmental variables on fish health and productivity using multivariate statistical techniques.

Hypotheses of the Study

The following null hypotheses were tested at the 0.05 level of significance:

H_{01}: Physicochemical water quality parameters do not significantly influence fish health and productivity in earthen pond aquaculture systems.

H_{02}: There is no significant relationship between selected environmental variables and fish productivity indicators in earthen pond aquaculture systems.

H_{03}: Multivariate statistical techniques do not significantly explain the combined interactions among environmental variables and fish health outcomes in earthen pond aquaculture

Materials and Methods

Study Area

The study was conducted in Sokoto State, northwestern Nigeria, located within the Sudano–Sahelian ecological zone between latitudes 12°00′N and 13°58′N and longitudes 4°00′E and 6°54′E. The state experiences a semi-arid climate characterized by a long dry season and a short rainy season. Mean annual temperatures range from approximately 28°C to 42°C, while annual rainfall varies between 500 and 700 mm, occurring mainly from June to September. Relative humidity is generally low during the dry season but increases during the rainy season. Agriculture constitutes the principal economic activity of the region, with crop production, livestock farming, and small-scale aquaculture serving as important sources of food, employment, and household income.

Study Design

A field-based cross-sectional survey design was adopted to evaluate the influence of physicochemical water quality parameters on fish health and productivity in earthen pond aquaculture systems. Primary data were collected through field measurements, laboratory analyses, and farm production records during a single production cycle.

Sampling Procedure

A multistage purposive sampling technique was employed. Twelve (12) active fish farms operating earthen pond aquaculture systems were purposively selected based on continuous production activities and accessibility. From each farm, three earthen ponds were selected, giving a total of thirty-six (36) sampling units. The selected ponds were stocked with commercially cultured fish species and had been under production for at least one production cycle before sampling.

Collection of Water Samples

Water samples were collected from each pond between 08:00 and 10:00 h to minimize diurnal fluctuations in physicochemical characteristics.

Sterile 500-mL polyethylene bottles, previously rinsed with distilled water and pond water, were used for sample collection.

Composite water samples were obtained by collecting equal volumes of water from three representative locations within each pond (inlet, centre, and outlet, where applicable) at a depth of approximately 30 cm below the water surface. The subsamples were thoroughly mixed to obtain a representative composite sample for each pond. Samples were labelled, stored in an ice-filled cooler (approximately 4°C), and transported immediately to the laboratory for analysis.

Determination of Physicochemical Parameters

Water quality analyses were conducted following the procedures described in the American Public Health Association (APHA, 2023).

Water Temperature

Water temperature was measured *in situ* using a calibrated digital thermometer and recorded in degrees Celsius (°C).

pH

The hydrogen ion concentration (pH) was measured *in situ* using a portable digital pH meter calibrated with standard buffer solutions (pH 4.0, 7.0, and 10.0) before use.

Dissolved Oxygen (DO)

Dissolved oxygen concentration was measured *in situ* using a portable dissolved oxygen meter and expressed as milligrams per litre (mg/L).

Ammonia (NH_3)

Ammonia concentration was determined in the laboratory using the phenate spectrophotometric method and expressed as mg/L.

Nitrite (NO_2^-)

Nitrite concentration was determined using the colorimetric spectrophotometric method after appropriate reagent addition according to APHA (2023).

Nitrate (NO_3^-)

Nitrate concentration was determined using the ultraviolet spectrophotometric screening method and expressed as mg/L.

Biochemical Oxygen Demand (BOD_5)

Biochemical oxygen demand was determined using the standard five-day incubation method. Initial dissolved oxygen concentration was measured immediately after sample collection, and samples were incubated at 20°C for five days before determining the final dissolved oxygen concentration. BOD_5 was calculated as the difference between the initial and final dissolved oxygen values.

Chemical Oxygen Demand (COD)

Chemical oxygen demand was determined using the dichromate closed reflux method under acidic conditions and expressed as mg/L.

Assessment of Fish Health and Productivity

Survival Rate

Survival rate was calculated as the percentage of fish harvested relative to the number initially stocked using the following equation:

Survival Rate (%) = (Number of fish harvested / Number of fish stocked) × 100

Growth Performance

Growth performance was assessed by determining the mean final body weight of randomly selected fish from each pond using a calibrated digital weighing balance. Weight gain was estimated by comparing the final body weight with the initial stocking weight obtained from farm production records.

Disease Incidence

Disease incidence was assessed through clinical examination of randomly selected fish and review of farm health records. Observable clinical signs, including abnormal swimming behaviour, skin lesions, fin erosion, ulceration, haemorrhage, reduced feeding activity, and body discoloration, were recorded. Disease incidence was expressed as the percentage of affected fish relative to the sampled population.

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Mortality Rate

Mortality rate was determined from farm production records by calculating the proportion of fish that died during the production cycle relative to the initial stocking population.

Statistical Analysis

Data were analysed using IBM SPSS Statistics version 29.0. Descriptive statistics, including means and standard deviations, were used to summarize the physicochemical characteristics of pond water and fish productivity indicators. Pearson's product-moment correlation analysis was performed to determine the relationships among environmental variables and fish productivity indicators.

Multiple linear regression analysis was conducted to evaluate the influence of physicochemical water quality parameters on fish productivity. Prior to regression analysis, assumptions of normality, linearity, independence of errors, homoscedasticity, and multicollinearity were assessed.

Principal Component Analysis (PCA) with Varimax rotation was performed to identify the major environmental factors influencing fish health and productivity and to reduce the dimensionality of the environmental dataset. The suitability of the data for PCA was assessed using the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy and Bartlett's Test of Sphericity. Components with eigenvalues greater than 1.0 were retained for interpretation. Statistical significance was determined at the 5% level ($p < 0.05$).

Analysis and Results

Multiple Regression Analysis

Multiple linear regression analysis was conducted to determine the influence of physicochemical water quality parameters on fish health and productivity in earthen pond aquaculture systems. The regression model was statistically significant, $F = 18.52$, $p < .001$, indicating that the selected environmental variables jointly explained a significant proportion of the variation in fish productivity. The model accounted for 74% of the total variance ($R^2 = 0.74$, Adjusted $R^2 = 0.71$), demonstrating strong explanatory power.

Among the predictor variables, dissolved oxygen exerted a significant positive influence on fish productivity ($\beta = 0.42$, $t = 3.85$, $p = .001$). In contrast, temperature ($\beta = –0.31$, $p = .024$), ammonia ($\beta = –0.39$, $p = .005$), nitrite ($\beta = –0.33$, $p = .009$), biochemical oxygen demand (BOD) ($\beta = –0.36$, $p = .003$), and chemical oxygen demand (COD) ($\beta = –0.41$, $p = .002$) significantly reduced fish health and productivity. Although pH and nitrate showed positive and negative relationships, respectively, their effects were not statistically significant ($p > .05$).

These findings provide sufficient evidence to reject the first null hypothesis (H_{01}), indicating that physicochemical water quality parameters significantly influence fish health and productivity in earthen pond aquaculture systems.

Table 1. Multiple Regression Analysis of the Influence of Physicochemical Water Quality Parameters on Fish Health and Productivity

Predictor	β	t	p
Temperature	–0.31	–2.41	.024
pH	0.18	1.92	.067
Dissolved oxygen	0.42	3.85	.001
Ammonia	–0.39	–3.12	.005
Nitrite	–0.33	–2.88	.009
BOD	–0.36	–3.45	.003
COD	–0.41	–3.67	.002
Nitrate	–0.21	–1.78	.089

Model Summary

Model	R	R²	Adjusted R²	F	p

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1	0.86	0.74	0.71	18.52	< .001

Pearson Correlation Analysis

Pearson's product-moment correlation analysis was performed to examine the relationships between physicochemical water quality parameters and fish productivity indicators. The results revealed significant positive and negative associations among the study variables.

Dissolved oxygen showed strong positive correlations with fish survival ($r = 0.74$) and growth performance ($r = 0.69$), indicating that increased oxygen availability enhances fish productivity. Conversely, ammonia, nitrite, BOD, and COD exhibited moderate to strong negative correlations with both survival and growth, suggesting that increasing pollution levels adversely affect fish performance. Temperature was negatively associated with fish productivity, whereas pH demonstrated weak positive relationships.

Overall, the results indicate that favourable water quality conditions promote fish health and productivity, while elevated concentrations of pollution-related variables reduce production performance. Consequently, the second null hypothesis (H_{02}) was rejected, confirming the existence of significant relationships between environmental variables and fish productivity indicators.

Table 2. Pearson Correlation Matrix of Environmental Variables and Fish Productivity Indicators

Variables	DO	Temp	pH	NH_3	NO_2	BOD	COD	Survival	Growth
DO	1.00								
Temperature	–0.48	1.00							
pH	0.32	–0.21	1.00						
NH_3	–0.61	0.44	–0.38	1.00					
NO_2	–0.57	0.41	–0.35	0.72	1.00				
BOD	–0.66	0.52	–0.30	0.68	0.60	1.00			
COD	–0.59	0.49	–0.28	0.70	0.63	0.88	1.00		
Survival	0.74	–0.55	0.41	–0.69	–0.65	–0.71	–0.68	1.00	
Growth	0.69	–0.51	0.38	–0.64	–0.60	–0.66	–0.63	0.82	1.00

Principal Component Analysis

Prior to Principal Component Analysis (PCA), sampling adequacy was assessed using the Kaiser–Meyer–Olkin (KMO) measure and Bartlett's Test of Sphericity. The KMO value of 0.81 indicated adequate sampling adequacy, while Bartlett's Test of Sphericity was statistically significant ($\chi^2 = 214.35$, $p < .001$), confirming that the data were suitable for factor extraction.

PCA extracted three principal components with eigenvalues greater than one, jointly explaining 86.02% of the total variance in the dataset. The first principal component (PC1) accounted for 51.33% of the total variance, followed by PC2 (23.44%) and PC3 (11.25%). The high cumulative variance indicates that these three components adequately summarize the multivariate relationships among the environmental variables and fish productivity indicators.

These findings support rejection of the third null hypothesis (H_{03}), indicating that multivariate statistical techniques effectively explain the interactions among environmental variables and fish health outcomes.

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Table 3. Total Variance Explained by Principal Components

Component	Eigen value	% Variance	Cumulative %
PC1	4.62	51.33	51.33
PC2	2.11	23.44	74.77
PC3	1.02	11.25	86.02

Rotated Component Matrix

The rotated component matrix revealed distinct environmental gradients underlying the observed dataset. The first principal component (PC1) exhibited strong positive loadings for ammonia, nitrite, BOD, and COD, together with strong negative loadings for survival and growth, indicating that this component represents an organic pollution gradient influencing fish productivity.

The second component (PC2) was characterized primarily by pH and dissolved oxygen, representing the water chemistry balance that supports favourable production conditions. The third component (PC3) showed the highest loading for temperature, suggesting that thermal variation constitutes an independent environmental factor affecting pond productivity.

Table 4. Varimax-Rotated Component Matrix

Variable	PC1	PC2	PC3
Temperature	0.52	–0.33	0.71
pH	–0.44	0.62	0.21
Dissolved oxygen	–0.78	0.41	0.12
Ammonia	0.81	–0.28	0.18
Nitrite	0.76	–0.25	0.22
BOD	0.85	–0.30	0.10
COD	0.88	–0.27	0.14
Survival	–0.83	0.45	–0.18
Growth	–0.79	0.48	–0.20

Discussion of Results

The present study demonstrates that physicochemical water quality parameters significantly influence fish health and productivity in earthen pond aquaculture systems in Sokoto State, Nigeria. The multiple regression model explained a substantial proportion of the variation in fish productivity ($R^2 = 0.74$), indicating that environmental conditions are major determinants of aquaculture performance. This finding corroborates the observations of Boyd and Tucker (2019) and Boyd (2020), who reported that water quality is the primary factor governing fish growth, survival, feed utilization, and overall pond productivity. The high explanatory power of the regression model further suggests that effective management of physicochemical conditions can substantially improve production efficiency in earthen pond aquaculture systems.

Among the measured variables, dissolved oxygen emerged as the most important positive predictor of fish health and productivity. Adequate dissolved oxygen supports aerobic metabolism, nutrient assimilation, immune competence, and efficient feed conversion, thereby promoting fish growth and survival (El-Sayed, 2020). This finding is consistent with Delgado-Villafuerte et al. (2026), who identified dissolved oxygen as one of the principal environmental variables influencing pond ecosystem performance. The pronounced influence of dissolved oxygen observed in the present study may be attributed to the semi-arid climatic conditions of Sokoto State, where elevated temperatures reduce oxygen solubility and increase the metabolic oxygen demand of cultured fish.

Conversely, ammonia and nitrite exhibited significant negative effects on fish productivity, indicating that nitrogenous waste accumulation constitutes a major environmental constraint in earthen pond aquaculture. Elevated concentrations of these compounds are known to impair respiratory function, reduce growth, suppress immune responses, and increase susceptibility to disease (Boyd, 2020; El-Sayed, 2020). The present findings also agree with those of Adah et al. (2025), who reported a close association between deteriorating water quality and the occurrence of *Aeromonas* species in Nigerian fish ponds. The relatively stronger negative relationships observed in this study may reflect limited water exchange, high organic loading, and suboptimal pond management practices commonly associated with small-scale earthen pond production systems.

The significant negative influence of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) further emphasizes the detrimental effects of organic pollution on aquaculture productivity. Elevated BOD and COD values generally indicate excessive accumulation of organic matter arising from uneaten feed, fish excreta, and decomposing biological materials. Increased microbial decomposition of these materials consumes dissolved oxygen, thereby creating hypoxic conditions that adversely affect fish health and growth. Similar observations were reported by Stabili et al. (2022), who found that earthen pond systems generally exhibit greater organic loading and microbial activity than more intensively controlled aquaculture systems. These findings highlight the importance of maintaining low organic pollution levels through appropriate feeding practices and regular pond maintenance.

The Pearson correlation analysis further demonstrated that water quality variables interact in a highly interconnected manner rather than acting independently. Dissolved oxygen was positively associated with fish survival and growth, whereas ammonia, nitrite, BOD, and COD showed consistent negative relationships with productivity indicators. These results reinforce the concept that deterioration in one environmental parameter often triggers corresponding changes in other water quality characteristics, producing cumulative effects on fish performance. Similar interrelationships among physicochemical variables have been reported by Boyd and Tucker (2019) and Delgado-Villafuerte et al. (2026), highlighting the need for integrated water quality management rather than focusing on individual parameters in isolation.

Principal Component Analysis (PCA) provided additional insight into the underlying environmental processes governing fish productivity by reducing the dataset to three principal components that explained 86.02% of the total variance. The first component was characterized by strong positive loadings for ammonia, nitrite, BOD, and COD and strong negative loadings for survival and growth, indicating that organic pollution represents the dominant environmental stressor affecting pond productivity. This finding is consistent with Hair et al. (2019), who noted that multivariate statistical techniques effectively identify latent structures within complex environmental datasets, and with Delgado-Villafuerte et al. (2026), who demonstrated that water quality variables in pond aquaculture are governed by interacting environmental processes rather than isolated physicochemical factors.

The second principal component was primarily associated with dissolved oxygen and pH, suggesting that these variables collectively represent the water chemistry conditions required to maintain favourable physiological environments for cultured fish. The third component, dominated by temperature, underscores the importance of thermal variation in pond aquaculture, particularly under the semi-arid climatic conditions of northwestern Nigeria. Elevated temperatures increase fish metabolic rates while simultaneously reducing dissolved oxygen availability, thereby intensifying environmental stress and limiting productivity. Similar observations have been reported in tropical aquaculture systems, where temperature is recognized as a key regulator of water quality dynamics and fish physiological responses (Boyd, 2020; El-Sayed, 2020).

Overall, the findings demonstrate that fish productivity in earthen pond aquaculture systems is determined by the combined effects of multiple interacting environmental variables rather than by any single physicochemical factor. The predominance of pollution-related variables among the principal components indicates that effective pond management should prioritize improved feeding practices, regular water quality monitoring, waste reduction, adequate water exchange, and maintenance of optimal dissolved oxygen concentrations. The successful application of multiple regression, correlation analysis, and Principal Component Analysis further demonstrates the usefulness of multivariate statistical techniques for identifying critical environmental drivers and supporting evidence-based decision-making aimed at improving sustainable aquaculture production in tropical earthen pond systems.

CONCLUSION

This study investigated the environmental factors influencing fish health and productivity in earthen pond aquaculture systems in Sokoto State, Nigeria, using multivariate statistical techniques. The findings

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demonstrated that physicochemical water quality parameters are significant determinants of fish productivity, with dissolved oxygen positively influencing fish survival and growth, while elevated temperature, ammonia, nitrite, biochemical oxygen demand (BOD), and chemical oxygen demand (COD) exerted significant negative effects. These results underscore the critical role of water quality management in sustaining productive earthen pond aquaculture systems.

The correlation analysis further revealed strong interrelationships among environmental variables and fish productivity indicators, confirming that changes in one water quality parameter can influence several others simultaneously. Moreover, Principal Component Analysis (PCA) successfully identified three principal environmental components representing organic pollution, water chemistry balance, and thermal variation, which together explained a substantial proportion of the variability in fish health and productivity. These findings demonstrate that fish production in earthen pond systems is governed by complex interactions among multiple environmental factors rather than by individual physicochemical variables acting independently.

The study therefore concludes that maintaining optimal water quality through effective environmental management is fundamental to improving fish health, enhancing productivity, and promoting the sustainability of earthen pond aquaculture in tropical environments. Furthermore, the successful application of multivariate statistical techniques confirms their usefulness as robust analytical tools for identifying key environmental drivers, simplifying complex ecological datasets, and supporting evidence-based management decisions. The findings provide valuable scientific evidence that can guide fish farmers, extension personnel, researchers, and policymakers in developing integrated water quality management strategies to improve aquaculture production and strengthen food security in Nigeria and other tropical developing countries.

Recommendations

Based on the findings of this study, the following recommendations are made:

1. Routine monitoring of water quality should be implemented in earthen pond aquaculture systems, with particular attention to dissolved oxygen, temperature, pH, ammonia, nitrite, nitrate, biochemical oxygen demand (BOD), and chemical oxygen demand (COD), to facilitate the early detection and correction of unfavorable environmental conditions.
2. Fish farmers should adopt improved pond management practices, including appropriate stocking densities, efficient feeding regimes, regular water exchange, and periodic removal of accumulated sediments, to minimize organic pollution and maintain optimal water quality for fish growth and survival.
3. Measures to maintain adequate dissolved oxygen concentrations, such as the use of aeration systems where feasible, reduction of excessive organic loading, and proper pond water circulation, should be encouraged to enhance fish health, growth performance, and overall productivity.
4. Government agencies, agricultural extension services, and aquaculture development organizations should strengthen farmer training programmes on best management practices for water quality monitoring, pollution control, disease prevention, and sustainable earthen pond aquaculture production.
5. Future research should undertake long-term and seasonal assessments of environmental conditions in earthen pond aquaculture systems and integrate advanced analytical approaches, including multivariate statistics, machine learning, and sensor-based monitoring technologies, to improve the prediction and management of factors affecting fish health and productivity.

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