

Dietary Turmeric Enhances Physiological Resilience of African Catfish (*Clarias gariepinus*) Following *Aeromonas hydrophila* Challenge: An Integrated Physiological Assessment

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ABSTRACT

Improving physiological resilience to bacterial infection has become an important objective in sustainable aquaculture because disease outbreaks continue to compromise fish health, survival and production efficiency. Although dietary turmeric (*Curcuma longa*) has been reported to improve fish health, its effects on the integrated physiological responses associated with bacterial challenge remain poorly understood in African catfish (*Clarias gariepinus*). This study evaluated the effects of graded dietary turmeric supplementation on physiological resilience following experimental *Aeromonas hydrophila* challenge through an integrated assessment of post-challenge survival, haematological profile, platelet indices, serum biochemical profile, electrolyte balance, antioxidant status and cortisol response. Fish were fed diets containing 0% (control), 0.5%, 1.0% or 2.0% dietary turmeric for 16 weeks before bacterial challenge. Dietary turmeric significantly improved post-challenge survival ($P < 0.001$), with the highest survival ($86.03 \pm 2.95\%$) recorded in fish fed the 1.0% turmeric diet compared with the control ($55.53 \pm 1.40\%$). Turmeric supplementation also produced coordinated improvements in haematological characteristics, platelet indices, serum biochemical profile and electrolyte homeostasis, while enhancing tissue reduced glutathione concentrations and moderating the cortisol response following bacterial infection. These physiological responses collectively indicate an improved capacity to maintain homeostasis during bacterial stress. The present study demonstrates that the benefits of dietary turmeric extend beyond improved survival to encompass coordinated physiological adaptations that enhance resilience to *A. hydrophila* infection. These findings support further evaluation of dietary turmeric as a functional phyto-genic feed additive for improving fish health and disease resilience in African catfish culture.

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INTRODUCTION

Bacterial diseases remain one of the greatest constraints to sustainable aquaculture, causing substantial economic losses through increased mortality, reduced growth and impaired production efficiency. Among these diseases, Motile Aeromonas Septicemia (MAS), caused by *Aeromonas hydrophila*, is one of the most important bacterial infections affecting freshwater aquaculture worldwide. The pathogen infects a wide range of cultured fish species, including African catfish (*Clarias gariepinus*), where it causes haemorrhagic septicaemia, skin ulceration, fin erosion and systemic infection that frequently result in high mortality. Recent reviews have further highlighted that the persistence of *A. hydrophila* in aquaculture systems, together with its ability to exploit environmental and host-related stressors, continues to make it a major obstacle to sustainable fish production (Abdella et al., 2024; Abdul Kari et al., 2022; Abdul Kari, 2025). Beyond the economic losses, *A. hydrophila* infection also compromises fish welfare by inducing physiological stress, tissue damage and disruption of normal biological functions, emphasising the need for effective and sustainable disease management strategies. The widespread use of antibiotics has traditionally been the primary strategy for controlling bacterial diseases in aquaculture. However, their extensive and often indiscriminate application has contributed to the emergence of antimicrobial-resistant bacteria, reduced treatment efficacy

and increased concerns regarding antimicrobial residues and environmental contamination. Recent surveillance studies have reported a high prevalence of antimicrobial resistance in *A. hydrophila* isolates from aquatic animals, highlighting the growing challenge of managing bacterial infections using conventional antibiotics (Jeamsripong et al., 2025). These concerns have accelerated the search for sustainable disease management strategies that enhance host resistance while reducing dependence on antimicrobial drugs. Recent reviews have therefore identified phyto-genic feed additives, probiotics, vaccines and other natural health-promoting compounds as promising alternatives for improving fish health and supporting sustainable aquaculture production (Elgendy et al., 2024; Kılıç & Gültekin, 2024).

Turmeric (*Curcuma longa*) has emerged as one of the most extensively investigated phyto-genic feed additives in aquaculture because of its broad biological activities and favourable safety profile. Its principal bioactive compound, curcumin, possesses well-documented antioxidant, anti-inflammatory, antimicrobial and immunomodulatory properties that can enhance fish health and improve resistance to environmental and pathogenic stressors. Recent experimental studies have demonstrated that dietary turmeric supplementation improves haematological characteristics, antioxidant capacity, immune function and disease resistance in several cultured fish species, although the magnitude of these responses varies with fish species, dietary inclusion

level and experimental conditions. For example, Eissa *et al.* (2024) reported that dietary curcumin improved antioxidant status, immune-related responses and blood biochemical indices in red tilapia, while El-Gammal *et al.* (2025) demonstrated enhanced antioxidant capacity, immune responses and resistance to *Aeromonas hydrophila* infection in Nile tilapia fed curcumin-supplemented diets. These findings suggest that turmeric is not only a growth-promoting feed additive but also an important nutritional strategy for strengthening physiological resilience against bacterial diseases in aquaculture.

African catfish (*Clarias gariepinus*) is one of the most important freshwater aquaculture species in sub-Saharan Africa because of its rapid growth, tolerance to diverse culture conditions and high market demand. Consequently, considerable effort has been directed towards identifying functional feed additives that improve health and increase resistance to infectious diseases in this species. Recent studies have shown that dietary turmeric supplementation enhances growth performance, digestive enzyme activity, haematological characteristics, antioxidant capacity and disease resistance in African catfish, indicating its potential as a multifunctional phytochemical feed additive (Wei *et al.*, 2024). Similar improvements in physiological and antioxidant responses have also been reported for other phytochemical additives in African catfish, suggesting that natural feed additives can strengthen host resilience under culture conditions (Jimoh *et al.*, 2024; Wei *et al.*, 2025). Despite these advances, most published studies have focused on growth performance or individual physiological indicators, with relatively few evaluating the integrated response of haematological, biochemical and oxidative stress biomarkers following bacterial challenge. As a result, the physiological mechanisms through which dietary turmeric enhances resilience against *A. hydrophila* infection in African catfish remain incompletely understood. Addressing this knowledge gap is important for developing evidence-based nutritional strategies that improve fish health while reducing reliance on antimicrobial agents in aquaculture. Recent work published in the FUDMA Journal of Sciences has also evaluated dietary interventions and feed utilisation in *C. gariepinus* (Sada *et al.*, 2025).

Despite the growing interest in dietary turmeric as a functional feed additive, important knowledge gaps remain regarding its role in improving physiological resilience during bacterial infection. Most previous studies have evaluated growth performance, antioxidant activity or selected immune responses independently, whereas integrated assessments of haematological, serum biochemical and oxidative stress responses following *Aeromonas hydrophila* challenge remain limited, particularly in African catfish. Consequently, it is still unclear whether the protective effects of dietary turmeric extend beyond improvements in production performance to include coordinated physiological adaptations that enhance the ability of fish to withstand bacterial infection. Addressing this gap is essential for understanding the mechanisms through which phytochemical feed additives improve fish health and for developing evidence-based nutritional strategies that support sustainable aquaculture.

Therefore, the present study evaluated the effects of graded dietary turmeric supplementation on post-challenge survival,

haematological characteristics, serum biochemical indices and oxidative stress responses in African catfish (*Clarias gariepinus*) following experimental *Aeromonas hydrophila* infection. By integrating conventional health indicators with oxidative stress biomarkers, the study aimed to provide a comprehensive assessment of the physiological responses associated with dietary turmeric supplementation during bacterial challenge. We hypothesised that dietary turmeric would enhance physiological resilience by improving haematological, biochemical and antioxidant responses, thereby increasing the ability of African catfish to withstand *A. hydrophila* infection.

MATERIALS AND METHODS

Experimental Fish and Ethical Approval

Apparently healthy African catfish (*Clarias gariepinus*) juveniles with an average initial body weight of approximately 50 g were obtained from a commercial hatchery in Benin City, Edo State, Nigeria, and transported to the Wet Laboratory of the Department of Fisheries, Delta State University, Abraka, Nigeria. Prior to the commencement of the feeding trial, the fish were acclimated to laboratory conditions for two weeks and fed a commercial catfish diet twice daily. During the acclimation period, fish were monitored daily to ensure good health, while dead or unhealthy individuals were removed immediately.

At the end of the acclimation period, healthy fish were randomly distributed into experimental tanks according to the experimental design. Throughout the study, fish were handled carefully to minimise unnecessary stress, and all experimental procedures involving fish complied with institutional guidelines for the care and use of experimental animals in research. The experimental protocol was reviewed and approved by the Research Ethics Committee of Delta State University, Abraka, Nigeria. All efforts were made to minimise fish suffering during routine handling, sampling and the subsequent *Aeromonas hydrophila* challenge experiment.

Experimental Diets

Four experimental diets were formulated to be isonitrogenous and isoenergetic, differing only in the level of dietary turmeric (*Curcuma longa*) supplementation. Turmeric powder was incorporated into the diets at 0% (control), 0.5%, 1.0% and 2.0% of the diet and designated as T1, T2, T3 and T4, respectively. All other dietary ingredients were maintained at similar proportions to ensure that differences in fish performance were attributable to dietary turmeric supplementation rather than nutrient composition. The dry ingredients were weighed individually, thoroughly mixed and pelleted using a laboratory pellet mill. The pellets were dried at room temperature, packaged in airtight polyethylene bags and stored in a cool, dry environment until use. Representative samples of each diet were analysed for proximate composition according to standard methods of the Association of Official Analytical Chemists (AOAC, 2019) to confirm that the diets met the intended nutritional specifications. The ingredient composition and analysed proximate composition of the experimental diets are presented in Table 1.

Table 1: Formulation and Analysed Proximate Composition of Experimental Diets Containing Graded Levels of dietary Turmeric Extract. A. Ingredient Composition of Experimental Diets (%). B. Analysed Proximate Composition of Experimental Diets (%)

Ingredient	Control (0%)	0.5% turmeric	1.0% turmeric	2.0% turmeric
Fishmeal (65.5% CP)	30.00	30.00	30.00	30.00
Soybean meal (48.0% CP)	40.00	40.00	40.00	40.00
Maize (9.5% CP)	15.00	15.00	15.00	15.00
Wheat bran (14.0% CP)	7.70	7.20	6.70	5.70
Palm oil	5.00	5.00	5.00	5.00
Mineral premix	1.00	1.00	1.00	1.00
Vitamin E supplement	0.60	0.60	0.60	0.60
Vitamin premix	0.40	0.40	0.40	0.40
L-Lysine	0.20	0.20	0.20	0.20
Methionine	0.10	0.10	0.10	0.10
Turmeric extract	0.00	0.50	1.00	2.00
Total	100.00	100.00	100.00	100.00
Moisture	9.27	9.27	9.27	9.27
Crude protein	41.35	41.31	41.27	41.19
Crude lipid	8.91	8.92	8.93	8.95
Crude fibre	3.12	3.16	3.19	3.26
Ash	7.75	7.75	7.74	7.74

Footnote: Experimental Diets were Formulated to be Isonitrogenous (Approximately 41.5% Crude Protein) and Differed only in Dietary Turmeric Extract Inclusion Level (0–2% of diet). Proximate Composition was Determined According to Standard AOAC Procedures

Experimental Design and Feeding Trial

Following the acclimation period, healthy African catfish (*Clarias gariepinus*) juveniles were randomly assigned to four dietary treatments in a completely randomised design, with three replicate tanks per treatment. Each treatment received one of the experimental diets containing 0% (control), 0.5%, 1.0% or 2.0% dietary turmeric. Fish were hand-fed to apparent satiation twice daily (09:00 and 17:00 h) for 16 weeks. Feed intake was monitored throughout the feeding trial, and any uneaten feed was removed to maintain good water quality. Fish were weighed collectively at two-week intervals to monitor growth and adjust feeding rates accordingly. Throughout the experiment, the fish were observed daily for feeding behaviour, general health and mortality. Dead fish, when observed, were removed immediately and recorded. Water quality parameters were monitored regularly and maintained within acceptable limits for African catfish culture to minimise environmental variation among treatments. At the end of the 16-week feeding trial, fish from each dietary treatment were subjected to an experimental *Aeromonas hydrophila* challenge to evaluate the effects of dietary turmeric supplementation on post-challenge physiological resilience.

Experimental *Aeromonas hydrophila* Challenge

Following the 16-week feeding trial, fish from each dietary treatment were subjected to an experimental *Aeromonas hydrophila* challenge to evaluate the effects of dietary turmeric supplementation on post-challenge physiological resilience. A virulent strain of *A. hydrophila* was obtained from the Department of Microbiology, Delta State University, Abraka, Nigeria, and cultured in Tryptic Soy Broth (TSB) at 28°C for 24 h. The bacterial suspension was subsequently adjusted to the required concentration using sterile phosphate-buffered saline (PBS), and the challenge dose was standardised by plate count prior to inoculation. Fish were lightly anaesthetised before challenge and individually injected intraperitoneally with 0.1 mL of the bacterial suspension containing 1×10^7 CFU mL⁻¹ of *A. hydrophila*. Following inoculation, fish were returned to their respective

experimental tanks and observed for seven consecutive days. Mortalities were recorded daily, and dead fish were removed immediately to maintain water quality. At the end of the observation period, post-challenge survival was calculated for each treatment and used as an indicator of resistance to *A. hydrophila* infection.

Blood Sampling and Serum Preparation

At the end of the 7-day post-challenge observation period, blood samples were collected from three fish per replicate tank (nine fish per treatment) that were randomly selected from the surviving fish. Prior to sampling, fish were anaesthetised to minimise handling stress. Blood was collected from the caudal vein using sterile disposable syringes fitted with 23-gauge needles. Approximately half of each blood sample was transferred immediately into tubes containing ethylenediaminetetraacetic acid (EDTA) for haematological analysis, while the remaining portion was dispensed into plain tubes and allowed to clot at room temperature. The clotted blood samples were centrifuged at $3,000 \times g$ for 10 min, after which the serum was carefully separated and transferred into sterile microcentrifuge tubes. Serum samples were stored at -20°C until analysis of biochemical and oxidative stress biomarkers.

Haematological Analysis

Haematological analyses were performed using fresh whole blood collected into EDTA-treated tubes immediately after sampling. Packed cell volume (PCV) was determined using the microhaematocrit method, while haemoglobin concentration (Hb) was measured using the cyanmethemoglobin method. Red blood cell (RBC) and white blood cell (WBC) counts were determined using a Neubauer haemocytometer following appropriate dilution of the blood samples. Erythrocyte indices, including mean corpuscular volume (MCV), mean corpuscular haemoglobin (MCH) and mean corpuscular haemoglobin concentration (MCHC), were calculated using standard formulae based on PCV, Hb and RBC values. Differential leukocyte counts (lymphocytes, neutrophils, monocytes, eosinophils and basophils) were

determined from Wright–Giemsa-stained blood smears by microscopic examination. All haematological analyses were conducted according to established procedures for fish haematology (Blaxhall & Daisley, 1973; Bain et al., 2016).

Serum Biochemical Analyses

Serum biochemical analyses were performed using standard diagnostic procedures. Liver function was evaluated by measuring aspartate aminotransferase (AST), alanine aminotransferase (ALT), alkaline phosphatase (ALP) and gamma-glutamyl transferase (GGT). Renal function was assessed using serum creatinine and urea concentrations. Serum electrolyte profiles included sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), chloride (Cl^-) and bicarbonate (HCO_3^-) concentrations. Serum protein status was evaluated by determining albumin, bilirubin, total bilirubin and total protein using standard laboratory methods.

Oxidative Stress Biomarkers and Serum Cortisol

Reduced glutathione (GSH) concentrations were determined in gut and liver tissues collected after the feeding trial using standard spectrophotometric procedures. Tissue samples were homogenized in an appropriate phosphate buffer, centrifuged, and the resulting supernatants were used for GSH determination according to established methods. GSH concentrations were expressed as U mg^{-1} protein.

To assess the endocrine stress response following *Aeromonas hydrophila* challenge, blood samples were collected at 0 h, 1 h, 24 h and 7 days post-challenge. Serum was separated by centrifugation and stored at -20°C until analysis. Serum cortisol concentrations were determined using a commercially available enzyme-linked immunosorbent assay (ELISA) kit according to the manufacturer's instructions and expressed as ng mL^{-1} .

Water Quality Monitoring

Water quality parameters were monitored throughout the feeding trial to ensure that environmental conditions remained suitable for African catfish culture. Water temperature ($^\circ\text{C}$), dissolved oxygen (mg L^{-1}) and pH were measured daily using a portable multiparameter meter. Water quality was maintained within the recommended ranges for *Clarias gariepinus* culture throughout the experimental period. Mean values for the measured water quality parameters are presented in Table 3.

Statistical Analysis

Data were analysed using IBM SPSS Statistics version 27.0 (IBM Corp., Armonk, NY, USA). Before statistical analysis, all datasets were examined for normality using the Shapiro–Wilk test and for homogeneity of variances using Levene's test. Percentage data were arcsine square-root transformed where necessary to satisfy the assumptions of parametric analysis. Differences among dietary treatments were evaluated using one-way analysis of variance (ANOVA). Where significant differences were detected ($P < 0.05$), treatment means were separated using Duncan's Multiple Range Test. Data are presented as mean $\pm$ standard deviation (SD), and statistical significance was accepted at $P < 0.05$.

RESULTS AND DISCUSSION

Results

Survival Following *Aeromonas hydrophila* Challenge

Survival before bacterial challenge did not differ significantly among dietary treatments ($P > 0.05$) (Table 2). However, following experimental *Aeromonas hydrophila* challenge, dietary turmeric supplementation significantly improved post-challenge survival ($P < 0.001$). Fish fed the 1.0% turmeric diet exhibited the highest survival ($86.03 \pm 2.95\%$), followed by the 2.0% ($75.90 \pm 2.15\%$) and 0.5% ($70.57 \pm 1.37\%$) treatment groups, whereas the control group recorded the lowest survival ($55.53 \pm 1.40\%$).

Table 2: Survival of *Clarias gariepinus* Fed Diets Containing Graded Levels of Dietary Turmeric Before and After *Aeromonas Hydrophila* Challenge

Parameter	Control (0%)	0.5% Turmeric	1.0% Turmeric	2.0% Turmeric	P-value
Survival before bacterial challenge (%)	84.44 ± 4.44^a	93.33 ± 3.85^a	84.44 ± 4.44^a	86.67 ± 6.67^a	>0.05
Survival after <i>Aeromonas hydrophila</i> challenge (%)	55.53 ± 1.40^c	70.57 ± 1.37^b	86.03 ± 2.95^a	75.90 ± 2.15^b	<0.001

Values are Presented as Mean $\pm$ Standard Deviation (SD) Based on Three Replicate Tanks per Treatment ($n = 3$). Means within the Same Row with Different Superscript Letters Differ Significantly ($P < 0.05$) According to one-way Analysis of Variance (ANOVA) Followed by Duncan's Multiple Range Test

The cumulative mortality pattern following *Aeromonas hydrophila* challenge is presented in Figure 1. Mortality increased progressively in all treatment groups during the first five days after challenge before reaching a plateau. Fish fed the control diet consistently exhibited the highest cumulative mortality throughout the observation period. In contrast, fish receiving dietary turmeric showed lower cumulative

mortality, with the 1.0% turmeric group maintaining the lowest mortality from the beginning of the challenge until the end of the seven-day observation period. The 0.5% and 2.0% turmeric groups also exhibited lower cumulative mortality than the control, although their responses were less pronounced than those observed at the 1.0% inclusion level.

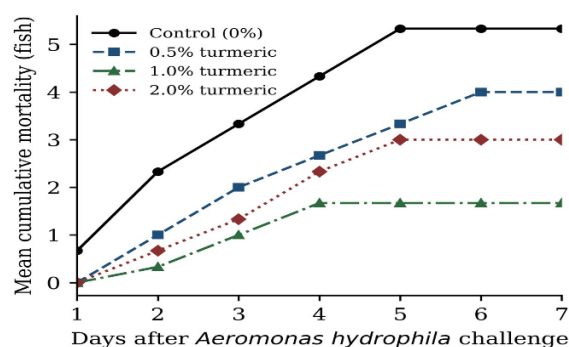


Figure 1: Mean Cumulative Mortality of *Clarias Gariepinus* Fed Diets Containing Graded Levels of Dietary Turmeric (0, 0.5, 1.0 and 2.0%) During the 7-day Period Following Experimental *Aeromonas hydrophila* Challenge. Values Represent the Mean Cumulative Number of Fish that Died per Replicate Tank (n = 3).

Water Quality

Water quality parameters remained within the acceptable range for African catfish culture throughout the 16-week feeding trial (Table 3). No significant differences ($P > 0.05$) were observed among dietary treatments for temperature, pH

or dissolved oxygen, indicating that environmental conditions were comparable across all experimental groups and were unlikely to have influenced the observed physiological responses.

Table 3: Water Quality Parameters Recorded During the 16-Week Feeding Trial

Parameter	Control (0%)	0.5% Turmeric	1.0% Turmeric	2.0% Turmeric	P-value
Temperature (°C)	26.65 ± 0.27	26.02 ± 0.17	26.40 ± 0.29	26.41 ± 0.27	>0.05
pH	6.18 ± 0.17	6.42 ± 0.14	6.32 ± 0.24	6.38 ± 0.14	>0.05
Dissolved oxygen (mg L ⁻¹)	7.27 ± 0.38	8.08 ± 0.35	7.68 ± 0.40	7.60 ± 0.52	>0.05

Values are Presented as Mean ± Standard Deviation (SD) Based on Weekly Measurements Collected Throughout the 16-Week Feeding Trial. No Significant Differences Among Treatments were Observed ($P > 0.05$).

Haematological Profile

Dietary turmeric supplementation significantly influenced most haematological parameters of *Clarias gariepinus* following *Aeromonas hydrophila* challenge (Table 4). Fish fed turmeric-supplemented diets exhibited significantly higher ($P < 0.05$) white blood cell count (WBC), lymphocyte percentage, red blood cell count (RBC), haemoglobin concentration (Hb), packed cell volume (PCV) and mean corpuscular haemoglobin concentration (MCHC) than the control group. The highest RBC, Hb and PCV values were

recorded in fish fed the 2.0% turmeric diet, whereas fish receiving the 1.0% turmeric diet showed the highest lymphocyte percentage. In contrast, granulocyte percentage decreased significantly with dietary turmeric supplementation compared with the control group. Mean corpuscular haemoglobin (MCH) differed significantly among treatments ($P = 0.011$), whereas mean corpuscular volume (MCV) was not significantly affected by dietary turmeric supplementation ($P = 0.312$).

Table 4: Haematological Profile of *Clarias gariepinus* Fed Diets Supplemented with Graded Levels of Turmeric Extract

Parameter	Control (0%)	0.5% turmeric	1.0% turmeric	2.0% turmeric	P-value
WBC ($\times 10^3 \mu\text{L}^{-1}$)	7.92 ± 0.21 ^c	8.14 ± 0.16 ^c	8.46 ± 0.12 ^b	8.48 ± 0.12 ^b	<0.001
Lymphocytes (%)	60.63 ± 1.59 ^c	60.43 ± 1.69 ^c	68.37 ± 1.98 ^b	68.38 ± 1.98 ^b	<0.001
MID (%)	4.97 ± 0.33 ^b	4.87 ± 0.58 ^b	5.63 ± 0.94 ^a	5.60 ± 0.94 ^a	<0.001
Granulocytes (%)	34.33 ± 1.43 ^a	34.63 ± 2.17 ^a	26.03 ± 1.09 ^b	26.03 ± 1.09 ^b	<0.001
RBC ($\times 10^{12} \text{L}^{-1}$)	6.34 ± 0.16 ^c	6.99 ± 0.05 ^b	7.04 ± 0.11 ^b	7.59 ± 0.14 ^a	<0.001
Haemoglobin (g dL ⁻¹)	12.10 ± 0.15 ^c	14.10 ± 0.44 ^b	13.90 ± 0.52 ^b	15.83 ± 0.49 ^a	<0.001
PCV/HCT (%)	36.10 ± 1.25 ^c	41.23 ± 0.96 ^b	40.97 ± 0.67 ^b	45.63 ± 1.05 ^a	<0.001
MCV (fL)	58.00 ± 1.00	59.03 ± 1.62	58.23 ± 1.79	60.17 ± 0.43	0.312 (NS)
MCH (pg)	19.07 ± 0.26 ^b	20.17 ± 0.79 ^a	19.80 ± 1.02 ^a	20.87 ± 0.35 ^a	0.011
MCHC (g dL ⁻¹)	32.97 ± 0.71 ^b	34.23 ± 0.39 ^a	33.90 ± 0.78 ^a	34.73 ± 0.63 ^a	0.018

Values are Presented as Mean ± SD (n = 3 Tanks Per Treatment). Means within the same Row Bearing Different Superscript Letters (a–c) Differ Significantly ($P < 0.05$) According to one-Way Analysis of Variance (ANOVA) Followed by Duncan's Multiple Range Test. Abbreviations: WBC, White Blood Cell Count; RBC, Red Blood Cell Count; PCV/HCT, Packed Cell Volume/Haematocrit; MCV, mean Corpuscular Volume; MCH, Mean Corpuscular Haemoglobin; MCHC, Mean Corpuscular Haemoglobin Concentration; MID, Combined Monocytes, Eosinophils and Basophils.

Platelet Profile

Dietary turmeric supplementation significantly influenced platelet indices of *Clarias gariepinus* following experimental *Aeromonas hydrophila* challenge (Table 5). Fish receiving turmeric-supplemented diets showed significantly higher ($P < 0.05$) platelet count, mean platelet volume (MPV), platelet distribution width (PDW), plateletcrit (PCT), platelet large

cell count (P-LCC) and platelet large cell ratio (P-LCR) than the control group. The highest platelet count was observed in fish fed the 1.0% turmeric diet, whereas the highest P-LCR was recorded in the 2.0% turmeric group. In contrast, red cell distribution width, expressed as both coefficient of variation (RDW-CV) and standard deviation (RDW-SD), did not differ significantly among dietary treatments ($P > 0.05$).

Table 5: Platelet Indices of *Clarias gariepinus* Fed Diets Supplemented with Graded Levels of Dietary Turmeric Following *Aeromonas hydrophila* Challenge

Parameter	Control (0%)	0.5% turmeric	1.0% turmeric	2.0% turmeric	P-value
Platelets ($\times 10^9 \text{ L}^{-1}$)	176.33 $\pm$ 5.75 ^c	207.33 $\pm$ 4.41 ^b	212.00 $\pm$ 22.56 ^b	196.00 $\pm$ 11.64 ^b	<0.001
MPV (fL)	8.23 $\pm$ 0.20 ^b	8.87 $\pm$ 0.27 ^a	8.77 $\pm$ 0.26 ^a	8.60 $\pm$ 0.23 ^a	0.012
PDW	12.13 $\pm$ 0.23 ^b	12.97 $\pm$ 2.51 ^a	13.90 $\pm$ 0.84 ^a	14.07 $\pm$ 1.42 ^a	0.018
PCT (%)	0.015 $\pm$ 0.001 ^c	0.018 $\pm$ 0.001 ^b	0.019 $\pm$ 0.002 ^b	0.017 $\pm$ 0.001 ^b	<0.001
P-LCC	39.33 $\pm$ 3.93 ^c	57.67 $\pm$ 8.21 ^b	61.67 $\pm$ 11.46 ^b	60.00 $\pm$ 7.55 ^b	<0.001
P-LCR (%)	22.50 $\pm$ 2.46 ^c	27.73 $\pm$ 3.55 ^b	28.67 $\pm$ 3.06 ^b	30.80 $\pm$ 4.22 ^a	<0.001
RDW-CV (%)	13.10 $\pm$ 1.46	13.73 $\pm$ 0.43	12.63 $\pm$ 0.75	14.10 $\pm$ 0.77	0.486 (NS)
RDW-SD (fL)	37.50 $\pm$ 2.04	38.43 $\pm$ 1.45	38.50 $\pm$ 1.97	35.07 $\pm$ 1.36	0.291 (NS)

Values are Presented as Mean $\pm$ Standard Deviation (SD) Based on Three Replicate Tanks Per Treatment ($n = 3$). Means within the Same Row Bearing Different Superscript Letters (a–c) Differ Significantly ($P < 0.05$) According to One-Way Analysis of Variance (ANOVA) Followed by Duncan's Multiple Range Test.

Serum Biochemical Profile

Dietary turmeric supplementation significantly influenced serum liver and renal biochemical indices of *Clarias gariepinus* following *Aeromonas hydrophila* challenge (Table 6). Serum liver enzyme activities, including aspartate aminotransferase (AST), alanine aminotransferase (ALT), alkaline phosphatase (ALP) and gamma-glutamyl transferase (GGT), decreased significantly ($P < 0.001$) with increasing

dietary turmeric supplementation, with the lowest values generally observed in fish fed the 2.0% turmeric diet. Similarly, renal function indices were significantly affected by dietary treatment. Fish receiving turmeric-supplemented diets exhibited lower serum creatinine and urea concentrations than the control group, with the lowest values recorded in the 2.0% turmeric treatment ($P < 0.001$).

Liver Function Indices

Table 6: Serum Liver and Renal Function Indices of *Clarias gariepinus* Fed Diets Supplemented with Graded Levels of Dietary Turmeric Following *Aeromonas hydrophila* Challenge

Parameter	Control (0%)	0.5% turmeric	1.0% turmeric	2.0% turmeric	P-value
AST (U L ⁻¹)	46.93 $\pm$ 0.64 ^a	44.42 $\pm$ 1.53 ^b	42.54 $\pm$ 1.47 ^b	35.72 $\pm$ 0.73 ^c	<0.001
ALT (U L ⁻¹)	46.04 $\pm$ 2.44 ^a	45.62 $\pm$ 1.31 ^a	43.12 $\pm$ 2.58 ^b	36.60 $\pm$ 1.17 ^c	<0.001
ALP (U L ⁻¹)	154.93 $\pm$ 3.52 ^a	148.45 $\pm$ 2.65 ^b	143.46 $\pm$ 6.19 ^b	116.51 $\pm$ 4.34 ^c	<0.001
GGT (U L ⁻¹)	110.15 $\pm$ 6.03 ^a	115.82 $\pm$ 1.53 ^a	99.69 $\pm$ 3.64 ^b	70.00 $\pm$ 3.81 ^c	<0.001
Creatinine (mg dL ⁻¹)	1.12 $\pm$ 0.04 ^a	1.09 $\pm$ 0.02 ^a	1.06 $\pm$ 0.03 ^b	0.96 $\pm$ 0.02 ^c	<0.001
Urea (mg dL ⁻¹)	22.10 $\pm$ 0.14 ^a	22.32 $\pm$ 0.74 ^a	20.76 $\pm$ 0.80 ^b	18.48 $\pm$ 0.26 ^c	<0.001

Values are Presented as Mean $\pm$ Standard Deviation (SD) Based on Three Replicate Tanks per Treatment ($n = 3$). Means Within the Same Row Bearing Different Superscript Letters (a–c) Differ Significantly ($P < 0.05$) According to One-Way Analysis of variance (ANOVA) Followed by Duncan's Multiple Range Test

Renal Function Indices

Dietary turmeric supplementation also significantly affected serum electrolyte and protein profiles (Table 7). Significant differences were observed in serum electrolyte concentrations ($P < 0.001$), with sodium, chloride and bicarbonate concentrations generally increasing following

turmeric supplementation, whereas potassium and calcium concentrations were lower in turmeric-fed fish than in the control group. In addition, serum albumin and total protein concentrations increased significantly, while bilirubin and total bilirubin concentrations decreased significantly compared with the control ($P < 0.001$).

Electrolyte Profile

Table 7: Serum Electrolyte and Protein Profile of *Clarias gariepinus* Fed Diets Supplemented with Graded Levels of Dietary Turmeric Following *Aeromonas hydrophila* Challenge

Parameter	Control (0%)	0.5% turmeric	1.0% turmeric	2.0% turmeric	P-value
Na ⁺ (mmol L ⁻¹)	116.82 $\pm$ 1.49 ^a	116.66 $\pm$ 1.24 ^a	119.29 $\pm$ 0.75 ^b	122.36 $\pm$ 0.44 ^c	<0.001
K ⁺ (mmol L ⁻¹)	4.65 $\pm$ 0.15 ^b	4.67 $\pm$ 0.15 ^b	4.15 $\pm$ 0.03 ^a	4.15 $\pm$ 0.03 ^a	<0.001
Ca ²⁺ (mmol L ⁻¹)	2.66 $\pm$ 0.02 ^c	2.50 $\pm$ 0.04 ^b	2.41 $\pm$ 0.05 ^a	2.43 $\pm$ 0.05 ^b	<0.001
Cl ⁻ (mmol L ⁻¹)	91.77 $\pm$ 0.56 ^a	94.50 $\pm$ 1.02 ^b	94.82 $\pm$ 1.11 ^b	96.04 $\pm$ 0.89 ^b	<0.01
HCO ₃ ⁻ (mmol L ⁻¹)	25.59 $\pm$ 0.34 ^{ab}	24.15 $\pm$ 0.15 ^a	25.18 $\pm$ 1.00 ^b	26.72 $\pm$ 0.57 ^c	<0.01
Albumin (g dL ⁻¹)	3.30 $\pm$ 0.07 ^a	3.61 $\pm$ 0.11 ^a	3.98 $\pm$ 0.08 ^b	4.67 $\pm$ 0.31 ^c	<0.001
Bilirubin (mg dL ⁻¹)	1.78 $\pm$ 0.22 ^b	1.60 $\pm$ 0.18 ^a	1.49 $\pm$ 0.09 ^a	1.18 $\pm$ 0.07 ^a	<0.01

Parameter	Control (0%)	0.5% turmeric	1.0% turmeric	2.0% turmeric	P-value
Total bilirubin (mg dL ⁻¹)	2.11 ± 0.26 ^c	1.91 ± 0.17 ^b	1.83 ± 0.08 ^{ab}	1.57 ± 0.05 ^a	<0.05
Total protein (g dL ⁻¹)	6.30 ± 0.09 ^a	6.61 ± 0.14 ^a	7.02 ± 0.11 ^b	7.71 ± 0.27 ^c	<0.001

Values are Presented as Mean ± Standard Deviation (SD) Based on Three Replicate Tanks Per Treatment (n = 3). Means within the Same Row Bearing Different Superscript Letters (a–c) Differ Significantly (P < 0.05) According to One-Way Analysis of Variance (ANOVA) Followed by Duncan's Multiple Range Test

Oxidative Stress Status and Serum Cortisol Response

Dietary turmeric supplementation significantly influenced tissue antioxidant status and the serum cortisol response of *Clarias gariepinus* following *Aeromonas hydrophila* challenge (Table 8). Reduced glutathione (GSH) concentrations in both the gut and liver increased significantly (P < 0.001) with dietary turmeric supplementation, with the highest values generally recorded in fish fed the 2.0% turmeric diet.

Serum cortisol concentrations increased in all treatment groups one hour after bacterial challenge but declined progressively thereafter. Fish receiving turmeric-supplemented diets exhibited significantly lower cortisol concentrations than the control group at 1 h, 24 h and 7 days post-challenge (P < 0.05). The 2.0% turmeric treatment consistently recorded the lowest cortisol concentrations throughout the post-challenge sampling period, whereas the control group maintained the highest cortisol levels.

Oxidative Stress Biomarker

Table 8: Oxidative Stress Status and Serum Cortisol Response of *Clarias gariepinus* Fed Diets Supplemented with Graded Levels of Dietary Turmeric Following *Aeromonas hydrophila* Challenge

Parameter	Control (0%)	0.5% turmeric	1.0% turmeric	2.0% turmeric	P-value
Gut GSH (U mg ⁻¹ protein)	23.40 ± 0.38 ^c	26.63 ± 0.41 ^b	30.23 ± 0.49 ^b	33.47 ± 0.41 ^a	<0.001
Liver GSH (U mg ⁻¹ protein)	29.30 ± 0.47 ^c	34.37 ± 0.43 ^b	40.43 ± 0.72 ^b	45.30 ± 0.69 ^a	<0.001

Serum Cortisol Response (ng mL⁻¹)

Table 8: (continued). Serum Cortisol Response of *Clarias gariepinus* Following *Aeromonas hydrophila* Challenge

Treatment	0 h	1 h	24 h	7 days
Control (0%)	14.63 ± 0.17 ^a	44.47 ± 0.91 ^a	39.17 ± 0.56 ^a	31.33 ± 0.48 ^a
0.5% turmeric	14.23 ± 0.21 ^b	37.77 ± 0.73 ^b	32.97 ± 0.39 ^b	25.83 ± 0.31 ^b
1.0% turmeric	13.97 ± 0.14 ^b	31.60 ± 0.84 ^c	26.60 ± 0.62 ^c	19.27 ± 0.44 ^c
2.0% turmeric	13.90 ± 0.19 ^b	25.70 ± 0.57 ^d	20.33 ± 0.71 ^d	14.77 ± 0.28 ^d

Values are Presented as Mean ± Standard Deviation (SD) Based on Three Replicate Tanks per Treatment (n = 3). Means within the Same Row Bearing Different Superscript Letters (a–d) Differ Significantly (P < 0.05) According to One-Way Analysis of Variance (ANOVA) Followed by Duncan's Multiple Range Test

Discussion

The principal finding of this study was that dietary turmeric enhanced the physiological resilience of *Clarias gariepinus* following experimental *Aeromonas hydrophila* challenge. Fish receiving turmeric-supplemented diets showed higher post-challenge survival together with marked improvements in haematological characteristics, platelet indices, serum biochemical profile, antioxidant status and cortisol response compared with the control group. These responses indicate that dietary turmeric supported multiple physiological systems involved in maintaining homeostasis during bacterial infection rather than influencing a single health indicator. Recent studies have similarly shown that dietary curcumin improves antioxidant capacity, immune competence and resistance to bacterial challenge in cultured fish. For example, El-Gammal *et al.* (2025) reported that curcumin supplementation enhanced antioxidant responses, increased white blood cell counts and reduced mortality following *A. hydrophila* infection in Nile tilapia, while Eissa *et al.* (2024) demonstrated improvements in blood metabolites, antioxidant status and immune-related responses in curcumin-fed red tilapia. Together, these findings support the view that turmeric functions as a broad-spectrum phytochemical feed additive capable of strengthening physiological resilience during bacterial stress rather than acting through a single protective mechanism.

Post-Challenge Survival

Dietary turmeric supplementation markedly improved the survival of *Clarias gariepinus* following experimental *Aeromonas hydrophila* challenge, with fish fed the 1.0%

turmeric diet exhibiting the highest post-challenge survival. This finding indicates that dietary turmeric increased the capacity of fish to tolerate bacterial infection under the conditions of the present study. Similar improvements in survival have been reported in other cultured fish species receiving dietary curcumin. El-Gammal *et al.* (2025) found that Nile tilapia fed curcumin-supplemented diets showed lower mortality and greater resistance following experimental *A. hydrophila* infection, with the greatest protection observed at the moderate dietary inclusion level. Likewise, earlier work by Abdel-Tawwab and Abbass (2017) demonstrated that dietary curcumin increased survival after bacterial challenge while improving several immune and antioxidant responses in Nile tilapia.

The superior survival observed in the present study is likely to reflect the combined physiological effects of dietary turmeric rather than a single protective mechanism. Fish that received turmeric supplementation also exhibited improved haematological characteristics, favourable serum biochemical responses, enhanced antioxidant status and lower cortisol concentrations after bacterial challenge. These responses suggest that dietary turmeric supported the maintenance of physiological homeostasis during infection, thereby improving the ability of fish to withstand the pathological effects of *A. hydrophila*. The lower survival recorded in fish fed the control diet further indicates that the absence of dietary turmeric reduced the capacity of fish to cope with bacterial stress under the experimental conditions.

Haematological Responses

Dietary turmeric supplementation markedly improved the haematological profile of *Clarias gariepinus* following experimental *Aeromonas hydrophila* challenge. Fish receiving turmeric-supplemented diets exhibited higher red blood cell counts, haemoglobin concentration and packed cell volume than the control group, indicating an improved capacity for oxygen transport during bacterial stress. White blood cell counts and lymphocyte percentages also increased significantly in turmeric-fed fish, whereas granulocyte percentages declined. Similar improvements in haematological characteristics have been reported in fish receiving dietary curcumin. El-Gammal et al. (2025) observed significant increases in white blood cell and lymphocyte counts in curcumin-fed Nile tilapia challenged with *A. hydrophila*, together with enhanced antioxidant and humoral immune responses. Likewise, Wei et al. (2024) reported that dietary turmeric improved several blood indices associated with physiological health in African catfish, supporting the beneficial effects of turmeric on fish health under culture conditions.

The improvement in erythrocytic parameters observed in the present study suggests that dietary turmeric helped maintain normal erythropoiesis and reduced the physiological disturbances commonly associated with bacterial infection. Higher haemoglobin concentration and packed cell volume may have improved tissue oxygen delivery, thereby supporting metabolic function during infection. The increase in white blood cell counts and lymphocyte percentage further suggests that turmeric enhanced the capacity of fish to respond to bacterial challenge, although specific immune functions were not measured in the present study. Together, these findings indicate that dietary turmeric contributed to maintaining haematological homeostasis during *A. hydrophila* infection, which may partly explain the higher post-challenge survival observed in the turmeric-fed groups.

Platelet Responses

Dietary turmeric supplementation also produced marked changes in platelet indices following *Aeromonas hydrophila* challenge. Fish receiving turmeric-supplemented diets showed significantly higher platelet count, mean platelet volume, platelet distribution width, plateletcrit and platelet large cell ratio than the control group. These findings indicate that dietary turmeric influenced thrombocyte-related responses during bacterial challenge. In teleost fish, thrombocytes perform functions that extend beyond haemostasis and are now recognised as important components of the innate immune system. Ortiz & Esteban (2024) highlighted that fish thrombocytes possess phagocytic activity and express pro-inflammatory and antigen-presenting molecules, enabling them to participate in pathogen recognition, microbial clearance and inflammatory regulation. These multifunctional roles suggest that thrombocytes contribute to both host defence and the maintenance of physiological homeostasis during infection.

Serum Biochemical Responses

Dietary turmeric supplementation produced marked improvements in the serum biochemical profile of *Clarias gariepinus* following *Aeromonas hydrophila* challenge. Fish receiving turmeric-supplemented diets exhibited lower activities of the hepatic enzymes AST, ALT, ALP and GGT, together with reduced serum creatinine and urea concentrations compared with the control group. In contrast, serum total protein and albumin concentrations increased, whereas bilirubin and total bilirubin concentrations declined

significantly. Collectively, these findings indicate that dietary turmeric helped maintain normal liver and kidney function during bacterial challenge. Similar responses have been reported in other cultured fish species. El-Gammal et al. (2025) found that dietary curcumin improved serum biochemical indices while reducing hepatic damage and enhancing resistance to *A. hydrophila* infection in Nile tilapia. Likewise, recent reviews have concluded that phytochemical feed additives, particularly curcumin, consistently improve hepatorenal function and physiological health in fish exposed to infectious or environmental stress (Ghosh et al., 2025).

The reduction in serum transaminases and other liver-associated enzymes observed in the present study may indicate reduced hepatocellular damage during bacterial infection, while the lower creatinine and urea concentrations suggest improved renal function. Increased serum protein and albumin concentrations further indicate that dietary turmeric supported normal metabolic and protein synthetic activity despite bacterial challenge. These responses are consistent with the antioxidant and cytoprotective properties of curcumin, which have been shown to reduce tissue damage and preserve organ function under stress conditions in fish (Mulla et al., 2025; Aly et al., 2025).

Electrolyte Homeostasis

Dietary turmeric supplementation significantly influenced serum electrolyte concentrations following *Aeromonas hydrophila* challenge, indicating improved regulation of fluid and ionic balance during bacterial infection. Fish fed turmeric-supplemented diets exhibited higher serum sodium, chloride and bicarbonate concentrations than the control group, whereas potassium and calcium concentrations were generally lower. These findings suggest that dietary turmeric contributed to maintaining electrolyte homeostasis under conditions of physiological stress. Disturbances in electrolyte balance are common during bacterial infections because tissue injury and impaired osmoregulatory function can alter ion transport and acid-base regulation. Consequently, the maintenance of relatively stable electrolyte concentrations is considered an important indicator of physiological integrity in fish.

Similar observations have been reported in studies evaluating phytochemical feed additives in aquaculture. For example, Eissa et al. (2024) observed that dietary curcumin improved blood biochemical characteristics and physiological status in red tilapia, while Wei et al. (2024) reported improved health-related responses in African catfish receiving dietary turmeric. Recent reviews have further suggested that phytochemical compounds can help preserve cellular membrane stability, reduce oxidative damage and support ion transport processes during environmental and pathogenic stress. The improved electrolyte profile observed in the present study therefore complements the favourable haematological and biochemical responses, indicating that dietary turmeric helped maintain internal physiological balance during *A. hydrophila* infection rather than simply improving a single health indicator.

Oxidative Stress Status and Cortisol Response

Dietary turmeric supplementation significantly improved antioxidant status and moderated the cortisol response of *Clarias gariepinus* following *Aeromonas hydrophila* challenge. Fish receiving turmeric-supplemented diets exhibited higher reduced glutathione (GSH) concentrations in both the gut and liver than the control group, together with a marked reduction in serum cortisol throughout the post-challenge period. These findings indicate that dietary turmeric

enhanced antioxidant defence while attenuating the physiological stress associated with bacterial infection. Similar responses have been reported in recent studies evaluating curcumin in cultured fish. Eissa *et al.* (2024) observed that dietary curcumin enhanced antioxidant capacity and increased the expression of antioxidant-related genes in red tilapia, whereas El-Gammal *et al.* (2025) demonstrated that curcumin supplementation improved antioxidant responses and reduced the detrimental effects of *A. hydrophila* infection in Nile tilapia. Recent reviews have likewise recognised curcumin as an effective nutritional antioxidant capable of strengthening endogenous antioxidant systems and improving stress tolerance in aquatic animals (Tuong *et al.*, 2023; El-Gammal *et al.*, 2025; Eissa *et al.*, 2024).

Reduced glutathione is one of the major intracellular antioxidants responsible for maintaining cellular redox balance and protecting tissues against oxidative injury. The higher GSH concentrations recorded in turmeric-fed fish therefore suggest a greater capacity to neutralise reactive oxygen species generated during bacterial infection. The lower cortisol concentrations observed after challenge further indicate that dietary turmeric moderated activation of the endocrine stress response. Previous studies have similarly shown that curcumin supplementation reduces cortisol concentrations while improving antioxidant capacity under stressful culture conditions, supporting its role in maintaining physiological stability during environmental and pathogenic stress (Banu *et al.*, 2025; Komal *et al.*, 2024). Together, these findings indicate that dietary turmeric enhanced the ability of African catfish to maintain redox balance and regulate stress responses during *A. hydrophila* infection, thereby contributing to the improved post-challenge survival observed in the present study.

Physiological Resilience as an Integrated Response

A notable feature of the present study is that the beneficial effects of dietary turmeric were observed across multiple physiological systems rather than being restricted to a single health indicator. Fish fed turmeric-supplemented diets exhibited improved post-challenge survival together with favourable changes in haematological variables, platelet indices, serum biochemical profile, electrolyte balance, antioxidant status and cortisol response. The consistency of these responses suggests that dietary turmeric promoted a coordinated physiological adaptation to *Aeromonas hydrophila* infection. Similar integrated responses have been reported in studies evaluating phytochemical feed additives in fish, where improvements in antioxidant capacity, blood characteristics and tissue integrity occurred simultaneously with increased resistance to bacterial challenge. For example, El-Gammal *et al.* (2025) reported that curcumin supplementation enhanced several physiological and biochemical indicators while improving survival following *A. hydrophila* infection in Nile tilapia, supporting the concept that phytochemical feed additives act through multiple complementary pathways rather than a single biological mechanism.

The present findings also highlight the importance of evaluating physiological resilience using a combination of complementary biomarkers. Reliance on survival alone provides limited information on the biological processes underlying disease resistance, whereas the integrated assessment used in this study provides a broader understanding of how dietary turmeric influenced the response of African catfish to bacterial infection. Collectively, the results indicate that dietary turmeric

supported the maintenance of physiological homeostasis during bacterial challenge, thereby improving the ability of fish to tolerate infection under the conditions of the present experiment.

Practical Implications for Sustainable Aquaculture

The findings of this study have important practical implications for African catfish production, where bacterial diseases remain a major cause of economic loss and reduced production efficiency. Under the conditions of the present study, dietary turmeric supplementation improved post-challenge survival while supporting favourable haematological, biochemical and antioxidant responses without disrupting normal water quality conditions. These findings suggest that turmeric has potential as a functional feed additive for improving fish health and increasing resilience to bacterial infection under culture conditions. Similar conclusions have been reached in recent studies evaluating phytochemical feed additives in aquaculture. For example, Eissa *et al.* (2024) concluded that dietary curcumin enhanced fish health and physiological performance, while El-Gammal *et al.* (2025) reported that curcumin supplementation improved resistance to *A. hydrophila* infection and reduced the adverse effects of bacterial challenge in Nile tilapia.

The increasing concern over antimicrobial resistance has intensified the search for sustainable alternatives to conventional antibiotics in aquaculture. Within this context, phytochemical feed additives have attracted considerable attention because they can enhance host resilience without contributing to antimicrobial resistance. The present findings provide further evidence that dietary turmeric may represent a practical nutritional strategy for strengthening the physiological capacity of African catfish to withstand bacterial challenge. However, responses to phytochemical feed additives can vary with fish size, diet formulation, farming system and disease pressure. Consequently, validation under commercial farming conditions will be necessary before broad recommendations for routine application can be made.

Study Limitations

The findings of this study should be interpreted within the scope of the experimental design. Although a comprehensive assessment of physiological resilience was achieved by integrating post-challenge survival with haematological, biochemical, antioxidant and cortisol responses, the study did not evaluate the molecular mechanisms underlying these physiological changes. Similarly, specific immune markers, inflammatory cytokines and antioxidant enzyme gene expression were not investigated, making it difficult to determine the precise pathways through which dietary turmeric enhanced resistance to *Aeromonas hydrophila*. In addition, the bacterial challenge was conducted under controlled laboratory conditions using a single pathogen and one production stage of African catfish. Consequently, the responses observed in the present study may differ under commercial farming conditions where fish are exposed to multiple environmental and biological stressors. Despite these limitations, the study provides a comprehensive physiological evaluation of dietary turmeric supplementation during bacterial challenge and establishes a strong foundation for future mechanistic investigations.

Future Research

The present findings provide several opportunities for future research on phytochemical feed additives in aquaculture. Further studies should investigate the molecular and cellular

mechanisms through which dietary turmeric enhances physiological resilience during bacterial infection by integrating physiological measurements with transcriptomic, proteomic and metabolomic approaches. Evaluating immune-related genes, inflammatory cytokines, antioxidant enzymes and signalling pathways would provide a more detailed understanding of the biological processes responsible for the responses observed in the present study. In addition, long-term field evaluations under commercial farming conditions, involving different production stages and naturally occurring disease outbreaks, are required to determine the consistency and practical applicability of dietary turmeric supplementation in African catfish culture. Such investigations will help establish evidence-based nutritional strategies for improving fish health while reducing dependence on antimicrobial agents in sustainable aquaculture.

CONCLUSION

Dietary turmeric supplementation enhanced the physiological resilience of African catfish (*Clarias gariepinus*) following experimental *Aeromonas hydrophila* challenge. Fish fed turmeric-supplemented diets exhibited improved post-challenge survival together with favourable haematological, platelet, serum biochemical, electrolyte, antioxidant and cortisol responses compared with the control group. These findings demonstrate that the beneficial effects of dietary turmeric extended beyond disease survival to include coordinated improvements in multiple physiological systems involved in maintaining homeostasis during bacterial stress. Under the conditions of this study, dietary turmeric showed considerable potential as a functional phytochemical feed additive for improving fish health and increasing resilience to bacterial infection. Further validation under commercial farming conditions and additional mechanistic studies will help define its role in sustainable African catfish production.

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DECLARATIONS

Ethics Approval and Consent to Participate

All experimental procedures involving animals were conducted in accordance with the institutional guidelines for the care and use of experimental animals and were approved by the Research Ethics Committee of Delta State University, Abraka, Nigeria.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIAL

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

COMPETING INTERESTS

The authors declare that they have no known financial or non-financial competing interests that could have appeared to influence the work reported in this paper.

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AUTHORS' CONTRIBUTIONS

Nwose Felix Onyeka: Conceptualization, methodology, investigation, data curation, formal analysis, visualization, writing original draft.

Francis Oster Nwachi: Supervision, methodology, writing review and editing.

Jerimoth Kesena Ekelemu: Validation, resources, writing review and editing.

All authors read and approved the final manuscript.

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