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Bioaccumulation, Histological and Structural Changes in the Gills of the Nile Tilapia (*Oreochromis niloticus*) Exposed to Heavy Metals

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ABSTRACT

Heavy metals are hazardous substances that affect aquatic organisms, especially the Nile tilapia, which is considered an important commercial fish. In addition, it has the ability to withstand and spread in Iraqi rivers and lakes of water. Therefore, this study aimed to assess the toxic effects of cadmium (Cd), lead (Pb), copper (Cu) and zinc (Zn) on the gills of tilapia exposed to sub-lethal concentrations for 96 hours. The accumulation of metals among fish organs for cadmium, copper and zinc was in the following order: liver > gills > muscles, while for lead it was in the order of gills > liver > muscles. The toxicity test of the elements at sub-lethal concentration was performed on the gills, and histopathological investigations showed an increase in the severity of gill tissues over 96 hours of exposure. In conclusion, tilapia fish are severely affected by the toxic and cumulative effects of toxic elements in gill and liver tissues, highlighting the urgent need for careful monitoring and consideration.

INTRODUCTION

Increasing pollutants, especially heavy metals, can bioaccumulate in fish tissues, leading to the deterioration of fish health and posing health risks to humans through the food chain **(Ray & Vashishth, 2024)**. Aquatic ecosystems have suffered from toxic heavy metals originating from widespread waste disposal associated with industrial, agricultural and urban activities. These pollutants have been identified as critical environmental hazards **(Saravanan *et al.*, 2024)**. Bioaccumulation in tissues has led to damage to cells and tissues, and then, a malfunction occurs in the functions of the fish organs. Additionally, the accumulation of heavy elements affects the DNA composition of aquatic organisms' cells **(Karim, 2022)**. This damage depends on the type of exposed organism, the levels of pollutants, environmental conditions and the duration of exposure

(Cordeli *et al*., 2023; Wang *et al*., 2024). Fish can be used as bioindicators of environmental pollution due to their ability to accumulate metals at concentrations hundreds or even thousands of times higher than those found in water, their long lifespan, and the ease with which they can be sampled and collected in large quantities. In aquatic ecosystems, metal pollution causes numerous morphological, chemical and physiological variations in aquatic organisms. Accumulation of heavy elements damages cells and tissues, and subsequently causes dysfunction of the organs of aquatic organisms. Therefore, histopathological damage to the organs involved plays an important character in assessing the toxic potential of pollutants with respect to living organisms. This damage depends on various factors including the type of organism exposed, pollutant levels, environmental conditions and exposure time **(Aldoghachi, 2022; Ghafarifarsani, *et al*., 2024; Renata *et al*., 2025)**. Limited researches have been conducted on the effects of environmental pollution on the Nile tilapia such as the study of **Jasim *et al.* (2016)** on bioaccumulation and histopathological changes in tilapia fish exposed to mercury (Hg) metal and the study of **Abduljabbar *et al.* (2025)** on the *Oreochromis niloticus* and the greenback mullet (*Planiliza suviridis*). Therefore, the main objective of the present research was to assess the histopathological state of fish gills and to determine the toxicity assessment of heavy elements (cadmium, copper, lead, and zinc) present in the gills, liver and muscles of the Nile tilapia.

MATERIALS AND METHODS

Experimental design

The experiment was conducted on the Nile tilapia (mean total length 14 ± 1.4cm and mean weight 110.01 ± 3.5g, mean ± standard error) collected from the aquariums of the Marine Science Center. The fish were acclimatized in aerated glass tanks for 2 weeks under laboratory conditions of 22 ± 1.5°C with a photoperiod of 12:12 light: dark. The fish were fed daily with commercial food containing 30% protein. Twenty liters of dechlorinated tap water was used in each glass tank (60 × 30 × 30cm), provided with oxygen aeration using an aeration system. The static bioassay method was used under static regeneration conditions, as described by **APHA (2012)**. A preliminary test was conducted to calculate the median lethal concentration (96hLC_{50}) of the element for 96h by means of concentration-response curves for probity transformation. Fish were divided into two groups, the first group was the control sample in which tap water was used, while the other group was exposed for 96h to 50% LC_{50} of the element. Ten fish were used per aquarium, with three replicates. During the experimental period (96h), fish were allowed to feed in both groups, then feeding was stopped 24 hours after exposure ended **(Handayani *et al*., 2019)**.

Bioaccumulation test

Active fish were collected from control and experimental tanks and were dissected using a stainless steel knife (scalpel) to isolate the gills, liver and muscles (dorsal surface of the fish). Then, the tissues were dried to be consistent in use in an oven for 24h at 105°C. A porcelain mortar and pestle were used to grind the dry samples of each organ separately, from each specimen, after which experimental and control fish tissues were digested in a microwave oven (Milestone Start D model, Italy) using a closed vessel. Nitric acid was used (65%) in a volume of 6ml with peroxide acid H_2O_2 (35%) in a volume of 1ml **(Uysal *et al*., 2008)**. ICP–OES (Perkin Elmer AA Analyzer) was used to determine heavy metal levels in fish specimens. The certified reference materials DORM-2 was used as quality control samples.

Histopathological investigation

Histopathological examination was performed on the gills of control and tissues exposed to a sublethal concentration of 50% of LC_{50} for 96h. Samples were stored in formalin for 48h, and then an ethanol series was used to dehydrate the tissues. Samples were embedded in paraffin, sectioned at a thickness of 7μm and stained with hematoxylin and eosin (H&E). The morphological and qualitative characteristics of the tissues were examined **(Triebskorn *et al*., 2008)**. Digital images were obtained using an XSZ-H biological microscope equipped with a MDCE-5C digital camera, using 10, 20 and 40X objective lenses.

RESULTS AND DISCUSSION

Toxicity assay

The results of the current experiment showed that the experimental fish exposed to high concentrations of heavy metals had higher mortality rates compared to those of the control fish (Table 1). This is due to the direct effect of toxic metals on the respiration process of tilapia. Heavy metal toxicity is due to decreased diffusion capacity of gills, disruption of physiological balance, decreased oxygen pressure and consumption, increased gill ventilation, gill cover movement, decreased blood pH and consequently increased respiratory rate and concentration of metabolic products. Moreover, heavy metals have a severe effect on smaller species which are more sensitive to toxicity than larger species **(Gashkina, 2024)**. Heavy metals disturb the aquatic equilibrium as they are non-biodegradable and bioaccumulative in nature, therefore, at the molecular level, heavy metals induce several cell death pathways, specifically autophagy, inflammation and apoptosis **(Kumar *et al.*, 2024)**. Heavy metal ions concentrate in cell membranes causing cell decomposition and damage to organ tissues. In addition, the bioaccumulation of these elements increases the activity of some enzymes important for the metabolic processing

of organic compounds in fish, thus affecting the survival of fish **(Aldoghachi, *et al*., 2019; Naz *et al*., 2023)**.

Table 1. Median lethal concentrations (LC_{50}) of heavy elements in tilapia fish *Oreochromus niloticus* in diverse exposure time

Metals	**LC_{50} (mg/L) after diverse exposure**			
	24h	**48h**	**72h**	**96h**
Cu	1.75	0.8	0.51	0.43
Cd	3.7	1.56	0.8	0.6
Zn	>5	> 5	5	2.09
Pb	>15	13.21	11	10

Bioaccumulation of toxic metals

The results of the present study showed significant differences (Analysis of Variance, $P< 0.05$) in all experimental minerals compared to control fish and the bioaccumulation of the studied heavy elements increased in the juvenile Nile tilapia with increasing concentrations of metal ions in the water. The accumulation of elements in fish organs was affected by the metal type and concentration differences (Table 2). Nevertheless, samples exposed to high concentrations recorded the highest bioaccumulation except for cadmium.

Among the different organs, the liver recorded the highest accumulation of gills followed by muscles of fish exposed to heavy metal ions, especially for copper and zinc. While gill tissues recorded higher levels than other tissues for cadmium and lead with values of 1 and 5mg L^{-1}, respectively. The accumulation of copper, cadmium and zinc was in the following order: liver > gills > muscles, while lead recorded the order gills > liver > muscles. In general, the liver recorded the highest level of accumulation of toxic elements (423mg/ kg for zinc, 136mg/ kg for copper and 72mg/ kg for cadmium) compared to other organs (Table 2). The results of the statistical analysis showed an increase in the levels of heavy elements with increasing the exposure period, except for cadmium.

Table 2. Bioaccumulation of heavy metals in muscles, gills and liver (mg/kg-1 dry weight) of the Nile tilapia (*Oreochromis* niloticus) exposed to different concentrations and periods

Toxic metal	**Fish organ**	**Concentrations (mg L^{-1})**				
		0.0	**0.5**	**1.0**	**3.0**	**5.0**
Cd	muscle	0.05e	0.34e	0.91e	1.36e	2.38e
	gill	0.33e	2.82e	22.06c	120.80a	32.59c
	liver	0.53e	20.58d	20.97d	35.70c	71.80b
Cu	muscle	1.35f	4.58f	2.50f	4.00f	--
	gill	6.33f	10.50e	6.35f	38.40d	--
	liver	19.38e	78.33c	117.50b	135.98a	--
Zn	muscle	11.50g	16.08g	18.09g	16.90g	30.80f
	gill	49.50f	40.26f	72.18e	105.38d	98.10d
	liver	93.92d	177.26c	184.96c	217.57b	422.78a
		Concentrations (mg L^{-1})				
		0	**11**	**13**	**15**	
Pb	muscle	1.60f	24.62e	21.90e	44.75e	
	gill	3.21f	144.83cd	152.36c	268.32a	
	liver	6.68f	51.33e	106.03d	207.92b	

Similar letters for values mean not significant (P> 0.05).

In the natural environment, toxic metals can be found widely due to various human activities. These metals can also reach the food sources of fish and thus reach the human diet, this is because tilapia have a low sensitivity to some heavy metals and therefore have a greater capacity for bioaccumulation of metals **(Aldoghachi *et al*., 2016)**. Several studies have proven the ability of tilapia fish to accumulate heavy elements at a rate double that of the concentrations found in the surrounding water. This accumulation depends on the concentration of the element and the period of exposure, as well as the interaction of one metal with another, water chemistry, and the metabolic activity of the fish. Such studies include the work of **Taweel *et al.* (2013)**, which investigated *Oreochromis niloticus* exposed for 96 hours to high concentrations of metals. The study

recorded bioaccumulation factors of 79, 774, 374, and 26 times for copper, cadmium, lead, and zinc, respectively, compared to control samples. Similarly, the study by **Kousar *et al.* (2014)** examined four freshwater fish species (*Cirrhina mrigala*, *Labeo rohita*, *Ctenopharyngodon idella*, and *Catla catla*), which exhibited varying levels of heavy metal accumulation in their bodies.

The data from the present study showed that the order of bioaccumulation level of the experimental elements in all organs was Zn > Cu > Pb > Cd, and the fatty tissues of the liver recorded the highest accumulation of these elements due to the lipophilic properties of the metal compounds. The study of **Lehel *et al*. (2024)** on the rainbow trout (*Oncorhynchus mykiss*) recorded an increase in concentrations above the regulatory limit for cadmium and lead by 30 and 10%, respectively. The liver is the main site for storing heavy metals in fish. The level of accumulation in the gills reflects the concentration of the element in the surrounding water. The high level of accumulation of elements in the liver is attributed to the sequestration and binding with metallothionein (MT), therefore, biochemical parameters will change and then damage the liver tissue **(Abdel-Warith *et al*., 2011)**.

The gills recorded a higher level of accumulation of lead and cadmium compared to other tissues (Table 2). This is due to the toxicity pressure of these elements, which leads to the need for fish to enter larger quantities of water through the gills to provide oxygen. This indicates that the absorption of lead and cadmium was primarily from water and not from the diet. Similar findings were reported by **Zaghloul *et al*. (2024)** in seven different species of fish from Bardawil Lake in Egypt in which gill tissues showed higher levels of cadmium and lead accumulation than liver or muscle.

Cadmium concentration of 3mg/ L recorded the highest accumulation level in gill tissues upon short-term exposure, and then the accumulation level in the liver increases upon long-term exposure because the gills are the first target for the accumulation of aqueous cadmium ions, and then it is distributed to other organs and is non-specifically bound to muco polysaccharides (which are glycoproteins) attached to the sides of the gills. The level of accumulation of elements depends on absorption rates, excretion and storage, thus the metal with rise absorption and low excretion will accumulate at a higher level with the interference of other factors such as temperature and salinity. A review by **Lee *et al*. (2025)** on cadmium bioaccumulation in various fish species, including tilapia, stated that cadmium is an extremely toxic element and poses a significant risk to fish in aquatic ecosystems. Exposure to heavy metals in fish occurs through waterborne pathways and diet. The concentration of accumulated metals depends on various factors, including exposure time, route of exposure, dosage, the biological condition of the fish, the type of metal, and ecological parameters such as dissolved oxygen, pH, salinity, and mineral composition. The gills are the first organ affected by environmental minerals, so

this causes more minerals to be absorbed and accumulated on the surface of the gills. In general, the level of bioaccumulation of elements depends on the different metabolic activities of the different organs (liver, kidney, spleen, and gills) in the metabolism of fish. Therefore, elements accumulate in them more than in muscle tissue and are difficult to get rid of, especially non-essential minerals.

The present study reported that muscle tissues had the lowest level of bioaccumulation of elements compared to other organs. This is consistent with **Kozak *et al*. (2021)** addressing the Prussian carp (*Carassius gibelio* Bloch) and elucidating that the concentration of cadmium in the muscles was very low to undetectable. Moreover, over time, cadmium concentrations in muscles will decrease, indicating that cadmium is entering directly through the skin rather than internally through the bloodstream.

In the current histopathological study, the gills of the control fish were shown to consist of four pairs of gill lamellae supported by a bony system on the sides (branchial arch). Fig. (1a, b) shows the distinct arrangement of the primary and secondary lamellae. Numerous capillaries were shown in the secondary lamellae; each was separated by single-layer vertical cells. Mucous and chloride cells were also identified and proliferation and hyperplasia of epithelial cells were recorded in the gills of fish exposed for 72h to cadmium, which caused fusion of adjacent secondary lamellae. (Fig. 1c). Curling of secondary lamellae and bulb shape of the large pavement cells were found at 96h (Fig. 1d).

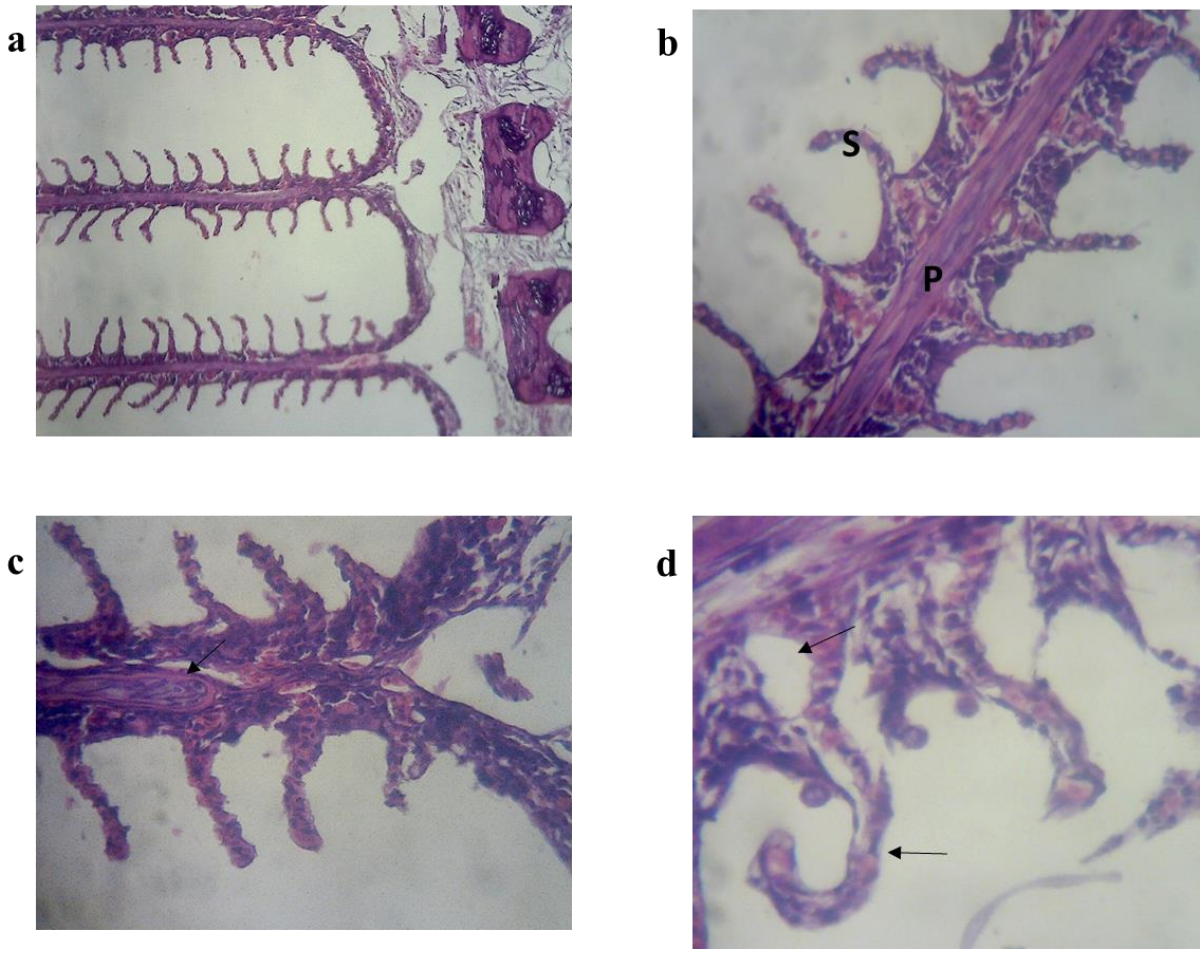

Fig. 1. Photomicrographs of the gill of *Oreochromis niloticus* (a & b). Gill filaments show a distinct arrangement in the control (P) and secondary lamellae (S) specimen. c) Fused secondary lamellae. d) After 72h exposure to cadmium ions, formation of vacuoles in epithelial cells (arrowhead), curling of secondary lamellae (arrow) and after 96h exposure, formation of a spherical shape at the end of lamellae (arrowhead)

The level of accumulation in the gill tissue depends on the rate of absorption and excretion. Therefore, increased accumulation of the metal leads to damage to the gill structure. These findings are consistent with the review by **Zulkipli *et al.* (2021)**, which highlighted that certain fish species, including *Oreochromis niloticus*, were exposed to toxic mercury through contaminated food or water. Affected fish were observed gasping for air, indicating gill dysfunction likely caused by pollution. This suggests damage to the secondary lamellae due to fusion or excessive mucus production, leading to impaired oxygen intake. Furthermore, the study by **Aldoghachi (2022)** on common carp (*Cyprinus carpio*) and the research by **El-Agri *et al.* (2021)** on *Solea aegyptiaca* confirmed that gills are highly sensitive to heavy metals, which can induce various histopathological changes,

including epithelial cell hyperplasia and hypertrophy, lamellar fusion, lamellar aneurysms, and excessive mucus secretion.

Histological alterations in the gills of fish treated to cadmium ions for 48 hours showed slight damage under the sub lethal concentration. A lesion was observed in the epithelial layer, vacuolization in the gill tissues, and hypertrophy of the mucous cells, which stimulated mucus secretion, in addition to increased bleeding, which led to a change in the color of the gills to red. Our findings are consistent with those of **Carvalho *et al.* (2020)**, who used histological biomarkers in the gill epithelium to assess the health conditions of two fish species, *Menticirrhus americanus* (Linnaeus, 1758) and *Micropogonias furnieri* (Desmarest, 1823). Their histological analysis revealed epithelial elevation, vascular dilation, and necrosis in the gills. Based on these observations, the study proposed the use of such biomarkers to assess environmental impacts in areas exposed to heavy metal pollution.

Litreature reviews have reported histological lesions in gill and structural alterations resulting from the effect of cadmium in the aqueous medium in several fish species; for example, the study of **Adam *et al*. (2020)** on the gambusia fish (*Gambusia affinis*) gills exposed to acute effect of cadmium recorded some severe changes in gills, including hyaline cartilage hyperplasia, chloride cell hypertrophy, mucus cell proliferation, hyperplasia and fusion in secondary lamellae.

The first defense mechanism in the gills is the secretion of acidic mucus against exposure to heavy elements for increasing the protective function against pollutants. According to the review of **Tavares-Dias (2021)**, in both freshwater and marine cultured fish, long and short-term exposure to metals ions often cause an accumulation of metals in the gills, liver, spleen and kidney. In the gills, this accumulation provokes changes in mucus and chloride cells, as well as hypertrophy or hyperplasia in edema of the gill epithelium, and lamellar fusion.

The cadmium ions affect the calcium balance in the gills, causing damage to the gill structure because cadmium is absorbed through the calcium channel in the epithelial layer of fish gills, and calcium displacement stimulates the loss of ions and water absorption. The study by **Bilal *et al.* (2024)** on the freshwater fish *Channa gachua* indicated that cadmium accumulation has a substantial effect on calcium levels in bones. The study revealed a clear pattern: as cadmium levels increased, calcium levels decreased.

CONCLUSION

Tilapia fish are severely affected by the toxic and cumulative effects of heavy metals in their gill and liver tissues. This highlights a critical concern that should be carefully considered in environmental monitoring and fish health assessments.

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