Journal of Life and Social Sciences
eISSN: 3006-2675
www.bbasrjlifess.com
*J. Life Soc. Sci, 2024; Volume, **3**: 24*

Review *Article* ***Open Access***

EFFECTS OF HEAVY METALS ON FISHES

WASIF Z[1], SAQLAIN M[2], HAYAT S[2*,] MAHMOOD S[3], SULEMAN S[3]

[1]*Department of Zoology, Lahore College for Women University, Lahore, Pakistan*
[2]*Institute of Molecular Biology and Biotechnology, The University of Lahore, Pakistan*
[3]*Department of Fisheries, Government of Punjab, Pakistan*
**Correspondence author email address: sikandar.hayat@imbb.uol.edu.pk*

(Received, 6th January 2023, Revised 21th March 2024, Published 26th March 2024)

Abstract *Among the most significant pollution concerns are heavy metals. The aquatic ecology and aquatic organisms are seriously threatened by heavy metals because of their non-biodegradable nature. When heavy metal concentrations are beyond their safety threshold, fish may experience negative consequences. The main category of pollutants in any industrial discharge is made up of heavy metals because they are frequently used in all industrial applications. As cofactors for several enzymes and necessities for metabolic processes, several heavy metals, including Zn, Cr, Co, Cu, Ni, Fe, and Mn are vital. Fish physiology, metabolism, growth, development, and reproduction are all adversely affected by waterborne heavy metals. Fish development defects can result from heavy metal sensitivity in their early stages. Additionally, normal fish behaviors like swimming and spawning are negatively impacted by heavy metals. Many heavy metals are thought to be vital nutrients that benefit fish health, but when concentrations of these metals rise, they become deadly for both fish and humans who consume them. Because a sizable portion of the population eats fish, human health is also at risk. Ecological system disruption is also a result of heavy metals. In this review, we assessed the impact of various heavy metals on fish health and also provided information that is currently known regarding the effects of heavy metals on fish physiology, behaviour, growth, development, and reproduction. Fish endocrine disruption is mostly caused by heavy metals. Many more studies on metal interactions are required to reach the point of likelihood.*

*[Citation: Wasif, Z., Saqlain, M., Hayat S., Mahmood, S., Suleman, S. (2024). Effects of heavy metals on fishes. J. Life Soc. Sci, **2024**: 24]*
Keywords: *Aquatic ecosystem; development; endocrine disruptors; growth; heavy metals; physiology*

Introduction

The word "heavy metal" has been defined in a variety of ways in literature. In scientific terms, a heavy metal is any material that has alkaline oxides, may develop compounds along with non-metals without interacting with each other, can exchange places with H-ions in acids, as well as is capable of becoming an electron donor as a valence ion. In terms of physical properties, it is any substance that can transfer electricity and heat efficiently, can be converted into metal plates as well as wire, has a metallic color, and is solid under ordinary conditions. However, in terms of their impacts, any metal that is harmful to any living organism in any situation can be referred to as a heavy metal, despite the way it is defined (TAŞTAN, 2018). Metals are generally classified as neither physiologically necessary nor unnecessary. The referred to as xenobiotics, or alien elements, such as aluminium (Al), cadmium (Cd), mercury (Hg), tin (Sn), as well as lead (Pb), among other non-essential metals, possess no known biological purpose and become more harmful at higher concentrations. On another hand, essential metals, such as nickel (Ni), cobalt (Co), zinc (Zn), molybdenum (Mo), chromium (Cr), copper (Cu), as well as iron (Fe), have a proven biological role but can be harmful at excessive doses or in metabolic shortages. Therefore, a shortage of essential metals could have a detrimental influence on health, while an elevated level of that metal can have negative effects that are just as harmful as or worse than those that are brought through non-essential metals. In fish organisms, heavy metals such as lead, cadmium, mercury, nickel, cobalt, molybdenum, chromium, zinc, copper, as well as tin are most frequently discovered. When it comes to fish malformations, these elements have been investigated the most: copper, chromium, zinc, lead, mercury, as well as cadmium (Sfakianakis et al., 2015).

Living organisms require trace amounts of heavy metals including copper, magnesium, cobalt, iron, and zinc for optimum health. However, organisms can be harmed by an excess of metals (Inayat et al., 2024). Heavy metals penetrate aquatic systems, disintegrate

in the water, and quickly accumulate in various aquatic living things, particularly fish. They then find their way into the bodies of fish. The physiological functions and overall health of fish are negatively impacted by the biological accumulation of heavy metals in fish (Jamil Emon et al., 2023). The accumulated amount of heavy metals within a tissue is primarily influenced by the metals' intent in water as well as the length of exposure, according to studies conducted in both the field as well as in laboratories. However, additional factors in the environment like pH, salinity, temperature as well hardness also have a big impact on metal accumulation. Pollution at lower levels can affect reproduction directly by affecting free gametes (ovum or sperm) discharged into water bodies, or indirectly by accumulating in the reproductive organs. Fish reproduction is highly controlled by a variety of factors; therefore, any stage of this process could be impacted by minimal pollution. According to the research, heavy metal pollution not exclusively impacts fish health but also can interfere with the fish's regular steroidogenesis patterning, which impairs the production of hormones in both males as well as female fish and even reduces the amount and quality of sperm as well as ova (Jamil Emon et al., 2023).

The natural ecosystem is mostly exposed to heavy metal releases through mining, treatment plants for wastewater, burning fossil fuels, as well as household along agricultural waste byproducts. The aquatic biota is subjected directly to a variety of heavy metals which are either dissolved in the water or found there as silt. Fish are mainly impacted because they are the primary consumers in the aquatic ecosystem. Fish neural systems can be harmed by heavy metal poisoning, which can alter how fish interact with their surroundings. Due to their omnivorous nature, humans are subjected to hazardous heavy metals through a variety of foods, including cereals, vegetables, and even seafood. Consequently, the presence of heavy metal pollution in aquatic species or plants can accumulate, remain in the food chain, or eventually transfer to humans. The toxicity of heavy metals to fish eaters has grown to be a major worldwide concern (Garai et al., 2021).

Fish can acquire metal through two different pathways: the gills in the water or the gut from their food. Since the fish's gills are the primary organ targeted by metal toxicity, the immediate absorption route is more significant (Sauliutė et al., 2015). The intake of heavy elements via food, whereby the food is broken down and absorbed, metabolized, as well as metabolic by-products are expelled, is one of the mechanisms of accumulation as well as aggregation. This process results in the elements building up within an organism's living tissues (Hamada et al., 2024). Fish deposit metals through several vital body tissues, including their skin, muscles, liver, kidney, and gills, they pose a major hazard to aquatic ecosystems that are contaminated with heavy metals. To adjust to this pressured state, fish need more energy, which comes from stored foods including protein, lipids, and carbs. Reactive oxygen species (ROS) are produced when certain metals (Cu, As, Fe, Pb, Cd, Cr, Hg, Ni, and Zn) react with one another. These ROS are crucial for preserving a particular fish physiology (Jamil Emon et al., 2023). Fish reproductive and developmental processes are among the physiological systems that are impacted by heavy metal contamination in water. Fish are susceptible to the impacts of waterborne metals due to their intake and accumulation within the organism. This can lead to metal-induced disruptions in the form and function of different tissues as well as organs. Fish that are in their early phases of development, such as those in which the eggshell is still protecting the embryos, are more vulnerable to intoxication. Unrest in the development of embryos could result from the impact of metals found in water on spawners. Therefore, heavy metals may harm several metabolic pathways in developing embryos, which may lead to morphological as well as functional abnormalities, development retardation, or even mortality in the most vulnerable cases. In fish, heavy metals can also cause endocrine disruptions. For example, studies have shown that cadmium lowers thyroid hormone levels. The primary processes by which heavy metals become toxic are associated with changes in enzyme production and activity as well as osmotic disruptions (Jezierska et al., 2009).

Because of the increasing quantities of various metals, industrialization has degraded the ecosystem. As evidenced by historical occurrences such as the mercury poisoning of Japanese waterways, toxic metals including Pb and Hg are extremely harmful. Furthermore, it is believed that the most significant harmful contaminants for aquatic life are heavy metals. Humans are extremely poisonous to As, Cd, Pb, and Hg, and can only tolerate very low doses of these substances. Fish age, development, and various other physiological variables all affect the levels of metals in different fish species. For humans, fish are the single greatest source of As as well as Hg (Pandey et al., 2014). Heavy metals, including lead (Pb), cadmium (Cd), nickel (Ni), as well as chromium (Cr) were examined in the body tissues, gills, livers, and also kidneys of control fish that were kept in natural water systems. Additionally, the majority of these metals are found in fish's edible parts. Eating fish has an impact on humans as well and can lead to certain health issues. The sex, age, location, and season of the fish all affect how much of certain harmful components they contain. The main reason for aquatic loss along with an unbalanced food chain is caused by human contamination in the waterways (Ali and US SA, 2014).

Since the neurological system is the most susceptible, damage to it can significantly alter a fish's behaviour and, as a result, its chances of survival. One well-known type of pollution in the aquatic ecosystem is heavy metals. Fish and environment communication

may be hampered by their interactions with pertinent chemical cues. The reason heavy metals are the most effective neurotoxins is their affinity for many ligands as well as macromolecules (Baatrup and Pharmacology, 1991). By altering the shape of the olfactory epithelium and decreasing the neurophysiological response to the olfactory stimulant, copper can disrupt the functioning of the olfactory system (Sabullah et al., 2015).

The hypothalamo-pituitary-interrenal (HPI) axis, which regulates the cortisol response to stress, has been demonstrated to be disrupted by a variety of metal and chemical substances. This disruption may potentially change typical fish behaviour. It has been demonstrated that toxicants alter plasma cortisol levels, either while the body is at rest or reacts to external stimuli (Scott and Sloman, 2004). It has been demonstrated that certain toxicants change the amounts of metabolic substrate. This is probably going to affect a lot of fish behaviours because the best foraging techniques are determined by energy availability as well as demand. Being exposed to several trace metals, especially cadmium, can cause disruptions to the accumulation or mobility of metabolic substrates, including lactate, glycogen, glucose, lipid, as well as protein (Scott and Sloman, 2004).

Many studies have previously employed swimming as a means of determining a compound's level of toxicity. The metals have an impact on swimming behaviour by raising the plasma ammonia concentration, which lowers the plasma's concentration of Na+, K+, and Ca2+. Numerous metabolic as well as physiological processes, including contraction of muscles, transmission at the neuromuscular junction, along activity of the central as well as peripheral nervous systems, are mediated by these ions (Sharma et al., 2019). The concentration of Na+, K+, and Ca2+ in plasma dropped during the copper exposure period due to an increase in total plasma ammonia concentration, which impacted swimming speed (Sabullah et al., 2015). Not only can fish be severely contaminated with heavy metals, but they can also have other negative impacts, such as major issues. A variety of organs may be poisoned by heavy metal exposure. Via soil erosion, atmospheric deposition, drainage, and different human activities, they may build up in water bodies. The biogeochemical cycle is impacted by rising environmental concentrations of heavy metals, which can be hazardous to fish and other species (Pandey et al., 2014).

Effects of heavy metals on growth and development of fishes

In growing fish (embryos in particular), heavy metals may have detrimental effects on a variety of metabolic processes that can lead to developmental delay, morphological and functional abnormalities, or even death in the most vulnerable species. Furthermore, heavy metals trigger energy-intensive detoxification procedures, which means that less energy may be utilized for growth in inebriated fish. The majority of research on the effects of heavy metals on fish embryos as well as larvae report high rates of death, delayed hatching, deformed bodies, and anatomical abnormalities (Sfakianakis et al., 2015). Extensive research demonstrated that there was a great deal of individual diversity in the embryos' susceptibility to intoxication: a few of them died during the initial stages of development, and some had morphological abnormalities (part of them did not hatch), while others matured normally (Jezierska et al., 2009). A newly discovered contaminant that is extensively present in aquatic habitats and poses a major risk to the health of humans and animals is lead (Pb). Gametogenesis, sex hormones, estrogen (ERα and ERβ), androgen (AR) receptors are all impacted by lead exposure (Ferreira et al., 2023). As among the most dangerous heavy metals, exposure to lead has been shown to cause pathological changes in the ovarian tissue of freshwater teleosts (*Mastacembelus pancalus*) (Garai et al., 2021). Fish health is immediately impacted by lead in the aquatic environment, but lead can also have an impact on the reproductive system. The ovarian tissue of *Mastacembelus pancalus* can suffer from necrotic oocysts and necrosis due to the toxic action of lead, which can also cause degradation of yolk globules, and infertility (K AL Taee et al., 2020). Many aquatic biota animals' reproductive processes may be directly impacted through transition metal contamination of aquatic habitats. Pinto et al.'s study assesses the impact of copper as well as cadmium on tambaqui (*Colossoma macropomum*) sperm. This indicates that the presence of copper and cadmium significantly hampered the process of fertilization as well as hatching. These findings suggest that *C. macropomum* gametes are negatively impacted by surroundings polluted with copper as well as cadmium (K AL Taee et al., 2020).

Among the pollutants emitted by the rise in human activity are metals. Heavy metals can be considered disruptors of the endocrine system once they can impact the reproductive aspects of diverse creatures. The study's goal was to assess any potential impacts of cadmium upon the HPGL (Hypothalamic-Pituitary-Gonadal-Liver) axis among female *Rhamdia quelen* animals that were subjected to nominal cadmium concentrations of 0.1, 1, 10, as well as 100 µg.L− 1. The findings show that freshwater environments include amounts of cadmium, which may have an impact on the female reproductive control axis HPGL of the Neotropical species *R. quelen* (Vicentini et al., 2022). Developmental abnormalities may also develop from the genotoxic activity of copper and cadmium. Heavy metal exposure frequently results in hatching delays, which have been linked to the metals' effects on divisions of mitosis (Sfakianakis et al., 2015). Alterations in selective membrane permeability caused by copper

have the potential to disrupt the exchange of ions across perivitelline fluid as well as water. 30–50% of the metal in zinc-exposed *Clupea harengus* eggs becomes bound to the chorion; the rest of the metal was primarily accumulated in the perivitelline fluid, with just traces found in the embryo. Therefore, even trace amounts of metal penetrating the egg may harm fish-developing embryos. Fish embryo development rate may be impacted by metals (Jezierska et al., 2009).

The purpose of the research was to investigate the impact of various environmental pollutants, particularly heavy metals, at various Lake Manzala locations on the reproduction of Oreochromis niloticus. There were two categories: fifty intoxicated fish from Abbasa Farm served as the control group, while fifty fish from the same farm made up the drunk group. Fish were brought into the lab to be studied for clinical indications, histological analysis, and accumulation of heavy metals in fish organs used in reproduction, such as the liver, brain, ovary, as well as testes. The intoxicated group as well as the control group differed significantly, according to the findings. The metal levels varied in order, Fe >Cu > Pb > Cd. The Cu and Fe accumulation were identified in the liver, brain, ovary, as well as testis, in that order. Pb was found to accumulate in the liver, brain, ovary, and testis, in that order. In contrast, Cd accumulates in the liver, brain, testis, and ovary in that order. These organs' histological analyses of the brain, liver, testes, and ovaries were noted. The fish's testis displayed a few degenerative alterations as well as fewer seminiferous tubules. They looked to be empty from several proliferating cells. The ovaries had severe lymphocytic infiltration as well as were deformed from their typical forms (Elgaml et al., 2019).

The physiological state as well as reproductive activity of Tetractenos glaber, a common estuary toadfish, were assessed in this study. Lipid content in the liver as well as gonad tissues correlated inversely with concentrations of Cd, As, Pb, along Co in sediments. On the other hand, the amount of protein in the gonad, liver, as well as muscle tissues correlated well with the Ni and Co sediments concentrations. Reduced oocyte density as well as diameter were linked to elevated Pb levels within gonads. This could eventually result in a decrease in the amount of eggs produced by females, as it implies a drop in egg size as well as fertility. Alterations in fish health and reproduction triggered by chemical contaminants can alter the fish population and structure in communities (Alquezar et al., 2006).

The purpose of this study was to look at how heavy metals including copper, zinc, iron, cobalt, chromium, aluminium, manganese, and molybdenum affected the rate at which zebrafish eggs hatched and the rate at which the larvae survived. To determine each metal's threshold level of tolerance, different concentrations of 0.05 mg/L, 50 mg/L, as well as 500 mg/L were employed. Zinc along with molybdenum were the tested metals that had the greatest effects on hatching time; iron, on the other hand, did not significantly alter results obtained by the control group. Zebrafish eggs were affected by cobalt, manganese, chromium, copper, and aluminium based on the exposure levels, which set the results distinct from the control group. Furthermore, the results of the study show that the heart rate of hatched eggs is significantly influenced by the levels of metals; in especially, greater metal concentrations are associated with higher heart rates. It has been determined that the three most hazardous heavy metals zinc, molybdenum, as well as copper, increase the risk of death and reduce the lifespan (Gouva et al., 2020).

At a lower level (005 and 025 mg l1 Cd), early hatching was observed; in contrast, delayed hatching was observed in the Cd group, with over 90% of hatching taking place on the final day during the hatching period. Exposure to Cd had a detrimental effect on larval growth that was concentration-dependent. At the last stage of the period of exposure, larvae subjected to Cd weighed 224 35% (mean S.E.) less than controls and had a total length (LT) that was 139 08% shorter. Both male and female subjected fish had higher plasma sex steroid levels (oestradiol in juvenile females as well as 11-ketotestosterone in juvenile males) after 28 days of being exposed to Cd (four to ten times over controls). These findings demonstrate that ecologically relevant levels (in the mg l1 range) of Cd can alter the growth and development of *O. mykiss* influencing embryos, larvae as well as juvenile fish (Lizardo-Daudt and Kennedy, 2008).

Some of the documented consequences of heavy metals in fish include reduced hatchability, enhanced abnormalities of newly formed larvae, lesser body size of larvae, as well as decreased larvae survivorship (Jezierska et al., 2009). The current study set out to find out how these metal concentrations in the environment affected preferred sperm quality, fertilization as well and hatching rates, along with embryo as well larval survivorship. Pejerrey sperm motility (in about 50% of cases) as well as velocity (in approximately 30% of cases) were found to be decreased when certain metals were present in aquatic environments. Because these outcomes were attained with the aid of a computational sperm analyzer, this analysis must be used as a tool or bioindicator of water pollution. Furthermore, the rate of fertilization decreased (by approximately 40%) across all treatments. In addition, the highest levels of metals evaluated showed zero hatching rate and 0% embryo as well as larval survival. Overall, these findings demonstrated that various reproductive parameters of among the most representative fish species in Argentinean waterways might be adversely affected by minimal metal concentrations (Gárriz and Miranda, 2020).

The current findings demonstrate that heavy metal contamination harms common carp fertilization along

with hatching rates as well as embryo development. The length of time and the amount of heavy metals utilized determine how much of an impact this has. Throughout this investigation, malformations of the yolk sac as well as the curvature of the abdominal cavity were also noted. The newly emerging larvae had significant physical deformities and were incapable of feeding or swimming (El-Greisy and El-Gamal, 2015). Metals were found to have a significant impact on embryonic development right after fertilization, during the enlargement of the egg. The perivitelline gap, which contains a colloidal suspension of proteins released by the vitelline membrane, absorbs water and causes fish eggs to enlarge. According to research done on *Cyprinus carpio* eggs, lead, cadmium, as well as copper significantly reduced dilatation in a concentration-dependent manner when compared to the control groups, which showed an increase in egg diameter of almost 40%. Metals may also have an impact on the surface characteristics of the egg. The selective membrane permeability of copper is altered by copper, disrupting the cation exchange across the water and the perivitelline fluid. Every stage of embryonic development is impacted by the degree of swelling. When eggs swell properly, the embryo can migrate every 5 to 10 seconds. When eggs swell insufficiently, the embryos possess too little room to move, which can lead to the hatching of deformed larvae (Jezierska et al., 2009). The embryos develop what are known as hatching glands on the head before hatching. The enzyme chorionase, which is required for the breakage of the eggshell during hatching, is produced by the glands. Water-based metals may have an impact on these glands' growth and operation. Metal-induced disruptions of both transcription and translation resulting in lower production of proteins, such as chorionase, were found by Kapur and Yadav (Kapur and Yadav, 1982). Researchers looking into the molecular processes of heavy metal impacts in fish are increasingly focusing on the mechanism of action that results from exposure to these metals in embryos as well as larvae, particularly alterations in enzymes and DNA. It is well known that the liver uses the enzymes catalase (CAT) along with superoxide dismutase (SOD) to change reactive oxygen species into non-toxic oxygen. It has been discovered that in the embryos as well as larvae of goldfish (*Carassius auratus*), such enzymatic activities were dramatically decreased owing to being subjected to high Cu concentration (1.0 mg/L), developing oxidative stress that causes lipid peroxidation. Furthermore, exposure to two-day-old Japanese medaka (*Oryzias latipes*) larvae exposed to Cd and Cu causes significant damage of DNA (Taslima et al., 2022).

In both small lakes as well as wetland environments, the bioaccumulation of selenium bioaccumulation was observed resulting in reproductive failure, egg as well as embryo mortalities, and developmental abnormalities and malformations in a variety of fish species (Kennedy et al., 2000). The primary finding of this study is that spinal deformity and Cd accumulation were significantly higher in the combination of exposure to high temperature as well as Cd than in either alone. The fact that juveniles subjected to Cd at 32C showed the highest prevalence of spinal abnormalities suggests that the toxicity of Cd is more severe at higher temperatures (Sassi et al., 2010). Based on the research, the impacts of 2 h pulse exposure of cadmium on the initial stages of life of Australian red spotted rainbow fish (*Melanotaenia fluviatilis*). Cadmium had an impact on spinal abnormalities, hatching, as well as larval survival. More negative impacts were produced by lower embryo age along with higher cadmium concentration. In the populations, there were up to 27% deformed specimens, including spinal malformations (Sfakianakis et al., 2015). Following exposure to copper (0–65 μg/L), lateral line receptor neurons' cytotoxic reactions were investigated in zebrafish larvae. Dissolved copper produced a dose-dependent loss of neurons in detected lateral line neuromasts at a concentration ≥20 μg/L. In a larval mechanosensory system, cell death occurred quickly (less than one hour). The lateral line of zebrafish subjected to copper recovered two days after being moved to clean water. On the other hand, larvae subjected to the dissolved copper (50 μg/L) consistently for three days did not show any recovery in their lateral line. All of these findings point to the vulnerability of peripheral mechanosensory neurons to copper's neurotoxic impacts (Linbo et al., 2006).

Johnson and his colleagues examined the effects of Cu on zebrafish (*Danio rerio*) embryos during fertilization up to 120 h. There were differences in the number of functioning neuromasts and the larvae's incapacity to position themselves in a water current between the two copper concentrations (68 and 244 μg Cu L1). In addition, the scientists noted larval development impairment, mortality, as well as impeded hatching (Johnson et al., 2007). There has been one study on the impact of chromium on African catfish. The five-day exposure period began immediately after fertilization. The most commonly reported abnormality was an atypical body axis (Sfakianakis et al., 2015). Chromium also caused issues with fish fertilization (Garai et al., 2021). Zinc builds up in fish gills, where it destroys the structure and impairs the fish's ability to grow, develop, as well as to survive. Additionally, it modifies fish behavior, hatchability, blood parameters, swimming ability, and balance (TAŞTAN, 2018). Fish development and survival are negatively impacted by structural damage caused by zinc at high levels (Ali and US SA, 2014). Embryos of *Cyprinus carpio* subjected to copper and lead first displayed developmental delay during the coloring of their eyes. Comparable outcomes were seen in common carp embryos cultured in cadmium-containing water; however, the decrease in growth

was related to concentration and first shown later in the heartbeat as well as body pigmentation stages. Our results indicate Pb-, Cu- or Cd-treated *Cyprinus carpio* eggs exhibited significant aberrations during cleavage. The whole blastula was distorted, and the blastomeres were distributed unevenly. During the organogenesis stage, metals also had an impact on the embryos. Lead-exposed *Ctenopharyngodon idella* embryos: each cell was detached, the whole blastula distorted, and the blastomeres varied in size and distribution. When *Fundulus heteroclitus* embryos were subjected to mercury, the ocular vesicles displayed a range of abnormalities, including cyclopia to partly joined eyes with two distinct lenses (Jezierska et al., 2009).

Low hatchability, a delayed hatch, increased mortality, morphological abnormalities, and shorter larvae are all caused by cadmium doping. Although the larvae's heartbeat as well as yolk absorption were considerably reduced at some high levels, they were less susceptible to the effects of Cd exposure than other endpoints (Cao et al., 2009). Red sea bream embryos and larvae were adversely affected by the waterborne zinc in terms of development, growth, and survival. Exposure to zinc delayed the time it took for embryos to hatch and resulted in low hatching rates, significant mortality, and morphological abnormalities in larvae and embryos. The four biological indicators were all dependent on the concentration of zinc and may serve as useful biological indicators for assessing the toxic effects of zinc to this fish during its early life (Huang et al., 2010). Sublethal levels of methylmercury exposure in *D. rerio* embryos consistently resulted in two kinds of morphological abnormalities. The incidence and severity of teratogenic to abnormalities were influenced by the length of the exposure, the developmental stage at which the problems occurred, and the concentration. A tissue anomaly of the median fin fold, as well as the tail fin primordium, constituted the initial deformity. The finfold's structure of tissue was chaotic in afflicted embryos, while in more extreme cases, the finfold's form and the actinotrichia that were growing changed (Samson and Shenker, 2000). Using gross morphology and histology, the impact of lead exposure on African catfish *Clarias gariepinus* embryos was investigated. Exposure to lead nitrate decreased the proportion of embryos and resulted in a gradually longer hatching delay. Gross morphological anomalies included two mild deformities (decrease of pigmentation as well as fold defect) as well as four large ones (pericardial oedema, yolk sac oedema, irregular head shape, and notochordal defect). There were four histological classifications identified: detached skin, gill malformation, eye malformation, along with notochordal abnormality. Only the embryos subjected to 300 and 500 g/L lead were found to have all of these abnormalities. The extent of histological lesions rose as the level of lead and exposure duration increased. Lead buildup in the chorion indicates that the chorion serves as an efficient barrier to keep the embryo safe. Lead's minimal effect on the prehatching phases may be attributed to the chorion's ability to protect as well as the perivitelline fluid's capacity to concentrate lead (Osman et al., 2007). The presence of accumulation of copper in the chorion indicates that it functions as a strong barrier to the absorption of Cu. Cu nonetheless had considerable fatal and sublethal effects even after penetrating the chorion and entering the embryo. Cu caused the embryos' morphological defects, high mortality, delayed hatching, reduced hatchability, and larger eggs. The overall length of the newly hatched larvae's body and their heartbeats both rose noticeably (Wang et al., 2020).

After the embryonic phase, the ability to survive of the embryos, the timing of hatching, and the size and quality of the freshly hatched larvae were assessed. Measurements were taken of the body as well as swim bladder sizes, and the times of yolk sac resorption, the start of active eating, and inflation of the swim bladder were assessed. The findings demonstrated that exposure to Cd and Cu during embryonic development greatly decreased embryonic survival, increased the incidence of body abnormalities and death in freshly hatched larvae, as well as delayed hatching. During the larval stage, being exposed to Cd and Cu hampered the development of the larvae and stunted their growth and survival (yolk utilization, commencement of active feeding, along with the inflation of their swim bladders). For the ide larvae and embryos, cadmium was more harmful than copper. Even in situations where the larvae developed in clean water, being subjected to metals at the embryonic stage alone harmed the performance of the larvae (Witeska et al., 2014).

Effects of heavy metals on the physiology of fishes

There is evidence of haematological and biochemical changes, as well as cellular and nuclear anomalies, in many fish species exposed to varying levels of heavy metals. Most fish organs (gills, liver, kidneys), including the intestine as well as muscles, displayed a variety of organ-specific pathologies following both acute and long-term exposure to various heavy metals. The expression of several genes associated with oxidative stress and heavy metal detoxification was also disclosed by this investigation (Shahjahan et al., 2022). The aquatic ecology is greatly threatened by heavy metal pollution, which eventually puts at risk the continuation of healthy and secure life on Earth. Fish that are exposed to contaminated water have pathological changes and behavioral abnormalities (Mishra et al., 2023). Aquatic animals' tissues may become poisonous when heavy metal accumulation reaches a noticeably high degree (Ali and US SA, 2014). By attaching to the receptor position, metals can interfere with hormone activity and cause a variety of hormonal abnormalities (Bolawa et al., 2014). On *Cyprinus carpio*, chronic exposure to chromium at concentrations ranging from 2 to 200

µmol/L resulted in cytotoxicity, reduced mitogen-induced lymphocyte activation, as well as impaired phagocyte activities. The total protein as well as lipid content in the muscle, liver, along gills of *Labeo rohita* is decreased by chromium deposition in the tissue (Garai et al., 2021).

Certain fish species exhibit harmful effects of chromium, which are reflected in blood abnormalities such lymphocytosis, anaemia, eosinophilia, as well as renal along with bronchial diseases. While higher amounts of Cr harm fish swimming close to the site of Cr disposal, chromium is recognized for accumulating less in fish bodies (Ali and US SA, 2014). Fish are extremely poisonous to cadmium. Histopathological changes have been documented, including fatty vacuolation in the liver, necrosis in hepatocytes, constriction of submucosal blood vessels in the intestine, as well as glomerular shrinkage along with necrosis in the tissue of the kidney of tilapia (*Oreochromis niloticus*). Higher copper concentrations in fish result in poor growth, shortened life spans, and weakened immune systems. Blood parameters such as haemoglobin and white blood cell counts decreased while the number of red blood cells increased in Nile tilapia subjected to nickel. Histopathological alterations in several tissues such gill, kidney, liver as well and intestine were detected in nickel-subjected freshwater fish *Hypophthalmichthys molitrix*. Fish exposed to lead, that is freshwater Teleost displayed necrosis of parenchyma cells, fibrosis of the hepatic cords as well as connective tissue, a decrease in growth as well as body weight, along collapsing blood vessels (Garai et al., 2021).

Lead causes serious harm to the kidneys, liver, brain, nerves, and several other organs. The most hazardous and non-essential heavy metal found in large quantities in the earth's crust as well as aquatic environments is cadmium. Both cadmium (Cd) and mercury (Hg) cause kidney damage as well as exhibit chronic toxicity symptoms, such as tumours, hypertension, hepatic dysfunction, as well reduced ability to reproduce (Ali and US SA, 2014). Freshwater fish that are consistently exposed to low concentrations of arsenic experience bioaccumulation, primarily in their kidney and liver tissue. The heart of the freshwater teleost *Channa punctata* was discovered to have a variety of histopathological changes, such as tissue necrosis (Garai et al., 2021).

Histological changes, such as peeling of the epithelium, oedema, as well as fibrosis of the sub-mucosal tissues in gallbladders, were observed in lake white fish (*Coregonus clupeaformi*) and lake trout (*Salvelinus namaycush*) fed dietary arsenate. Fish that were exposed to arsenic for extended periods in the lab or in naturally occurring As-contaminated environments showed histopathological lesions in their kidney, gallbladder, as well as liver, which had an impact on their ability to function as liver along with kidneys. The gastrointestinal, cardiovascular, neurological, respiratory, and haematological systems are just a few of the organ systems that may be affected by the acute and subacute effects of arsenic, particularly after prolonged exposure. Because buildup in tissues depends on how quickly each organ absorbs and processes waste materials (Kumari et al., 2017).

The purpose of the study was to assess the histopathological alterations in the fish organs as well as the concentrations of heavy metals (Cu, Pb, Cd as well as Zn) in a variety of freshwater fish. Histopathological examination of the fish's muscles, livers, as well as gills revealed hemorrhagic, vacuolar degenerative, edematous, and necrotic conditions (Hidayat et al., 2020). Depending on the fish's developmental stage, the effects of the Cu + Zn mixture on physiologic (gill ventilation frequency, survival, and gill-somatic index) characteristics were investigated in rainbow trout. The largest proportion of mortality was observed in hatching embryos, that were most sensitive to the effects of metals both individually and in combination. Variations in specific examined criteria (e.g., juvenile gill-somatic index, mortality of embryos, particularly hatching embryos) suggested that the metal mixture was more hazardous to rainbow trout throughout their ontogenesis (Kazlauskiene and Vosyliene, 2008). The purpose of the study was to ascertain the absorbed amounts of manganese as well as chromium in the gills, intestine, muscles, and skin, along with bones of common carp (*Cyprinus carpio*), as well as the acute toxicity as well as impacts on haematological and biological parameters. In the study, a sublethal dose of manganese sulfate along with chromium chloride solution was exposed to adult carps for 96 hours. The gills had the largest bioaccumulation, followed by the colon, muscles, skin, and bones (Ali et al., 2021).

Because mercury is so hazardous, it negatively impacts aquatic life, which in turn affects people. The objective of this study was to evaluate the histological changes in the tissues of *Clarias batrachus*, an Indian catfish. The fish exposed to the conditions showed degenerative alterations in their stomach, liver, as well as gill tissues. Higher concentrations were correlated with higher levels of alterations. In the gill tissues of subjected fish, there was evidence of epithelial layer rupture, club-shaped gill filament, damaged gill lamellae, the formation of vacuoles, blood conjugation, as well as necrosis in gill filaments. Hepatic dissociation, inflammatory hepatocytes, unclear swelling, vacuole development, and hydropic degeneration were among the liver injury manifestations. Additionally, there were other instances of altered stomach tissues, including thinner serosa, vacuolization, muscular injury, as well as necrosis. The study showed that even at extremely low concentrations, mercury poses a risk to life. Data analysis showed that sediments had higher concentrations of Fe, Pb, and Ni as compared to

the sample of water. The intestinal variety displayed submucosal hyperplasia, dissolution of the muscular layer accompanied lymphocytic infiltration, enlarged mucous cells, vacuolar degenerations, along with separation of the mucosal epithelial layer of the intestinal villus. Hepatocytes displayed lymphocytic infiltration, lipid droplet accumulation, as well as ballooning degeneration (Mishra et al., 2023).

The goal of the current study was to look into how various heavy metals bioaccumulate and sequester in *Tilapia zillii*. The current investigation demonstrated that, except for Mn, liver samples had a greater degree of bioaccumulation as well as biosedimentation factors; gills displayed high levels of accumulation, but muscle samples had lower levels of all the metals under investigation. The findings showed that various heavy metal accumulations occurred in various fish tissues. Compared to other organs, the liver of *T. zillii* collected higher concentrations of Cd, Cu, Fe, as well as Zn. According to histopathological findings, renal tubules had multifocal necrotic regions and obstruction in the interstitial blood vessels (Hadi et al., 2012; YH and Fisheries, 2021).

According to the study, the metal levels in the tissues of the two fish varied, with the non-edible sections accumulating more metals compared to the edible muscles. The amounts of Cu, Zn, Pb, as well as Cd in the fish muscles, were below the highest allowable level; however, the level of Fe in the muscles was above the allowable limit. Due to the accumulation of metals, various histopathological changes were found in the analyzed tissues of both fish. These changes included vacuolar degenerative conditions with focal areas of necrosis in the liver, the proliferation in the epithelium of gill filaments as well as fusion of extracellular lamellae, chronic degenerative as well as necrotic alterations to the intestinal mucosa along with seminiferous tubules, deterioration and atrophy in cardiac muscle fibres, as well deterioration in muscle bundles (Mohamed, 2008).

The levels of lead (Pb), chromium (Cr), as well as copper (Cu) were observed in the brain, liver, muscles, gills, kidneys, as well as intestinal tissues of subjected along with control fish. The highest number of scoring lesions were found in the gills, which were followed by the kidneys, intestines, muscles, brain, as well as liver, which was the organ least impacted. The histological abnormalities were documented in concentrations as well as progressive time-related series. Moreover, the organs were not impacted evenly by the metals; in fact, every analyzed organ has shown mild to severe responses towards the hazardous metals where lead was demonstrated to induce more serious ulcers when compared with copper as well as chromium (Shah et al., 2021).

The majority of biological and physical functions are hampered by aluminium. The plasma membrane induces respiratory stress, coagulation of mucus on the gill, lamellar fusion, and abnormalities in osmoregulation as well as ionic balance. In addition to endocrine disturbance, fish exposed to Al experience pathological alterations in the cardiovascular, respiratory, ion-regulatory, and haemoglobin concentration, along with growth. Arsenic intoxication induces histopathological alterations in indifferent organs including degenerations in kidneys or liver with focal hepatic necrosis as well as bile duct expansion with plugs comprising intranuclear arsenic inclusion in parenchymal hepatocytes. Despite severe inflammation in the liver as well as blood vessel deterioration, mercury toxicity is associated with cellular as well as structural changes such as disengagement in the gills with the fusion of secondary filaments in the gills of the fish *Clarias batrachus*, as well as changes in cognition and behavior such as convulsions as well as ataxia. Additionally, it was shown that the guppy (*Poecilia reticulata*) subjected to waterborne methylmercury had a noticeable deterioration of the renal tubules (Shah et al., 2021). In contrast to the fish subjected to heavy metals (Cd + Pb + Cr + Ni), the liver of the control group displayed a usual structural pattern, hemosiderin was present, and there was fibrosis. The results in the kidney showed the accumulation of lipofuscin granules in the impacted cells of macrophages (Vinodhini and Narayanan, 2009).

Exposure to common carp to heavy metals (Cr, Cd, and Pb) was investigated using concentrations that were appropriate for the environment (Rajeshkumar et al., 2017). There were hepatocytes in the liver that had big vacuoles and a frothy appearance. The gills had many walled-off structures with bluish coloring and moderate congestion in their capillaries. The fish heart's myocardial fibres were severely thinned. The dwellings were only slightly crowded. The amount of lead, Pb, manganese, and iron in the fish organs was higher than what the WHO allowed for fish. It is evident that the accumulated heavy metals in the tissues, as well as organs of fish, negatively impacted the histopathological state of the fish, which in turn affected the health of the fish (Abiona et al., 2019). Fish gill respiration shortage may result from mercury poisoning, and yellow fin seabream's capacity for gas exchange may be reduced by HgCl2. lesions caused by mercury in fish liver, Necrosis, degeneration, nuclei change, swelling, lipidosis, cytoplasmic vacuolization of the hepatic cells, bile stagnation, dilatation of the sinusoids, atrophy, and pre-necrotic lesions within numerous hepatocytes are among the pathological signs in the liver induced by mercury pollution. The fish's kidney lesions from mercury poisoning can result in bile duct hyperplasia, kidney tissue necrosis, and interstitial inflammation, as well as inflammation. Through the blood barrier, both organic and inorganic mercury can harm the Central Nervous System (CNS) of the brain in teleost fish. Additionally, mercury exposure alters central processing and sensory perception in the brain, which results in altered behavioral responses which are

known to have neurotoxic consequences such as a decrease in heart rate variability as well as normal motor speed (Zulkipli et al., 2021).

An increase in lead concentrations in the water may have negative impacts on some aquatic life as well as change fish and other aquatic creatures' neurological systems and blood parameters. Copper diminishes the resistance of fish to diseases by disturbing migration; modifying swimming; causing oxidative damage; affecting oxygenation; altering osmoregulation structure as well as pathology of critical organs that include gills, kidneys, liver and various stem cells. The primary target organ for cadmium poisoning as well as chronic exposure in nearly all species of animals is the kidney, which exhibits varying degrees of damage to the kidneys (TAŞTAN, 2018).

Nickel is also reported to cause nephrotoxicity, hepatotoxicity, as well as teratogenesis. The primary site of nickel accumulation in *C. carpio* is its gills. *C. carpio* is primarily gill-mediated when it comes to Ni toxicity (Ghosh et al., 2018). Reduced brain ATPase activity was seen in freshwater fish *Oreochromic niloticus* exposed to nickel both acutely and chronically. When freshwater fish *Prochilodus lineatus* were exposed to nickel, their liver's antioxidant defense system was impacted, and their gills and blood cells also experienced DNA damage. Because mercury is lipophilic and may accumulate in fish nervous systems, it is thought to be the most damaging chemical. It can also cross the blood-brain barrier (Garai et al., 2021).

Fish are similarly susceptible to endocrine disruption caused by heavy metals. For example, studies have shown that cadmium lowers thyroid hormone levels, blocks estrogen receptors, and alters growth hormone expression. Lead, on the other hand, suppresses the production of thyroid hormone by interfering with iodine metabolism. Fish that are exposed to prooxidative metal ions may experience oxidative stress as well as cell membrane deterioration. Lead, copper, along cadmium all have genotoxic effects on fish (Jezierska et al., 2009). Exposure to toxins can also alter brain neurotransmitter levels. In various fish species, exposure to mercury, copper, or lindane decreased brain serotonin as well as dopamine levels; in comparison, lead exposure raised norepinephrine and serotonin levels among fathead minnows (Scott and Sloman, 2004).

Fish tissues had maximum quantities of lead, mercury, and cadmium that were greater than what was considered safe for ingestion by humans. There were also notable variations in the levels of steroid hormones across the middle as well as two other sampling zones. Therefore, exposure to heavy metals can effectively reduce fish's secretion of androgens and estrogens. The findings demonstrated that fish exposure to heavy metals can alter the secretion of reproductive hormones (Scott and Sloman, 2004). Because of their difficult metabolism and ability to bioaccumulate in the tissues of aquatic species, particularly fish muscle, which is frequently consumed as food around the world, heavy metals are regarded as important contaminants of aquatic habitats. Certain metals, including aluminium (Al), cadmium (Cd), copper (Cu), as well as lead (Pb), can harm fish cells and also interfere with their ability to produce hormones. Metals including aluminium (Al), cadmium (Cd), copper (Cu), as well as lead (Pb) are categorized as metalloestrogens because they can impede the activity of oestrogenic hormones in addition to causing damage to cells. Endocrine disrupting chemicals (EDCs) are generally substances that can interfere with an organism's endocrine system as well as cause one of three types of disturbances: (1) impairing endogenous hormone production along with metabolism; (2) mimicking or opposing the functions of hormones; or (3) affecting the synthesis and function of the receptors (Paschoalini et al., 2019).

Table 1: Effects of heavy metal on fishes

Metal	Effect
Chromium	▪ Anaemia, renal as well as bronchial lesions, eosinophilia, with lymphocytosis (Ali and US SA, 2014). ▪ Physiological problems, damaged DNA, microscopic lesions, decreased development and survival rate. Fish growth as well as embryo hatching may be impacted by chromium poisoning. (Garai et al., 2021)
Cadmium	▪ Physical abnormalities (Sfakianakis et al., 2015). ▪ Fish gills with muscle protein segment electrophoretic configurations have been found to differ from CD. (Ali and US SA, 2014). ▪ Cadmium causes oxidative stress, immunotoxicity, impairment of neuromast cells along with olfactory pits, as well as a decrease in olfactory-dependent predator responses. (Planchart et al., 2018).
Lead	▪ Epithelioma is caused by lead, inadequate resorption of the yolk, as well as tail erosions (Jezierska et al., 2009). ▪ Pb produces trembling, muscle spasms, hyperactivity, hyperventilation, as well as irregular swimming.(Planchart et al., 2018). ▪ Lead accumulation also caused morphological abnormalities and impeded free movement. (Garai et al., 2021).

Mercury	▪ Mercury (Hg) causes harm to the kidneys, liver dysfunction, malignancies, reduced ability to reproduce, and symptoms of chronic poisoning. (Ali and US SA, 2014). ▪ The least neurotoxic substance is thought to be mercury. It tampers to the physical characteristics along with the structural stability of the cell membrane. (Garai et al., 2021).
Nickel	▪ Nickel exterminating in fishes comprises surfacing, speedy mouth along with opercular movements, preceding death, shakings as well as loss of equilibrium. Demolition of the gill lamellae through ionic nickel declines the aeration rate and also can cause blood hypoxia as well as death (Sassi et al., 2010). ▪ It may cause a rise in kidney as well as gill ammonia. Before they died, fish with nickel poisoning displayed changes in body stability as well as behavioral abnormalities such as surfacing along with the quick mouth and operculum movements (Ghosh et al., 2018).
Zinc	▪ Zinc leads to gill tissue problems, hypoxia, and disruptions of the control of ions and acid-base. Additionally, it results in damage to the structure, which has an impact on fish development, survival, and rehabilitation (Ali et al., 2021). ▪ Elevated levels of zinc caused abnormalities in the otic as well as ocular capsules, and also in the jaw along with branchial arches (Jezierska et al., 2009). ▪ By raising the degree of hepatic lipid peroxidation, a hallmark of oxidative stress, and lowering liver catalase (CAT) activity, zinc caused an oxidative stress response (Garai et al., 2021).
Arsenic	▪ Many aberrant behaviors, including erratic movement, rapid opercula movements, leaping out of the test mediums, lateral to swim, as well as loss of equilibrium, were brought on by exposure to arsenic. When freshwater perch was exposed to arsenite, ovarian deterioration was seen (Kumari et al., 2017). ▪ Fish exposed to arsenic exhibited histological changes in their liver along with gill tissues. Epithelium hyperplasis, lamellar fusion, epithelium lifting as well as swelling, desquamation, along with necrosis were the changes observed in the gills. Fish physiological processes, including development, reproduction, the immune system, ion control, expression of genes, as well as histopathology, are all impacted by the accumulation of arsenic (Vinodhini and Narayanan, 2009).
Iron	▪ A possible explanation for the toxicity of iron is a physiological blockage of the gills, which causes respiratory disturbance. iron flocs depositing onto the gill epithelium, causing injury as well as blockage of the gills (Dalzell and Macfarlane, 1999).
Copper	▪ The neurological system's spirality is brought on by copper (Johnson et al., 2007). ▪ The oxidative stress responses were triggered by exposure to watery copper. It results in impaired growth, a shortened life span, a weakened immune system, and issues with conception. Apoptosis was induced by copper poisoning in the gills (Garai et al., 2021).
Cobalt	▪ Cobalt damages the perception of smell (El-Greisy and El-Gamal, 2015). ▪ It alters fish blood parameters and causes oxidative stress, apoptosis, aberrant growth, therefore cobalt exposure, which damages sperm DNA as well as increases the expression of a gene associated with DNA repair in the testes that reduces reproductive success (Shahjahan et al., 2022).
Selenium	▪ The gill tissue bleeding and the dilatation of gill lamellae caused by selenium can result in decreased respiratory capacity, poor blood flow, with a potentially fatal metabolic stress response. It may impact the cornea as well as the lens (Vinodhini and Narayanan, 2009). ▪ Selenium's immediate impact on heart tissue and its indirect impact on the kidney were linked to the incidence of pericarditis as well as myocarditis (Inayat et al., 2024).

Conclusion

In conclusion, heavy metals have a significant negative influence on fish health and have a range of consequences on the physiological, behavioral, and ecological aspects of these aquatic creatures. Because heavy metals can harm cells, interfere with immune system function, and inhibit development and reproduction, they pose substantial hazards to fish populations and the overall health of aquatic habitats. Some solutions for minimizing pollution from heavy metals include enforcing rigorous industrial discharge regulations, improving wastewater treatment facilities, promoting environmentally friendly agricultural practices, and raising public awareness of the risks of heavy metal contamination. It is imperative to take urgent action to eliminate the primary sources of pollution to safeguard fish health and preserve the integrity of aquatic habitats for future generations.

References

Abiona, O. O., Anifowose, A. J., Awojide, S. H., Adebisi, O. C., Adesina, B. T., and Ipinmoroti, M. O. J. J. o. T. U. f. S. (2019). Histopathological biomarking changes in the internal organs of

Tilapia (Oreochromis niloticus) and catfish (Clarias gariepinus) exposed to heavy metals contamination from Dandaru pond, Ibadan, Nigeria. **13**, 903-911.

Ali, A. S., and US SA, A. R. J. R. J. C. E. S. (2014). Effect of different heavy metal pollution on fish. **2**, 74-79.

Ali, Z., Yousafzai, A. M., Sher, N., Muhammad, I., Nayab, G. E., Aqeel, S. A. M., Shah, S. T., Aschner, M., Khan, I., and Khan, H. J. T. R. (2021). Toxicity and bioaccumulation of manganese and chromium in different organs of common carp (Cyprinus carpio) fish. **8**, 343-348.

Alquezar, R., Markich, S. J., and Booth, D. J. J. E. P. (2006). Effects of metals on condition and reproductive output of the smooth toadfish in Sydney estuaries, south-eastern Australia. **142**, 116-122.

Baatrup, E. J. C. B., and Pharmacology, P. P. C. C. (1991). Structural and functional effects of heavy metals on the nervous system, including sense organs, of fish. **100**, 253-257.

Bolawa, O., Gbenle, G., and Ebuehi, O. J. I. J. o. A. (2014). Endocrine disruption by the consumption of fish (Tilapia oreochromis) from heavy metals polluted river sites and its reversal using zinc. **4**.

Cao, L., Huang, W., Shan, X., Xiao, Z., Wang, Q., Dou, S. J. E., and safety, e. (2009). Cadmium toxicity to embryonic–larval development and survival in red sea bream Pagrus major. **72**, 1966-1974.

Dalzell, D., and Macfarlane, N. J. J. o. F. B. (1999). The toxicity of iron to brown trout and effects on the gills: a comparison of two grades of iron sulphate. **55**, 301-315.

El-Greisy, Z. A., and El-Gamal, A. H. A. J. T. E. J. o. A. R. (2015). Experimental studies on the effect of cadmium chloride, zinc acetate, their mixture and the mitigation with vitamin C supplementation on hatchability, size and quality of newly hatched larvae of common carp, Cyprinus carpio. **41**, 219-226.

Elgaml, S. A., Saad, T. T., Hamed, M., and Zaki, V. H. J. I. j. F. A. (2019). Effects of heavy metal pollutants on the reproduction of Nile tilapia. **7**, 542-547.

Ferreira, C. S., Ribeiro, Y. M., Moreira, D. P., Paschoalini, A. L., Bazzoli, N., and Rizzo, E. J. C. (2023). Reproductive toxicity induced by lead exposure: Effects on gametogenesis and sex steroid signaling in teleost fish. **340**, 139896.

Garai, P., Banerjee, P., Mondal, P., and Saha, N. J. J. C. T. S. (2021). Effect of heavy metals on fishes: Toxicity and bioaccumulation. **18**.

Gárriz, Á., and Miranda, L. A. J. E. (2020). Effects of metals on sperm quality, fertilization and hatching rates, and embryo and larval survival of pejerrey fish (Odontesthes bonariensis). **29**, 1072-1082.

Ghosh, A., Kaviraj, A., Saha, S. J. E. S., and Research, P. (2018). Deposition, acute toxicity, and bioaccumulation of nickel in some freshwater organisms with best-fit functions modeling. **25**, 3588-3595.

Gouva, E., Nathanailides, C., Skoufos, I., Paschos, I., Athanassopoulou, F., and Pappas, I. S. J. A. R. (2020). Comparative study of the effects of heavy metals on embryonic development of zebrafish. **51**, 3255-3267.

Hadi, A., Alwan, S. J. I. J. o. P., and Sciences, L. (2012). Histopathological changes in gills, liver and kidney of fresh water fish, Tilapia zillii, exposed to aluminum. **3**.

Hamada, N. H., Ali, R. A., El-Tabakh, M. A., and Bream, A. S. J. R. S. i. M. S. (2024). Environmental monitoring: Tobara fish as bioindicators of heavy metal pollution in a coastal ecosystem. **69**, 103335.

Hidayat, S., Suyatna, I., Rafii, A., and Ghitarina, G. J. J. o. W. E. M. (2020). Heavy metals contents and histopathological analysis of some organs of fish obtained from Payau River, Anggana, Kutai Kartanegara, Indonesia. **8**, 148-156.

Huang, W., Cao, L., Shan, X., Xiao, Z., Wang, Q., Dou, S. J. A. o. e. c., and toxicology (2010). Toxic effects of zinc on the development, growth, and survival of red sea bream Pagrus major embryos and larvae. **58**, 140-150.

Inayat, I., Batool, A. I., Rehman, M. F. U., Ahmad, K. R., Kanwal, M. A., Ali, R., Khalid, R., and Habib, S. S. J. B. T. E. R. (2024). Seasonal variation and association of heavy metals in the vital organs of edible fishes from the River Jhelum in Punjab, Pakistan. **202**, 1203-1211.

Jamil Emon, F., Rohani, M. F., Sumaiya, N., Tuj Jannat, M. F., Akter, Y., Shahjahan, M., Abdul Kari, Z., Tahiluddin, A. B., and Goh, K. W. J. T. (2023). Bioaccumulation and Bioremediation of Heavy Metals in Fishes—A Review. **11**, 510.

Jezierska, B., Ługowska, K., Witeska, M. J. F. p., and biochemistry (2009). The effects of heavy metals on embryonic development of fish (a review). **35**, 625-640.

Johnson, A., Carew, E., and Sloman, K. J. A. T. (2007). The effects of copper on the morphological and functional development of zebrafish embryos. **84**, 431-438.

K AL Taee, S., Al-Mallah, K. H., and Kh Ismail, H. J. J. o. A. V. S. (2020). Review on some heavy metals toxicity on freshwater fishes. **5**, 78-86.

Kapur, K., and Yadav, N. J. A. H. H. (1982). Effects of certain heavy metal salts on the development of eggs in common carp, Cyprinus carpio var. communis. **10**.

Kazlauskiene, N., and Vosyliene, M. J. P. J. o. E. S. (2008). Characteristic features of the effect of

Cu and Zn mixtures on rainbow trout Oncorhynchusmykiss in ontogenesis. **17**, 291.

Kennedy, C., McDonald, L., Loveridge, R., Strosher, M. J. A. o. E. C., and Toxicology (2000). The effect of bioaccumulated selenium on mortalities and deformities in the eggs, larvae, and fry of a wild population of cutthroat trout (Oncorhynchus clarki lewisi). **39**, 46-52.

Kumari, B., Kumar, V., Sinha, A. K., Ahsan, J., Ghosh, A., Wang, H., and DeBoeck, G. J. E. c. l. (2017). Toxicology of arsenic in fish and aquatic systems. **15**, 43-64.

Linbo, T. L., Stehr, C. M., Incardona, J. P., Scholz, N. L. J. E. T., and Journal, C. A. I. (2006). Dissolved copper triggers cell death in the peripheral mechanosensory system of larval fish. **25**, 597-603.

Lizardo-Daudt, H., and Kennedy, C. J. J. o. f. b. (2008). Effects of cadmium chloride on the development of rainbow trout Oncorhynchus mykiss early life stages. **73**, 702-718.

Mishra, A., Behera, B. J. J. o. A., and Science, N. (2023). Effect of mercury on histological alterations in gill, liver and stomach tissues of Indian catfish, Clarias batrachus. **15**, 685-691.

Mohamed, F. A. J. G. V. (2008). Bioaccumulation of selected metals and histopathological alterations in tissues of Oreochromis niloticus and Lates niloticus from Lake Nasser, Egypt. **2**, 205-218.

Osman, A. G., Wuertz, S., Mekkawy, I. A., Exner, H. J., and Kirschbaum, F. J. E. T. A. I. J. (2007). Lead induced malformations in embryos of the African catfish Clarias gariepinus (Burchell, 1822). **22**, 375-389.

Pandey, G., Madhuri, S. J. R. J. o. A., Veterinary, and Sciences, F. (2014). Heavy metals causing toxicity in animals and fishes. **2**, 17-23.

Paschoalini, A., Savassi, L., Arantes, F., Rizzo, E., Bazzoli, N. J. E., and safety, e. (2019). Heavy metals accumulation and endocrine disruption in Prochilodus argenteus from a polluted neotropical river. **169**, 539-550.

Planchart, A., Green, A., Hoyo, C., and Mattingly, C. J. J. C. e. h. r. (2018). Heavy metal exposure and metabolic syndrome: evidence from human and model system studies. **5**, 110-124.

Rajeshkumar, S., Liu, Y., Ma, J., Duan, H. Y., Li, X. J. F., and immunology, s. (2017). Effects of exposure to multiple heavy metals on biochemical and histopathological alterations in common carp, Cyprinus carpio L. **70**, 461-472.

Sabullah, M., Ahmad, S., Shukor, M., Gansau, A., Syed, M., Sulaiman, M., and Shamaan, N. J. I. F. R. J. (2015). Heavy metal biomarker: Fish behavior, cellular alteration, enzymatic reaction and proteomics approaches.

Samson, J. C., and Shenker, J. J. A. T. (2000). The teratogenic effects of methylmercury on early development of the zebrafish, Danio rerio. **48**, 343-354.

Sassi, A., Annabi, A., Kessabi, K., Kerkeni, A., Saïd, K., Messaoudi, I. J. F. p., and biochemistry (2010). Influence of high temperature on cadmium-induced skeletal deformities in juvenile mosquitofish (Gambusia affinis). **36**, 403-409.

Sauliutė, G., Svecevičius, G. J. Z., and Ecology (2015). Heavy metal interactions during accumulation via direct route in fish: a review. **25**, 77-86.

Scott, G. R., and Sloman, K. A. J. A. t. (2004). The effects of environmental pollutants on complex fish behaviour: integrating behavioural and physiological indicators of toxicity. **68**, 369-392.

Sfakianakis, D., Renieri, E., Kentouri, M., and Tsatsakis, A. J. E. r. (2015). Effect of heavy metals on fish larvae deformities: a review. **137**, 246-255.

Shah, N., Khisroon, M., and Shah, S. S. A. J. B. T. E. R. (2021). Metals distribution, histopathological alterations, and health risk assessment in different tissues of fish (Ctenopharyngodon idella). **199**, 2730-2752.

Shahjahan, M., Taslima, K., Rahman, M. S., Al-Emran, M., Alam, S. I., and Faggio, C. J. C. (2022). Effects of heavy metals on fish physiology–a review. **300**, 134519.

Sharma, M., Thakur, J., Verma, S. J. I. J. o. F., and Studies, A. (2019). Behavioural responses in effect to chemical stress in fish: A review. **7**, 1-5.

Taslima, K., Al-Emran, M., Rahman, M. S., Hasan, J., Ferdous, Z., Rohani, M. F., and Shahjahan, M. J. T. R. (2022). Impacts of heavy metals on early development, growth and reproduction of fish–A review. **9**, 858-868.

TAŞTAN, Y. J. M. K. Ü. S. Ü. F. D. (2018). Effects of Heavy Metals on Fish. **4**, 36-47.

Vicentini, M., Fernandes, L. d. S. P., Marques, A. E. M. L., Osório, F. H. T., Baika, L. M., Risso, W. E., dos Reis Martinez, C. B., Grassi, M. T., Fávaro, L. F., and Mela, M. J. C. (2022). Effects of cadmium on the female reproductive axis of a Neotropical fish. **286**, 131639.

Vinodhini, R., and Narayanan, M. (2009). Heavy metal induced histopathological alterations in selected organs of the Cyprinus carpio L.(Common Carp).

Wang, R.-F., Zhu, L.-M., Zhang, J., An, X.-P., Yang, Y.-P., Song, M., and Zhang, L. J. C. (2020). Developmental toxicity of copper in marine medaka (Oryzias melastigma) embryos and larvae. **247**, 125923.

Witeska, M., Sarnowski, P., Ługowska, K., Kowal, E. J. F. p., and biochemistry (2014). The effects of cadmium and copper on embryonic and larval development of ide Leuciscus idus L. **40**, 151-163.

YH, E. J. E. J. o. A. B., and Fisheries (2021). Effect of bioaccumulation and biosedimentation of some heavy metals on histological features in the cichlid fish, Tilapia zillii inhabiting Lake Qarun, Egypt. **25**, 695-711.

Zulkipli, S. Z., Liew, H. J., Ando, M., Lim, L. S., Wang, M., Sung, Y. Y., Mok, W. J. J. E. P., and Bioavailability (2021). A review of mercury pathological effects on organs specific of fishes. **33**, 76-87.

Declarations

Data Availability statement

All data generated or analyzed during the study are included in the manuscript.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Funding

Not applicable

Author contribution statement

All authors contributed equally.

Conflict of Interest

Regarding conflicts of interest, the authors state that their research was carried out independently without any affiliations or financial ties that could raise concerns about biases.