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Physiological and Growth Responses of Cultured Fish to Chronic Fluoride Exposure under Controlled Aquaculture Conditions

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Abstract: Aquaculture productivity and sustainability are increasingly challenged by declining water quality, particularly in regions affected by fluoride contamination. Fluoride enters aquatic environments through natural geochemical processes and anthropogenic activities, and its chronic presence in aquaculture water sources poses potential risks to cultured fish. The present study investigated the effects of prolonged fluoride exposure on growth performance, survival, and physiological health of a commonly cultured freshwater fish, Labeo rohita, under controlled laboratory conditions. Healthy fingerlings were exposed to three sub-lethal fluoride concentrations, along with a fluoride-free control, for a period of 60 days following a completely randomized experimental design. Growth parameters, including weight gain, specific growth rate, feed conversion ratio, and survival percentage, were assessed, along with behavioral and physiological indicators of stress. Water quality parameters were maintained within optimal ranges, and fluoride concentrations were regularly monitored to ensure exposure consistency. Statistical analyses were performed using one-way analysis of variance to evaluate treatment effects. The results revealed a clear concentration-dependent decline in survival, growth performance, and physiological condition of fluoride-exposed fish. Significant reductions in weight gain and specific growth rate were observed in all fluoride-treated groups compared to the control, accompanied by elevated feed conversion ratios, indicating impaired feed utilization efficiency. Behavioral alterations such as reduced feeding activity, sluggish movement, and loss of equilibrium were evident at higher fluoride concentrations. The body condition factor declined progressively with increasing fluoride exposure, reflecting compromised health status. The findings demonstrate that chronic fluoride exposure, even at sub-lethal concentrations, can exert substantial negative impacts on fish health and aquaculture productivity. These results highlight the importance of regular monitoring of fluoride levels in aquaculture water sources and the implementation of effective mitigation strategies. Ensuring fluoride-safe water is essential for sustainable aquaculture development, fish welfare, and long-term economic viability in fluoride-affected regions.

Keywords: Fluoride toxicity, Chronic exposure, Aquaculture, Labeo rohit, Survival rate, Physiological stress, Water quality, Fish health.

Introduction

Aquaculture has emerged as one of the fastest-growing food-producing sectors worldwide, playing a vital role in ensuring nutritional security, generating employment, and supporting rural livelihoods. With capture fisheries reaching or exceeding sustainable limits, freshwater aquaculture has become increasingly important in meeting the global demand for high-quality animal protein, particularly in developing countries where fish constitutes a primary dietary component. The long-term sustainability and productivity of aquaculture systems are critically dependent on water quality, which is increasingly compromised by various chemical contaminants originating from both natural and anthropogenic sources.

Among these contaminants, fluoride has gained attention as an emerging environmental concern in aquatic ecosystems. Fluoride occurs naturally in water bodies through the weathering of fluoride-rich rocks, volcanic emissions, and mineral dissolution. These natural sources, anthropogenic activities such as industrial discharge, coal combustion, excessive use of phosphate fertilizers, aluminum smelting, and improper waste disposal have significantly increased fluoride concentrations in surface and groundwater in many regions of the world (Fawell et al., 2006; Barbier et al., 2010). In fluoride-endemic areas, groundwater contaminated with elevated fluoride levels is frequently used for drinking, irrigation, and aquaculture, thereby increasing the likelihood of chronic exposure in cultured fish species.

Previous research has demonstrated that fluoride can exert toxic effects on aquatic organisms by interfering with key physiological and biochemical processes. Fluoride exposure has been shown to disrupt enzymatic activity, impair metabolic pathways, alter ion regulation, and induce oxidative stress in fish and other aquatic fauna (Cao et al., 2013; Keshavarz et al., 2015). At the cellular level, fluoride can affect membrane integrity, mitochondrial function, and antioxidant defense systems, leading to reduced physiological efficiency and increased vulnerability to stress. Despite these documented effects, the majority of existing studies have focused on acute toxicity or ecological impacts in wild fish populations, often under short-term exposure conditions. The aquaculture systems typically involve prolonged and continuous exposure to sub-lethal concentrations of contaminants, including fluoride, through water, feed, and sediments. Chronic exposure scenarios are therefore more representative of real-world aquaculture conditions, yet they remain inadequately investigated. Subtle physiological disturbances caused by long-term fluoride exposure may not result in immediate mortality but can significantly impair growth performance, feed utilization efficiency, immune competence, and overall health of cultured fish (Bezerra et al., 2022). Such chronic effects are particularly concerning because they directly influence production efficiency and economic returns in fish farming operations.

Growth rate, survival, and feed conversion efficiency are among the most important indicators of aquaculture productivity and profitability. Any reduction in these parameters can lead to substantial economic losses for fish farmers. Chronic physiological stress induced by toxicants such as fluoride may force fish to allocate metabolic energy toward detoxification, stress response, and maintenance functions at the expense of somatic growth and biomass accumulation (Hassan & Yousef, 2009). Over time, this energy reallocation can result in stunted growth, poor feed efficiency, increased susceptibility to disease, and elevated mortality rates, thereby undermining the sustainability of aquaculture systems. The expanding reliance on aquaculture and the increasing prevalence of fluoride contamination in freshwater resources, there is a critical need to systematically evaluate the chronic effects of fluoride exposure on cultured fish under controlled conditions. The present study aims to investigate the physiological and growth responses of cultured fish subjected to prolonged fluoride exposure in a laboratory-based aquaculture setting. By simulating environmentally relevant exposure scenarios, this research seeks to bridge existing knowledge gaps and provide empirical evidence on the risks posed by fluoride contamination to fish health, production performance, and aquaculture sustainability.

2. Literature Review

Fluoride is a naturally occurring element widely distributed in the environment, particularly in groundwater and surface water systems influenced by geological formations rich in fluorine-bearing minerals. In recent decades, anthropogenic activities such as industrial effluents, coal combustion, phosphate fertilizer application, and aluminum processing have significantly increased fluoride concentrations in aquatic environments, raising concerns about its ecotoxicological effects (Fawell et al., 2006; Barbier et al., 2010). In fluoride-endemic regions, contaminated water is often utilized for aquaculture, leading to prolonged exposure of cultured fish to sub-lethal fluoride levels. Numerous studies have documented the toxic effects of fluoride on aquatic organisms, particularly fish. Fluoride has been shown to disrupt key physiological processes, including enzymatic activity, carbohydrate metabolism, and ionic regulation. Cao et al. (2013) reported that fluoride exposure interferes with metabolic enzymes and antioxidant defense systems, resulting in oxidative stress and cellular damage in fish tissues. Similarly, Lamolle et al. (2009) observed alterations in energy metabolism and physiological imbalance in fish exposed to fluoride-contaminated water.

Growth performance is a critical parameter in aquaculture, directly influencing productivity and profitability. Several studies have demonstrated that fluoride exposure negatively affects growth rate and biomass accumulation in fish. Hassan and Yousef (2009) reported a significant reduction in weight gain and feed utilization efficiency in fluoride-exposed fish, attributing these effects to metabolic stress and impaired nutrient assimilation. Chronic fluoride exposure has also been associated with increased mortality rates, even at concentrations considered sub-lethal, suggesting cumulative toxic effects over time (Susa et al., 1997). Behavioral alterations represent another important indicator of fluoride toxicity in fish. Altered swimming patterns, reduced feeding activity, and lethargy have been observed in fish exposed to fluoride, reflecting neurological and physiological disturbances (Karami et al., 2019). Such behavioral changes can further exacerbate growth impairment by reducing feed intake and increasing vulnerability to environmental stressors.

Reproductive and physiological health impacts of fluoride have also been reported. Studies indicate that fluoride can impair gonadal development, reduce fecundity, and disrupt endocrine function in fish, potentially affecting population sustainability (Cooper et al., 2006). Despite the growing body of literature on fluoride toxicity, most studies have focused on acute exposure or wild fish populations. Limited attention has been given to chronic exposure under controlled aquaculture conditions, where fish experience continuous low-level fluoride exposure over extended periods. Bezerra et al. (2022) emphasized the need for controlled experimental studies to better understand the long-term implications of fluoride contamination on fish growth, health, and aquaculture productivity. Numerous studies have demonstrated that elevated fluoride concentrations adversely affect aquatic organisms, particularly freshwater fish, by disrupting physiological, biochemical, and reproductive processes (Singh et al., 2014). Fish are considered sensitive bioindicators of fluoride pollution due to their continuous exposure to contaminated water and their capacity to bioaccumulate fluoride in tissues.

At the cellular and molecular level, fluoride toxicity has been shown to induce oxidative stress, enzyme inhibition, and mitochondrial dysfunction. Similar oxidative stress–mediated damage has been reported in fish liver and gill tissues following fluoride exposure (Chakrabarti & Mukherjee, 2010; Ghosh et al., 2013). These biochemical alterations often lead to lipid peroxidation, protein oxidation, and reduced metabolic efficiency.

Several reviews have comprehensively documented the toxic effects of fluoride on fish health and aquatic ecosystems Keshavarz et al. (2015) reported that chronic fluoride exposure affects growth, hematological parameters, enzymatic activities, and survival rates in fish. Gupta and Banerjee (2011) also highlighted the broader ecological implications of fluoride toxicity, including trophic transfer and biodiversity loss. Histopathological studies have provided strong evidence of fluoride-induced tissue damage in fish. Structural alterations in gills, liver, and kidney tissues such as epithelial lifting, necrosis, vacuolization, and cellular degeneration have been widely reported (Pal & Ghosh, 2012). These pathological changes impair respiratory efficiency, osmoregulation, and detoxification functions, ultimately affecting fish survival and fitness. Fluoride exposure has also been associated with significant reproductive toxicity in fish. Cooper et al. (2006) and Karami et al. (2019) observed alterations in gonadal structure, reduced fecundity, and behavioral abnormalities linked to reproductive success. Maiti and Chatterjee (2004) further demonstrated that fluoride negatively influences growth rate and reproductive performance, thereby threatening population stability in contaminated habitats. The aquatic toxicity, fluoride has been extensively studied for its systemic effects in animals and humans. Das et al. (2004) and the World Health Organization (2017) documented fluoride's toxicological implications, emphasizing that prolonged exposure beyond permissible limits leads to fluorosis, neurological impairment, and endocrine disruption. Experimental studies have also revealed neurotoxic effects of fluoride, suggesting potential risks to higher trophic organisms through environmental exposure (Mullenix et al., 1995).

3. Materials and Methods

3.1 Experimental Fish and Acclimatization

Healthy fingerlings of a commonly cultured freshwater fish species, Labeo rohita, were selected for the present investigation due to their economic importance, wide use in Indian freshwater aquaculture, and known sensitivity to waterborne contaminants. Fingerlings were procured from a government-certified hatchery to ensure genetic uniformity and disease-free stock. Prior to selection, fish were visually examined to confirm the absence of physical deformities, external parasites, or signs of disease. Fish of uniform size and weight were chosen to minimize experimental variability. The initial mean body weight and length were recorded before acclimatization. Acclimatization was carried out for a period of 14 days in aerated fiberglass tanks containing dechlorinated tap water under laboratory conditions. During this period, fish were maintained at ambient temperature (26–28 °C) with a natural photoperiod (12 h light:12 h dark). Continuous aeration was provided using air pumps to maintain adequate dissolved oxygen levels.

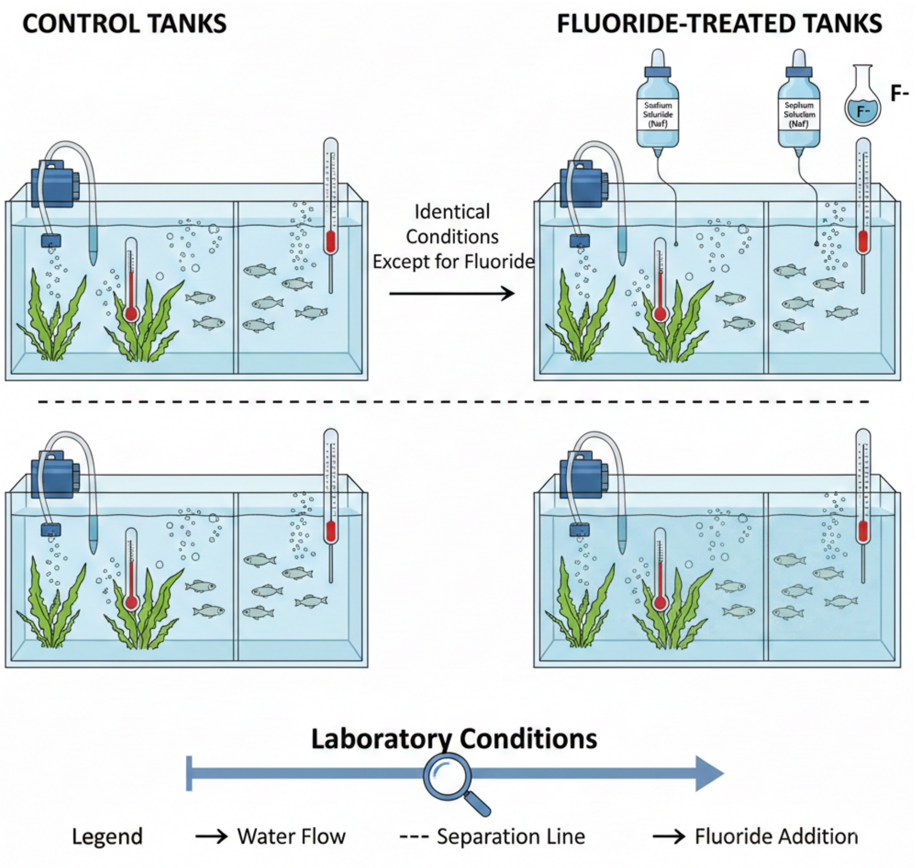

Figure 1. Schematic representation of the experimental setup showing control and fluoride-treated aquaculture tanks under laboratory conditions

During acclimatization, fish were fed a commercially available pelleted feed containing approximately 30–32% crude protein, twice daily at a fixed ration. Feeding was discontinued 24 hours prior to the initiation of fluoride exposure to reduce metabolic variability. Any mortality during acclimatization was recorded, and dead fish were removed immediately. Only healthy and active fish were used for experimentation.

3.2 Experimental Design

The experiment followed a completely randomized design (CRD) with four experimental groups: one control and three fluoride-treated groups. Each group was maintained in triplicate tanks to ensure statistical robustness and minimize tank-related bias. Each tank contained an equal number of fish and a uniform volume of water. Fluoride exposure was achieved using analytical-grade sodium fluoride (NaF), which was dissolved in distilled water and added to the experimental tanks to obtain the desired fluoride concentrations. The selected fluoride concentrations represented environmentally relevant and sub-lethal levels commonly reported in fluoride-contaminated freshwater sources. The experimental groups were defined as follows:

Table 1. Experimental design and fluoride exposure concentrations

Group	Treatment Description	Fluoride Concentration (mg L^{-1})	Replicates
C	Control	0.0 (Fluoride-free)	3
F_1	Low fluoride	Sub-lethal (environmental level)	3
F_2	Medium fluoride	Moderately elevated	3
F_3	High fluoride	Upper sub-lethal concentration	3

The exposure period was maintained for 60 days to simulate chronic exposure conditions typical of aquaculture systems using fluoride-contaminated groundwater. Throughout the experiment, fish behavior, feeding response, and survival were monitored daily.

3.3 Water Quality Monitoring

Water quality parameters were monitored regularly to ensure that observed effects were attributable to fluoride exposure rather than environmental stress. Temperature, pH, dissolved oxygen (DO), and total hardness were measured at regular intervals using standard water quality meters and protocols. Temperature was maintained within the optimal range for L. rohita culture (26–28 °C). Dissolved oxygen levels were maintained above 5.0 mg L^{-1} through continuous aeration. pH values were maintained near neutral (7.0–7.5), and total hardness remained within acceptable limits for freshwater fish culture.

Fluoride concentrations were verified at weekly intervals using an ion-selective electrode method, following standard procedures. Partial water renewal was performed to maintain consistent fluoride concentrations, and freshly prepared fluoride solutions were used during each renewal cycle to avoid concentration fluctuations.

3.4 Feeding and Maintenance

Fish were fed a nutritionally balanced commercial pelleted feed at a fixed percentage of body weight per day. Feeding was conducted twice daily, once in the morning and once in the evening, to minimize feed wastage and ensure uniform intake. Feed quantity was adjusted periodically based on changes in body weight. Uneaten feed, fecal matter, and other debris were siphoned daily to prevent deterioration of water quality. Partial water renewal (approximately 25–30%) was conducted at regular intervals using water containing the appropriate fluoride concentration for each experimental group. Strict hygienic conditions were maintained throughout the experimental period.

3.5 Growth Performance Assessment

Growth performance was assessed by recording body weight and total length at the beginning and end of the experimental period. Fish were gently netted, blotted dry, and weighed using a digital balance to minimize handling stress. Growth indices were calculated using standard formulae commonly employed in aquaculture research. The following parameters were evaluated:

Weight gain (WG): Final weight - Initial weight

Specific growth rate (SGR):

$$SGR(\%day^{-1}) = \frac{\ln(\text{ Final weight }) - \ln(\text{ Initial weight })}{\text{Experimental duration (days)}} \times 100$$

Feed conversion ratio (FCR):

$$FCR = \frac{\text{Feed intake (g)}}{\text{Weight gain (g)}}$$

Survival rate (%):

$$\text{Survival } = \frac{\text{Number of fish survived}}{\text{Initial number of fish}} \times 100$$

3.6 Physiological Health Assessment

Physiological health was assessed through visual examination and general condition indices throughout the experimental period. Fish were observed daily for signs of stress, including lethargy, reduced feeding activity, abnormal swimming patterns, surface gasping, and loss of equilibrium. The body condition factor (K) was calculated to evaluate overall health and nutritional status. External morphological changes such as discoloration, fin erosion, or mucus secretion were also recorded. Mortality was monitored daily, and dead fish were removed immediately to prevent water quality deterioration.

4. Results

4.1 Survival Rate

Survival rate of Labeo rohita fingerlings was markedly influenced by chronic fluoride exposure and exhibited a clear dose-dependent pattern over the 60-day experimental period. Fish maintained in the control group (fluoride-free water) showed the highest survival percentage, indicating that laboratory conditions and husbandry practices were suitable for normal growth and health.

The fluoride-treated groups demonstrated a progressive decline in survival with increasing fluoride concentration. The low fluoride group showed only a marginal reduction in survival compared to the control, suggesting that environmentally relevant sub-lethal fluoride concentrations exert minimal lethal effects over prolonged exposure. The medium and high fluoride groups experienced significantly higher mortality, particularly during the later phase of exposure (days 40–60), indicating the cumulative toxic effects of fluoride. Mortality in high fluoride treatments was often preceded by behavioral abnormalities such as erratic swimming, surface gasping, and loss of balance, suggesting severe physiological stress prior to death. Statistical analysis using one-way ANOVA revealed that survival rates in medium and high fluoride groups were significantly lower ($p < 0.05$) compared to the control group.

Table 2. Survival rate (%) of Labeo rohita exposed to different fluoride concentrations for 60 days

Experimental Group	Fluoride Concentration	Survival Rate (%)
Control	0 mg/L	96.7 ± 2.9
Low fluoride	Sub-lethal (low)	90.0 ± 3.5
Medium fluoride	Moderate	78.3 ± 4.2*
High fluoride	Upper sub-lethal	65.0 ± 5.1*

*Significantly different from control ($p < 0.05$)

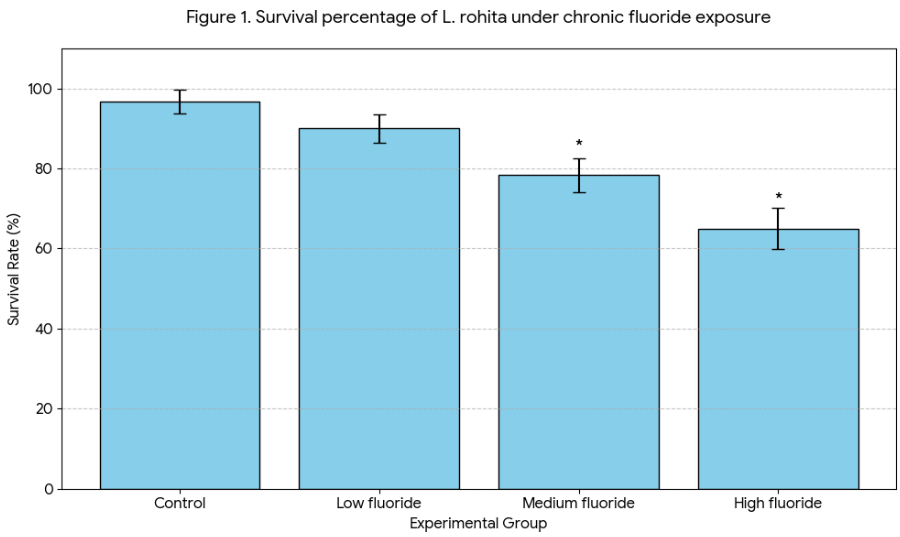

Figure 2. Survival percentage of L. rohita under chronic fluoride exposure

4.2 Growth Performance

Growth performance parameters including final body weight, weight gain, specific growth rate (SGR), and feed conversion ratio (FCR) were significantly affected by fluoride exposure. Fish in the control group exhibited steady growth throughout the experimental period, reflecting efficient feed utilization and optimal physiological functioning. In fluoride-exposed groups, growth suppression was evident and intensified with increasing fluoride concentration. The low fluoride group showed a slight reduction in weight gain and SGR. These differences were not statistically significant when compared to the control. Conversely, fish in the medium and high fluoride groups exhibited pronounced growth retardation, characterized by significantly lower final body weight and SGR values.

The highest fluoride concentration resulted in the most severe growth inhibition, indicating impaired metabolic efficiency and possible disruption of nutrient absorption and assimilation. Reduced feeding activity observed in fluoride-treated fish likely contributed to diminished growth rates. Fluoride toxicity may interfere with endocrine regulation of growth, enzymatic activity, and protein synthesis, further limiting somatic growth. Feed conversion ratio increased significantly in fluoride-treated groups, particularly in the medium and high fluoride treatments. Elevated FCR values indicate poor feed utilization efficiency, suggesting that more feed was required to achieve a unit increase in body weight. This inefficiency reflects metabolic stress and energy diversion toward detoxification and stress response mechanisms rather than growth.

Table 3. Growth performance indices of L. rohita following chronic fluoride exposure

Parameter	Control	Low F	Medium F	High F
Initial weight (g)	12.4 ± 0.6	12.3 ± 0.5	12.5 ± 0.4	12.4 ± 0.6
Final weight (g)	28.9 ± 1.2	26.7 ± 1.4	22.3 ± 1.6*	18.6 ± 1.8*
Weight gain (g)	16.5 ± 1.1	14.4 ± 1.3	9.8 ± 1.5*	6.2 ± 1.6*
SGR (%/day)	1.92 ± 0.08	1.75 ± 0.09	1.32 ± 0.10*	0.98 ± 0.12*
FCR	1.45 ± 0.07	1.61 ± 0.09	1.89 ± 0.11*	2.21 ± 0.14*

*Significantly different from control ($p < 0.05$)

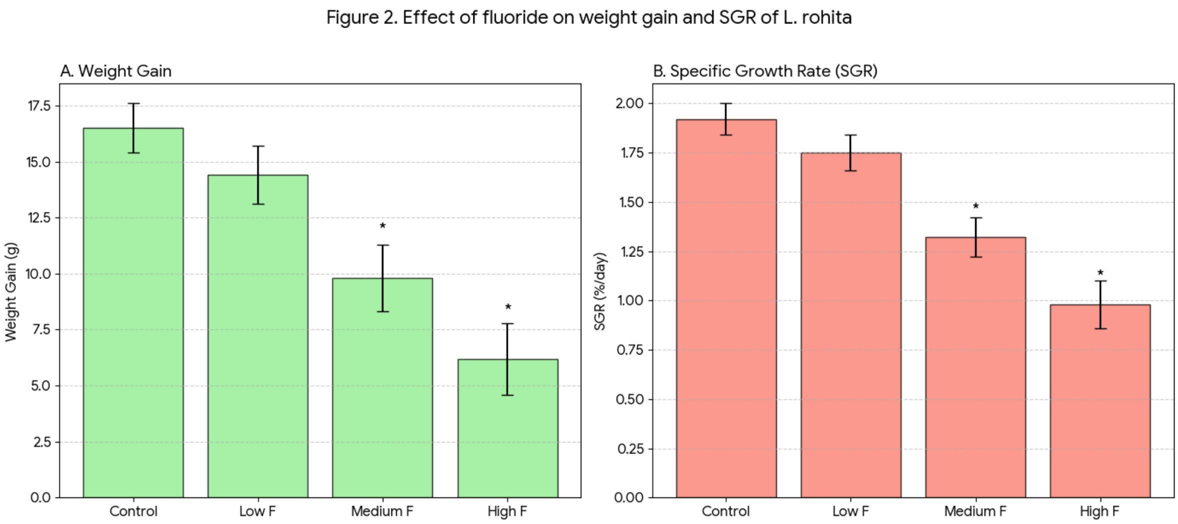

Figure 3. Effect of fluoride on weight gain and SGR of L. rohita

4.3 Physiological Responses

Chronic exposure to fluoride induced distinct physiological and behavioral alterations in L. rohita, with severity increasing proportionally to fluoride concentration. Fish in the control group remained active, exhibited normal schooling behavior, and responded quickly to feeding stimuli throughout the experimental period. The fluoride-exposed fish displayed signs of physiological stress, including reduced feeding activity, sluggish movement, and prolonged resting at the tank bottom. These symptoms were sporadic in the low fluoride group but became pronounced and persistent in medium and high fluoride treatments. Fish in the high fluoride group occasionally exhibited loss of equilibrium and erratic swimming, particularly during later stages of exposure.

The body condition factor (K) declined progressively with increasing fluoride concentration, indicating compromised nutritional and health status. Reduced condition factor reflects muscle wasting, energy depletion, and impaired physiological functioning due to chronic toxic stress. Statistical analysis confirmed a significant reduction ($p < 0.05$) in condition factor in medium and high fluoride groups compared to the control. The increased mucus secretion and pale body coloration were occasionally observed in higher fluoride treatments, suggesting epithelial irritation and stress-induced physiological imbalance. Although no histopathological analysis was conducted in the present study, these external manifestations strongly indicate systemic toxicity and physiological disruption.

Table 4. Physiological health indicators of L. rohita under fluoride exposure

Parameter	Control	Low F	Medium F	High F
Condition factor (K)	1.72 ± 0.06	1.65 ± 0.07	1.42 ± 0.08*	1.21 ± 0.09*
Feeding response	Normal	Slightly reduced	Reduced	Severely reduced
Swimming behavior	Normal	Mildly sluggish	Sluggish	Erratic
Stress signs	Absent	Mild	Moderate	Severe

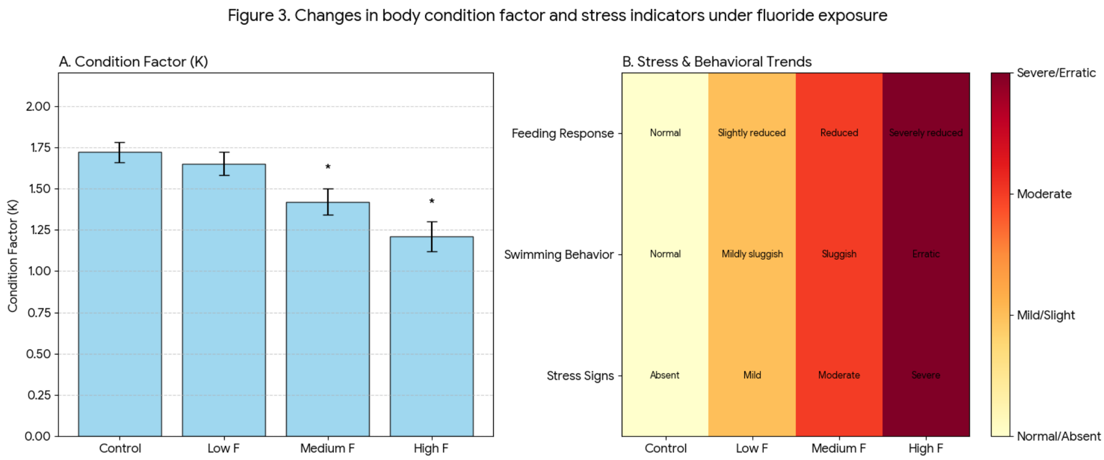

Figure 4. Changes in body condition factor and stress indicators under fluoride exposure

The results clearly demonstrate that chronic fluoride exposure adversely affects survival, growth performance, and physiological health of cultured freshwater fish. While low fluoride concentrations may exert minimal short-term effects, prolonged exposure to moderate and high fluoride levels significantly compromises fish health and productivity. These findings highlight the potential risks associated with fluoride-contaminated water sources in aquaculture systems and underscore the need for regular water quality monitoring and management strategies to mitigate fluoride toxicity.

5. Discussion

The present investigation clearly demonstrates that chronic fluoride exposure exerts adverse effects on survival, growth performance, and physiological health of cultured freshwater fish (Labeo rohita) under controlled aquaculture conditions. Unlike acute toxicity studies that primarily focus on short-term lethal thresholds, this study emphasizes the long-term sub-lethal impacts of fluoride, which are more representative of real-world aquaculture scenarios where fish are continuously exposed to contaminated water sources. The concentration-dependent deterioration in biological performance observed in this study highlights fluoride as a significant environmental stressor in freshwater aquaculture systems.

5.1 Effects of Fluoride on Survival

Survival rate is a fundamental indicator of environmental suitability and overall fish health. In the present study, survival declined progressively with increasing fluoride concentration, with significantly higher mortality recorded in medium and high fluoride treatments. These findings are consistent with earlier reports indicating that fluoride accumulation over prolonged periods compromises physiological homeostasis and reduces stress tolerance in fish. Chronic fluoride exposure can impair vital organ functions, particularly gills, liver, and kidneys, leading to reduced oxygen uptake, detoxification inefficiency, and ionic imbalance. The delayed onset of mortality, particularly during the later stages of exposure, suggests a cumulative toxic effect rather than immediate lethality. Sub-lethal fluoride concentrations may not cause instant mortality but gradually weaken physiological resilience, rendering fish vulnerable to secondary stressors such as handling, feeding competition, and water quality fluctuations. This pattern aligns with previous studies reporting that fluoride-induced mortality often manifests after prolonged exposure due to progressive tissue damage and metabolic exhaustion.

5.2 Growth Suppression under Chronic Fluoride Stress

Growth performance is a critical determinant of aquaculture productivity and profitability. The significant reduction in weight gain and specific growth rate (SGR) observed in fluoride-exposed groups reflects growth suppression induced by chronic toxic stress. Several physiological mechanisms may explain this phenomenon. Fluoride is known to interfere with enzymatic processes involved in carbohydrate, lipid, and protein metabolism. Disruption of these metabolic pathways reduces the availability of energy required for somatic growth. The fluoride exposure may impair digestive enzyme activity and intestinal absorption efficiency, leading to poor nutrient assimilation even when adequate feed is supplied. The observed reduction in feeding activity further exacerbates growth retardation, as fish exposed to fluoride exhibited diminished appetite and feeding responsiveness. Reduced feed intake combined with impaired metabolic utilization ultimately results in stunted growth.

Growth inhibition under fluoride exposure has been reported in several freshwater fish species, suggesting that this response is not species-specific but represents a generalized toxicological effect. Chronic stress also affects endocrine regulation, particularly growth hormone and thyroid hormone pathways, which play a vital role in regulating growth and metabolism in fish. Suppression of these hormonal systems under fluoride stress may further contribute to reduced growth performance.

5.3 Feed Conversion Efficiency and Economic Implications

Feed conversion ratio (FCR) is a crucial parameter linking biological performance to economic outcomes in aquaculture. The significant increase in FCR observed in fluoride-treated groups indicates reduced feed utilization efficiency, meaning that fish required more feed to achieve a unit increase in body weight. This inefficiency likely arises from metabolic energy being diverted toward stress adaptation, detoxification, and tissue repair rather than growth.

From an economic perspective, elevated FCR directly translates into higher production costs, as feed constitutes the largest operational expense in aquaculture systems. Even moderate increases in FCR can substantially reduce profit margins, particularly in small-scale and semi-intensive farming operations. Therefore, chronic fluoride contamination of culture water poses not only biological risks but also serious economic challenges for aquaculture sustainability.

5.4 Physiological and Behavioral Alterations

Physiological and behavioral responses observed in fluoride-exposed fish provide valuable insights into the underlying mechanisms of toxicity. Reduced feeding activity, sluggish movement, and abnormal swimming behavior are classic indicators of stress-induced neurological and metabolic disturbances. Fluoride has been shown to interfere with neural transmission and muscular coordination, which may explain the loss of equilibrium and erratic swimming observed at higher concentrations. The progressive decline in body condition factor with increasing fluoride exposure further confirms compromised health status. Condition factor is an integrated index reflecting nutritional status, muscle development, and overall physiological well-being. Reduced condition factor suggests depletion of energy reserves, muscle wasting, and impaired protein synthesis, all of which are consistent with chronic toxic stress. Increased mucus secretion and changes in body coloration observed in higher fluoride treatments may indicate epithelial irritation and gill dysfunction. Since gills are the primary site of ion exchange and respiration, fluoride-induced gill damage can severely disrupt osmoregulation and oxygen uptake, leading to hypoxia and metabolic stress.

5.5 Chronic Exposure versus Acute Toxicity

A key strength of the present study lies in its focus on chronic exposure conditions, which are often overlooked in conventional toxicity assessments. Acute toxicity studies typically determine lethal concentrations over short durations, but such approaches may underestimate the ecological and economic risks posed by prolonged exposure to low or moderate pollutant levels. The present findings demonstrate that even sub-lethal fluoride concentrations can produce significant long-term impacts on fish growth, health, and survival.

In aquaculture settings, fish are continuously exposed to water quality conditions throughout their culture cycle. Therefore, chronic exposure studies provide more realistic risk assessments and better inform management decisions. The subtle yet persistent effects observed in this study highlight the importance of incorporating chronic toxicity endpoints into environmental monitoring and regulatory frameworks.

5.6 Implications for Aquaculture Management

The results of this study have important implications for aquaculture practices, particularly in regions where groundwater and surface water sources contain elevated fluoride levels. Regular monitoring of fluoride concentration in culture water should be prioritized, especially in fluoride-prone areas. Where contamination is unavoidable, water treatment strategies such as dilution, defluoridation, or blending with low-fluoride sources may be necessary to mitigate adverse effects. Selection of fluoride-tolerant species or strains, along with optimized feeding and stress management practices, may also help reduce production losses. Incorporating biomarkers of chronic stress and growth impairment into routine health assessments can facilitate early detection of fluoride-related problems.

6. Conclusion

The present study provides clear experimental evidence that chronic fluoride exposure exerts significant adverse effects on the growth performance, survival, and physiological health of cultured freshwater fish (Labeo rohita) under controlled aquaculture conditions. Unlike short-term toxicity assessments, this investigation highlights the cumulative and persistent nature of fluoride toxicity, demonstrating that even sub-lethal concentrations can lead to biologically and economically meaningful impacts when exposure is prolonged.

Fish exposed to fluoride exhibited a concentration-dependent decline in survival rate, indicating reduced physiological resilience under chronic stress. Growth-related parameters, including weight gain and specific growth rate, were significantly suppressed in fluoride-treated groups, while feed conversion ratios increased markedly. These findings suggest that fluoride disrupts metabolic efficiency and nutrient utilization, likely due to interference with enzymatic activity, energy metabolism, and physiological homeostasis. Reduced feeding activity, behavioral abnormalities, and declining body condition factors further confirm that fluoride exposure compromises overall fish health and welfare. From an aquaculture perspective, these outcomes are particularly concerning, as growth performance and feed efficiency directly influence production sustainability and profitability. Increased feed requirements coupled with reduced biomass gain can substantially elevate operational costs, especially in small-scale and semi-intensive farming systems. The fluoride contamination represents not only an environmental toxicological issue but also a significant economic risk for aquaculture enterprises in fluoride-prone regions. The results underscore the importance of regular monitoring of fluoride concentrations in aquaculture water sources, particularly where groundwater is used for fish culture. Implementation of appropriate water management strategies, such as dilution with low-fluoride water, defluoridation techniques, or source substitution, is essential to mitigate fluoride-related risks. The incorporating chronic exposure assessments into environmental risk evaluation frameworks would improve the accuracy of toxicity predictions and management decisions.

7. Future Perspectives

While the present study provides important insights into the chronic effects of fluoride exposure on growth, survival, and physiological health of cultured freshwater fish, several critical research gaps remain that warrant further investigation. Future studies should prioritize species-specific sensitivity assessments, as different fish species and life stages may exhibit varying degrees of tolerance to fluoride toxicity. Understanding these differences will support informed species selection and stocking strategies in fluoride-affected aquaculture regions. Long-term studies examining the reproductive and transgenerational impacts of chronic fluoride exposure are particularly needed. Sub-lethal fluoride stress may impair gonadal development, endocrine regulation, fecundity, and larval viability, thereby influencing population sustainability and hatchery success. Investigations into early life stages, including embryos and larvae, would provide valuable information on developmental toxicity and long-term fitness consequences. Further research should also focus on elucidating the molecular, biochemical, and histopathological mechanisms underlying fluoride-induced toxicity. Assessments of oxidative stress biomarkers, antioxidant enzyme responses, hormonal alterations, and tissue-level damage in key organs such as gills, liver, kidney, and brain would enhance mechanistic understanding and enable the development of reliable early-warning indicators of fluoride stress. In real-world aquaculture environments, fish are rarely exposed to a single contaminant. Therefore, future studies should explore the interactive effects of fluoride with other waterborne pollutants, such as heavy metals, pesticides, and excess nutrients, which may exert synergistic or antagonistic effects on fish health. Such multi-stressor studies are essential for realistic ecological risk assessment.\

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