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Research Article

Metalliferous accumulation and deposition in Fish within contaminated environments

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Abstract

There is an accumulation of toxic metal ions in an aquatic habitat that modifies the physical and chemical characteristics of water, posing a threat to aquatic organisms. The fish's body absorbs heavy metals through the gills, dorsal surface, and gastrointestinal system when they eat foodstuff that has high levels of these metals. Zinc, Lead, Mercury, Copper, Arsenic, Nickel, chromium and cadmium are the primary heavy metal contaminants responsible for inducing toxicity in fish. Oxidative stress, or oxidative damage, is the primary chemical process responsible for metal poisoning. Stress undermines a low immune system, leading to harm to organs and tissues, developmental irregularities, and reduced reproductive capacity. Due to the copious availability of vitamins, proteins, and fatty acids such as omega-3 found in fish, individuals are inclined to consume seafood as their primary nutritional source. Consequently, the aggregation of toxic metallic elements in fish tissues has a direct impact on people, causing detrimental effects that accelerate the onset of various diseases. To effectively enforce aquatic conservation regulations and protect human lives, it is imperative to investigate the origins of toxic metals and their detrimental effects on the health of fish.

Keywords: Fish, copper, heavy metals, diet, rivers, Gomati, toxic metals

Introduction

The existence of elevated concentrations of toxic metals in water bodies presents a substantial peril to the organisms residing in these habitats, specifically fish (Elumalai *et al.* 2023). Heavy metals are inherent in the surroundings, but their overuse in various industries for varied reasons has greatly disrupted the ecological system (Sharma *et al.* 2023). This disruption is caused by the excessive release of these elements into the soil and water bodies. Typically, human activities, such as growing crops, erosion from farms, and the release of industrial and residential trash, are (Kakade *et al.* 2023) recognized as the primary contributors to heavy metals in water systems (Saidon *et al.* 2024a). Upon entering aquatic systems, heavy metals undergo dissolution in water and readily accumulate among various components of aquatic species, such as fish. Consequently, these fish, which are tainted, act as a means of heavy metal exposure for consumers. (Chatha *et al.* 2023; Ozuni *et al.* 2010a). The buildup of heavy metals in fish through the process of bioaccumulation leads to various difficulties in terms of fish health and their physiological roles (Ozuni *et al.* 2010a). The degree of metal poisoning (cancer-causing, mutagenic, and teratogenic) varies greatly depending on the type of fish, the metal concentration, and the exposure period (Zhang *et al.* 2024) Water-dwelling species, such as fish, can get polluted with heavy metals that originate from both the water and sediments of aquatic environments (Nyarko *et al.* 2023).

Environmental contamination by metallic substances has a detrimental effect on the neurological system of fish, leading to a disruption in their ability to interact with their surroundings (Javanshir Khoei, 2023) The unregulated utilization and buildup of these metals have emerged as a significant health problem, as the majority of them cannot decompose into harmless forms. Consequently, they have detrimental impacts on human health and aquatic creatures (Ozuni *et al.* 2010b).

The existence of elevated concentrations of toxic metals in the natural world has a detrimental impact on fish's development and functions related to reproduction. This is evident through a decrease in their gonad somatic index (GSI), fertilization, fecundity, and rate of hatching (Green &Planchart, 2018). In addition, the presence of heavy metals hinders the proper development and advancement of embryos of fish as well as larvae. While certain metals are necessary for the functioning of living beings (Shahjahan *et al.* 2022a), the majority of them pose significant risks, even in minuscule quantities. In addition, certain metals like cadmium (Cd), arsenic (As), copper (Cu), chromium (Cr), lead (Pb), mercury (Hg), zinc (Zn), nickel (Ni), selenium (Se), and others, are not only extremely poisonous but also cause cancer and genetic mutations (Taslima *et al.* 2022). While various physic-chemical procedures can be used to eliminate harmful heavy metals, many of these strategies prove to be inefficient when the levels of metals are below 100 mg/L (Paschoalini & Bazzoli, 2021a). Due to the solubility of numerous heavy metals in water and their ability to dissolve in polluted water, separating them using physical methods is extremely challenging (Djedjibegovic *et al.* 2020). Bioremediation, which is a biological approach, can be a favorable alternative to restore the natural state of the environment affected by heavy metal pollution (Shahjahan *et al.* 2022b). Bioremediation is widely recognized as an ecologically sound and sustainable method for mitigating various forms of water pollution, hence enhancing the efficiency of aquaculture systems (Garai *et al.* 2021a).

In general, bioremediation is highly efficient at decreasing the toxicity of contaminants by transforming them into less hazardous forms using either microorganisms (Paschoalini & Bazzoli, 2021b) or their enzymes, hence reducing contamination (Garai *et al.* 2021b). This approach is regarded as an environmentally beneficial and economically efficient technique for rejuvenating the polluted ecosystem (Moiseenko & Gashkina, 2020). Microorganisms possessing catabolic capabilities or their byproducts, such as enzymes and physiological surfactants, offer a novel approach to enhance the effectiveness of remediation (Saidon *et al.* 2024b).

Microorganisms can produce metals, which is commonly employed as an environmentally friendly method for mitigating metal-related pollution (Saidon *et al.* 2024c). The utilization of various microbes for the production of nanomaterials has been extensively utilized for wastewater treatment on a global scale (Rajak *et al.* 2024). The microorganism-synthesized nanoparticles can efficiently eliminate and reuse heavy metals from aquatic systems that are contaminated with heavy metals while maintaining their stability (Mehnaz *et al.* 2023a).

Multiple studies have documented that genetically modified microbes can effectively boost their ability to adsorb substances and be successfully utilized in the process of remediation (Mehnaz *et al.* 2023b). The ability of microorganisms to remediate can be improved by implementing various modifications, such as the addition of biochar, biosurfactants, compost, and inorganic fertilizers. In addition, various contemporary methods in microbe-assisted biological technologies, such as rhizoremediation, organisms with genetic modification (Saidon *et al.* 2024a), and nanotechnological assistance in microbial bioremediation, have been extensively utilized for the removal of various toxic heavy metals from the environment. There is currently a lack of complete information regarding the remediation of toxic heavy metals in fish, despite the detrimental effects caused by the buildup of these metals. Hence, this review provides a concise overview of the most up-to-date knowledge on the accumulation of heavy metals in fish and the advancements made in bioremediation methods.(Mehnaz *et al.* 2023b)

Deposition of Metals in Various Fish tissue

Bioaccumulation evaluation is a crucial indicator for monitoring the biogeochemical cycle of pollutants in the aquatic ecosystem. The harmful consequences and oxidation of heavy metals differ depending on their distinct forms and types of metal. Chromium (Cr) is often found in six different oxidation states (+1 to +6), with hexavalent Cr being particularly harmful to fish. Figure 1 demonstrates that fish in aquatic systems contaminated with heavy metals pose a significant danger, as they store these metals in several vital tissues such as the gills, the kidneys, and the liver. Fish need additional energy to adapt to this stressful state, which they obtain from stored resources such as protein, lipids, and carbs. Certain metals (such as Arsenic, Cadmium, Chromium, Copper, Iron, Mercury, Nickel, Lead, and Zinc) possess redox potential and have the ability to generate reactive oxygen species (ROS). These ROS are crucial for maintaining specific physiological processes in fish. Reactive oxygen species (ROS) serve as markers of oxidative stress, which impairs cellular function by breaking down proteins, lipids, and DNA. Heavy metals accumulate in various aquatic creatures in the food chain and pose significant health risks to humans when consuming polluted seafood. (Garai *et al.* 2021b).

The buildup of heavy metals in various fish organs is detailed in Table 1, while the diverse harmful impacts of heavy metals on fish are illustrated in Table 2.

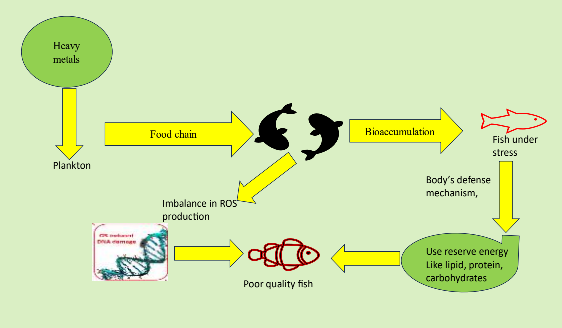

Figure 1. Routes of heavy metal buildup in fish include the presence of reactive oxygen species (ROS)

Table 1. Deposition of toxic metals in various fish tissues

Doses	**Species**	**Exposure Time (Days)**	**Bioaccumulation Rate in Organs**	**References**
		Arsenic		
806.5 µg/g	*Oreochromis niloticus*	20	3.74 ± 3.38 µg/g in Muscle, 10.04 ± 2.99 µg/g in liver, 4.94 ± 4.62 µg/g in gills	(Garai *et al.* 2021a)

1500 µg/g	*Siganusfuscescens*	42	79.0–95.2% in muscle, 63.3–91.3% in liver	(Ozuni *et al.* 2010b)
Cadmium				
1.0 mg/L	*Oreochromis niloticus*	30	2.02–2.50 µg/g in muscle, 114.5–274.9 µg/g in liver, 22.34–32.26 µg/g in gills.	(Zhang *et al.* 2024)
5.03 mg/L	*Oreochromis niloticus*	30	0.08–1.41 µg/g in muscle, 0.41–138.12 µg/g in liver, 0.28 µg/g in gills	(Chatha *et al.* 2023)
5 mg/L	*Cyprinus carpio*	32	4.31–5.32 µg/g in the kidney, 4.82–5.64 µg/g in the liver, 6.23–6.94 µg/g in gills	(Sharma *et al.* 2023)
1.0 mg/L	*Oreochromis niloticus*	30	2.50 µg/g in muscle, 274.9 µg/g in liver, 32.26 µg/g in gills.	(Elumalai *et al.* 2023)
1500 mg/kg	*Oncorhynchus mykiss*	30	1.03–1.82 µg/g in Carcass, 1.20–6.47 µg/g in liver, 0.54–1.77 µg/g in gills.	(Saidon *et al.* 2024a)
Chromium				
3.41 mg/L	*Cyprinus carpio*	4	0.60–0.60 µg/g in bones, 0.30–0.35 µg/g in skin, 0.40–0.45 µg/g in muscle.	(Mehnaz *et al.* 2023b)
4.00 mg/L	*Cyprinus carpio*	1	3.21 µg/g in the skin, 3.9 µg/g in the intestine, 5.43 µg/g in the gills.	(Saidon *et al.* 2024d)
6.00 mg/L	*Cyprinus carpio*	2	3.03 µg/g in the skin, 3.63 µg/g in the intestine, and 4.69 µg/g in the gills.	(Ferdous *et al.* 2024)
Copper				
5.0 mg/L	*Oreochromis sp.*	ND	1.4–4.0 mg/kg in muscle 19.4–136 mg/kg in liver, 6.3–38.4 mg/kg in gills.	(Hamada *et al.* 2024)
0.1 mg/L	*Sparus aurata*	11	0.85–1.49 µg/g in muscle, 3.24–7.02 µg/g in liver.	(Hamada *et al.* 2024)

Table 2. Fish toxicity caused by heavy metals

Species	Toxicity	**References**
Arsenic		
Tilapia mossambica	The hemato-biochemical analysis revealed a large increase in the levels of white blood cells, MCHC, and MCH while the levels of Hb, red blood cells, and PCV showed a substantial decrease.	(Bemani&Okati, 2024)
Clarias batrachus	Hematological: There was a considerable decrease in serum protein level.	(Sevak & Pushkar, 2024)

Danio rerio	Reproduction: The quantity of the eggs, and hatching rate experienced a substantial decrease.	(Misra *et al.* 2024)
Clarias batrachus	Kidney: Contains vacuoles and melanomacrophages.	(Misra *et al.* 2024)
Oreochromis mossambicus	Liver: Presence of infiltrated macrophages as the reduction in size and congestion of hepatic cells, enlargement, and formation of vacuoles	(Sevak & Pushkar, 2024)
Cadmium		
Channa striata	The hemato-biochemical analysis revealed a rise in HDL, TP, as well as ALT levels, but the Glu level fell.	(Panigrahi *et al.* 2024)
Clarias gariepinus	The hemato-biochemical analysis revealed an increase in AST, ALT, Glu, as well as MCH levels, while CK and MCV levels were found to be lowered.	(Panigrahi *et al.* 2024)
Pelteobagrusfulvidraco	Markedly reduced weight gain as well as particular growth rate	(Bautista *et al.* 2024)
Chromium		
Anabas testudineus	The renal tissues exhibited the presence of kidney edema, interstitial hemorrhage, and deteriorated renal tubules.	(Kafouris *et al.* 2024)
Pangasianodonhypophthalmus	Erythrocyte abnormalities: Various aberrations detected in blood cells The levels of red blood cells (RBC), hemoglobin (Hb), and packed cell volume (PCV) showed a considerable drop in the field of hematology.	(Kafouris *et al.* 2024)
Oreochromis niloticus	There was a decrease in both weight gain as well a particular growth rate.	(Kafouris *et al.* 2024)
Oryziasmelastigma	The liver exhibits the presence of vacuoles pyknotic cells, and aberrant nuclei in its hepatic cells.	(Bautista *et al.* 2024)
Copper		

Leuciscus idus	Malformation of the yolk sac decreased lower-extremity length and the perimeter, and curved vertebrae.	(Yasmeen & Rafique, 2024)
Oryziasmelastigma	Malformed skeletal features, abnormalities in the circulatory system, reduced pigmentation of the embryos	(Chatha *et al.* 2024)
Poecilia reticulata	Reproduction: Substandard reproductive outcomes, prolonged birthing duration, elevated larval mortality	(Chatha *et al.* 2024)

Different heavy metals' harmful effects and bioaccumulation

Chromium

Both seawater and the Earth's crust contain minute quantities of chromium. This element is not present solely as a metal, but can be found in the environment in three different oxidation states: divalent (Cr^{2+}), trivalent (Cr^{3+}), and hexavalent (Cr^{6+}). The most stable variants among these are Cr^{3+} and Cr^{6+}. The Cr^{3+} oxidation state poses less risk due to its limited membrane permeability, non-corrosive properties, and reduced potential for bioaccumulation in the food chain. Cr^{6+} poses a greater risk because of its robust ability to cause oxidation and its tendency to infiltrate cell membranes. (Prabakaran *et al.* 2024)

Anthropogenic sources such as leather tanneries, metal manufacturing, petroleum refining, textile production, alloy preparation, and wood preservation contribute to the presence of chromium toxicity in aquatic ecosystems. The toxicity of chromium to aquatic creatures is affected by several biotic factors such as age, developmental stage, and species type, as well as abiotic variables including pH, temperature, and alkalinity of the water. The fish that were initially exposed to chromium exhibited a variety of behavioral abnormalities, such as irregular swimming patterns, excessive mucus production, alterations in body pigmentation, decreased hunger, and other symptoms(Chatha *et al.* 2024). *Cyprinus carpio* exhibited cytotoxicity, decreased lymphocyte activation in response to mitogens, and modified phagocyte activity following prolonged exposure to chromium at concentrations ranging from 2 to 200 mol/L. The presence of chromium in *Tilapia sparrmanii* resulted in the observation of internal hemorrhaging, as evidenced by a decreased blood coagulation time and an elevated pH level. Chromium accumulation in the tissues of the Indian big carp leads to a reduction in protein and fat content in the muscle, liver, and gill. Before chromium therapy, *Colisa fasciatus*, a freshwater teleost, exhibited depleted levels of liver glycogen. Exposure to Cr^{6+} at pH levels of 7.8 and 6.5 caused respiratory and osmoregulatory failure in rainbow trout, *Salmo gairdneri*. Chronic chromium exposure had several detrimental consequences on Chinook salmon, such as DNA damage, microscopic lesions, physiological anomalies, and reduced growth and survival rates. The hatching of rainbow trout *Salmo gairdneri* embryos and the growth of the fish were impacted by the presence of chromium at a concentration of 2 mg/L. The chromium concentration in fish tissues differs, as seen in Table 1. The gills, liver, and kidney contain the highest levels of chromium, whereas the lowest levels are present in muscle tissue. (Chatha *et al.* 2024).

Cadmium (Cd)

Cadmium is a trace element found in the earth's crust at concentrations ranging from 0.1 to 0.5 parts per million. It is commonly present in zinc, copper, and lead ores. The mean content in ocean water varies between 5-110 mg/L, but surface and groundwater generally exhibit amounts below 1 ug/L. Naturally occurring cadmium does not exist in elemental form. Instead, cadmium chloride, cadmium oxide, cadmium sulfide, cadmium carbonate, cadmium nitrate, and cadmium cyanide are frequently seen. Cadmium enters marine environments through several natural and anthropogenic sources (Bautista *et al.* 2024). Cadmium is extracted from the earth's crust and mantle through volcanic eruptions and the process of rock weathering. Researchers have identified several anthropogenic sources of pollution, which include the combustion of fossil fuels, the use of fertilizers, the disposal of agricultural waste, and the industrial utilization of plastic stabilizers, pigments, batteries, and electroporation. Cadmium, a non-essential metal, poses a significant threat to fish due to its high level of toxicity. The study by researchers demonstrated that it enhances the generation of reactive oxygen species (ROS) while inhibiting the electron transport chain in mitochondria. *Cyprinus carpio* had DNA damage as a result of little cadmium exposure (Bautista *et al.* 2024). Cadmium ions (Cd^{+2}) were discovered to limit the movement of calcium across the epithelial cells in the gills of rainbow trout. Exposure to cadmium chloride for a relatively short period caused fish to generate cells with abnormal nuclei in their blood, gills, and liver. Fish that were subjected to cadmium had a distinct hematological reaction. The kidney tissue of tilapia exhibited histological alterations including hepatic fatty vacuolation, hepatocyte necrosis, submucosal blood vessel congestion in the gut, and glomerular shrinkage and necrosis. Exposure of American eel fish *(Anguilla rostrata*) to a concentration of 150 g/L of cadmium for 8 weeks leads to the development of anemia, characterized by a drop in both hemoglobin and erythrocyte counts. Following exposure to cadmium, there was a notable increase in the number of leukocytes and large lymphocytes. Exposure of *Cyprinus carpio* to sublethal concentrations of cadmium resulted in a significant decrease in glycogen reserves in both the muscle and liver, accompanied by an increase in blood glucose levels. Cadmium, a known endocrine disruptor, has been discovered in rainbow trout, Oncorhynchus mykiss, where it inhibits vitellogenesis (Panigrahi *et al.* 2024) Exposure to cadmium chloride had an impact on both the gonad function and sexual maturity of the common carp *Cyprinus carpio*. The larvae of *Leuciscus idus* that were exposed to cadmium had physical deformities and a reduced rate of embryonic survival as a result of mortality in freshly emerged larvae. The slow excretion rate of cadmium leads to significant environmental risks due to its accumulation. The epidermis exhibits the least amount of cadmium bioaccumulation, while the liver, kidney, and gills demonstrate the highest levels. The gill is the organ that efficiently eliminates cadmium toxins. Cadmium poses a significant threat to aquatic organisms due to its high bioaccumulation rate, making it one of the most dangerous heavy metals(Kafouris *et al.* 2024).

Lead (Pb):

Lead, when mixed with components like oxygen and nitrogen, is considered one of the most hazardous heavy metals in existence. Various human activities, such as metal mining, combustion of coal, oil, and gasoline, battery manufacturing, use of lead-arsenate pesticides, lead-based paint, pigments, and food cans, significantly elevate the levels of lead in the environment (in the form of PbS, $PbSO_4$, and $PbCO_3$). The aquatic environment is promptly affected by the release of lead from various industries, agricultural fields, street runoff, lead dust, and municipal wastewater, resulting in toxicity to aquatic organisms. The solubility of lead in water is influenced by several elements such as pH, salinity, hardness, and other variables. Lead quickly dissolves in water that is both soft and acidic. The acceptable range for lead exposure in fish is limited to concentrations ranging from 10 to 100 mg/L (Kafouris *et al.* 2024). Sublethal lead exposure causes fish to have modified behavior, reproductive dysfunction, and stunted growth. Katti observed that prolonged exposure to a small amount of lead nitrate resulted in alterations in the lipid and cholesterol composition of the liver, brain, and gonads of *Clariasbatrachus*(Panigrahi *et al.* 2024). Lead exposure resulted in histological abnormalities in the gill and liver tissue *of Clarias gariepinus*, an African catfish species. Exposure to lead caused histological alterations in the ovarian tissue of freshwater teleosts (*Mastacembeluspancalus*). Lead-exposed fish exhibited symptoms of parenchyma cell necrosis, hepatic cord, and connective tissue fibrosis, reduced growth and body weight, and blood vessel collapse. *Nile tilapia* exposed to lead exhibited decreased levels of hemoglobin, red blood cell count, and hematocrit values. Lead exposure induces oxidative stress in fish, leading to synaptic damage and neurotransmitter dysfunction. Exposure to lead, both in lethal and non-lethal doses, caused alterations to the immunological parameters of Tench fish (*Tinca tinca*). Researchers have identified the liver, spleen, kidney, and gills as the main locations where lead bioaccumulates in fish. Lead bioaccumulation caused morphological defects in Acipenser sinensis, a Chinese sturgeon species.(Panigrahi *et al.* 2024).

Impact of heavy metals on reproductive hormones

Hormones related to reproduction have a crucial role in the effective breeding of fish. Gonadotropin (GTH) is a crucial hormone in the control of fertility. GTH serves two separate functions in terms of structure and chemistry and exists in two distinct forms. GTH-I is responsible for spermatogenesis, which is the early stage of gametogenesis. On the other hand, GTH-II participates in sperm formation and spermiation. The hypothalamus secretes GnRH, a hormone that stimulates the pituitary gland to produce and synthesize GTH, specifically FSH and LH. FSH and LH control the yearly reproductive cycle, including the generation of sex hormones in both males and females, fertilization in females, and the release of sperm in males. FSH and LH can stimulate the production of steroids and the development of gametes in the gonads.(*Gautam et al.* 2024)

Gonadotropic hormones are transported to the gonads, where they stimulate steroidogenesis, leading to the synthesis of sex steroid hormones that control the reproductive process. These hormones also interfere with the regulatory functions of the pituitary gland and hypothalamus through mechanisms of feedback. Gonadotropin release interruption can profoundly affect fertility. The synthesis of fish hormones for reproduction is disrupted when there is a compromise in the hypothalamic-pituitary system. Testosterone, a sexual hormone, plays a role in the growth of gonads at the end of the period of menstruation and serves as a precursor for the generation of estradiol.(Echevarría *et al.* 2024)

Women are the primary synthesizers of estradiol (E2). Additionally, it plays a vital function in men by controlling the growth of spermatogonia and the functioning of Sertoli cells, both of these are controlled by nuclear estrogen receptors (ERs). Estrogen receptors (ERs) play a crucial role in the differentiation of sexuality and maturation processes, including the development of testes, oogenesis, as well as vitellogenesis. The reference is from a study conducted by Kim *et al.* in 2014. Estradiol is a hormone that is required for the stimulation of calcitonin production, which in turn affects the secretion of vitellogenin and the development of oocytes. Testosterone levels increase as the gonads develop in both male and female fish. The growth of males' testicles is regulated by the hormones testosterone (T) and ketotestosterone (11-KT), with 11-KT being more potent than T(Marinaro *et al.* 2024). 11-KT is believed to play a significant role in male sexual behavior and the release of LH. This mechanism involves an intricate combination of endocrine and neuroendocrine input from many receptors, together with local autocrine as well as paracrine secretory modulation and feedback control. Contaminants that disturb the balance of gonadotropin and sexual hormones can potentially affect the reproductive process of fish.Sex hormonal substances are crucial in the processes of sex differentiation, maturity, and reproduction (Gautam *et al.* 2024; Marinaro *et al.* 2024)

The decline in hormone levels caused by pollution can be used as important indicators and tools to evaluate the impact of stress on fish. Cadmium is a highly dangerous metal for fish, as it disrupts the endocrine system and has various negative effects on reproduction. These effects include changes in additional sexual traits, increased levels of 11-ketotestosterone, a decrease in the gonadosomatic index, reduced sperm motility, and alterations in estrogen levels in Nile Tilapia due to exposure to Cadmium. Garriz et al. (2017) discovered that male *pejerrey* fish who received Cd had elevated levels of testosterone-releasing hormone expression. Cadmium (Cd) may inhibit the correct functioning of enzymes involved in the production of sex hormones in the gonads and the metabolism of steroids in the liver. Exposure to cadmium concentrations of 0.4 ppm or 4 ppm has been shown to result in an elevation of LH levels in the blood plasma of *Carassius gibelio B*, together with a delay in gonad maturity.(Zulfahmi *et al.* 2024).

Out of all heavy metals, only a few number, including cadmium, zinc, copper, lead, and mercury, have been discovered to have detrimental effects. Consequently, the majority of studies have concentrated on investigating the implications of these specific heavy metals. Approximately 33% of the Cadmium present in aquatic habitats is believed to originate from the production and use of phosphate fertilizers. The exposure of fish to Cd can lead to the buildup of the substance, with the specific processes varying according to the trophic level of the species. This particular heavy metal exerts a distinctive influence on sperm cells. The discussion focused on the effects of the substance on the quality of sperm in several species of freshwater fish, such as *D. rerio* , *C. carpio* , and *Gymnotuscarapo* . Treatment with Cadmium (Cd) also led to decreased motility and velocities in the spermatozoa of *Prochilodusmagdalenae*. The study conducted by (Vasconcelos *et al.* 2024) revealed that exposing *Colossomamacropomum* to cadmium concentrations of 0, 0.6, 1.2, and 1.8 ppm resulted in a decrease in the motility rate of spermatozoa. Furthermore, the rates of fertilization and hatching were also shown to be reduced. The exposure of *Prochilodusmagdalenae* to cadmium at concentrations of 2.5 parts per million (ppm) and 25 ppm for 27.3 seconds resulted in a decrease in both sperm motility and velocity, as reported by (Zulfahmi *et al.* 2024). In addition, the study conducted by (Gautam *et al.* 2024) revealed a decrease in the quality of eggs and sperm in Gasterosteus aculeatus when exposed to a level of 1ppb of cadmium for durations of 15, 60, and 120 days. The study conducted by (Bautista *et al.* 2024) discovered that exposure to cadmium at concentrations ranging from 20 to 110 ppm in Rhamda queen resulted in decreased sperm motility. The provided information corresponds to Table 3.

Table 3. Impact of metal poisoning on fish reproductive processes

Heavy metals	Fish name	Effects	References
Cd	*Trematomusbernacchii*	Oocyte deterioration leads to a decrease in fertility.	(Bautista *et al.* 2024)
Cd	*Colossomamacropomum*	The decline in the rate of fertilization and hatching	(Kafouris *et al.* 2024)
Cd	*Oreochromis spp.*	Suppressed reproductive process in females, compromised growth of ovaries, a notable decline	(Kafouris *et al.* 2024)
Pb	*Oreochromis niloticus*	The Nile tilapia larvae exhibit deformities such as lordosis, kyphosis, and bent tails.	(Waichman *et al.* 2024)
Cu	*Trematomusbernacchii*	Oocyte degeneration leads to a decrease in fertility. The motility rate of spermatozoids has decreased, resulting in a fall in both fertilization and hatching rates.	(Waichman *et al.* 2024)
Cu	*Danio rerio*	The reduction of gonad maturation is associated with a decrease in gonadsomatic index (GSI) and steroidogenesis.	(Waichman *et al.* 2024)

Cu	*P. vivipara*	Disruption of spermatic mitochondria and neuroendocrine functioning	(Vasconcelos *et al.* 2024)
Cu	*Gambusia affine*	Premature births	(Vasconcelos *et al.* 2024)
Cu	*Pelteobagrusfulvidraco*	Egg yolk granules, ovarian metamorphosis,Oncorhynchus mykiss Modified mitochondria	(Vasconcelos *et al.* 2024)

Remediation of Heavy Metal Toxicity in Fish via Bioremediation

Bioremediation is a practical and environmentally beneficial approach that can be employed to remediate a polluted environment by extracting harmful metals from it (Rengarajan *et al.* 2024). Bioremediation of toxicants can be achieved through adsorption, physio-biochemical pathways and molecular processes. catalase (CAT), Superoxide dismutase (SOD), reduced glutathione (GSH), and glutathione S transferase (GST), are important in maintaining the balance of reactive oxygen species (ROS) through detoxification (Figure 2). SOD possesses the ability to transform superoxide radicals into hydrogen peroxide radicals, which subsequently transform into harmless oxygen and water radicals through the action of CAT enzymes (Rengarajan *et al.* 2024). Conversely, GST facilitates the detoxification of harmful substances by catalyzing the conversion of electrophiles into GSH. In addition, GSH undergoes nonenzymatic oxidation of electrophilic molecules, such as free radicals and ROS, resulting in the conversion of GSH into glutathione disulfide (Kurella *et al.* 2024a).Microorganisms possess many mechanisms that confer resistance to heavy metals, such as extracellular sequestration, intracellular sequestration, reduction of heavy metal ions within the microbial cell, and the presence of extracellular barriers. Various microorganisms, including bacteria, fungi, and algal species, have been employed to eliminate toxic heavy metals and maintain environmental cleanliness (Ozturk *et al.* 2024). These microorganisms are included in Table 3. Furthermore, alongside natural microbes, several genetically enhanced artificial microorganisms, particularly those that have been modified on their surface, have been created to utilize in the process of remediating specific heavy metals. Multiple studies have documented that genetically modified microorganisms possess superior skills compared to normal bacteria in eliminating organic substances, such as heavy metals, within natural environmental systems (Khan, 2024)

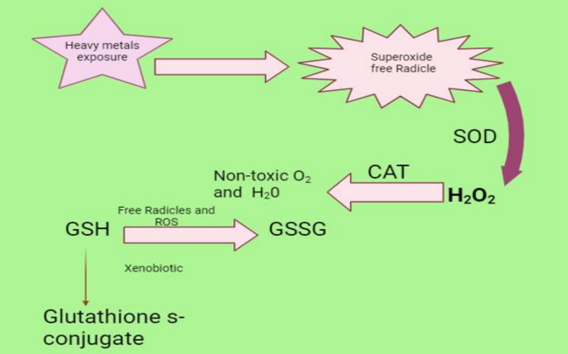

Figure 2. The mechanism of detoxification of heavy metals involves the enzymes SOD, CAT, and GST, as well as the molecules GSH, GSSG, and ROS.

Bio precipitation

The bioavailability and toxicity of hazardous metals can be decreased when they precipitate into insoluble complexes. Many microorganisms are reported to facilitate the bio-precipitation of heavy metals. For instance, *Providentiaalcalifaciens* 2EA, a lead-resistant strain bio precipitates Pb as lead phosphate i.e. $Pb_9(PO_4)_6$. Lead has also been found to precipitate as PbSby *Klebsiella sp.* grown on phosphate-limited media.Both lead-sensitive and lead-resistant strains of *S. aureus* were found capable of precipitating lead, but the resistant variants were more successful. (Ren *et al.* 2024). *Pseudomonas sp.* was observed to produce an insoluble compound that contained both lead and phosphorus, indicating that the substance was lead phosphate. Lead is also precipitated by lead-resistant strain *Bacillus iodinium GP13 and Bacillus pumilus S3* as lead sulphide (PbS) (Khan, 2024). *E. cloacae,* which is phosphate solubilizing bacteria, resists lead by immobilizing it as the insoluble lead phosphate mineral pyromorphite. The microbial precipitation approach has proven to be an efficient, reasonably economical, and environmentally acceptable technical alternative for the reclamation of lead-polluted surroundings (Ren *et al.* 2024)

According to one study by (Agarwal *et al.* 2024). *W6* bacteria adsorbed 66% Pb from synthetic groundwater in Bangladesh at the ideal pH and temperature, compared to *P. Aeruginosa MTCC 2474* bacteria (19.9%), *P. alcaligenes MJ7* bacteria (45.3%), and *P. ficuserectae PKRS 11* bacteria (29.8%). *Pseudomonas sp. W6's* ability to remove lead from synthetic water demonstrated that it can also promote Pb remediation in natural water.

(Mangueina *et al.* 2024; Ren *et al.* 2024) most recent study found that the microorganisms *Spirogyra spp.* and *Cladophora spp.*could effectively sequester lead with oxidation state II, or Pb (II) as well as Cu (II). Similarly, *Spirogyra* and *Spirulina* species can sequester a variety of heavy metals, including Cr, Cu, Fe, Mn, and Zn. Despite its increased scope, studies, as well as practical applications, are advised since the blending of different tactics could demonstrate the potential for the recovery of contaminated environments. Given below is a depiction of some potential microorganisms that are utilized to sequester certain heavy metals. (Table 4).

Table 4. Sequestration of different heavy metals by microorganisms.

Class of Microorganisms	Heavy Metal Sequestered	References
1. Bacteria		
Bacillus cereus	Cr (VI)	(Ren *et al.* 2024)
Kocuria flava	Cu	(Ren *et al.* 2024)
Sporosarcinaginsengisoli	As (III)	(Ren *et al.* 2024)
Bacillus cereus strain XMCr-6	Cr (VI)	(Khan, 2024)
Pseudomonas veronii	Cd, Zn, Cu	(Ozturk *et al.* 2024)
Enterobacter cloacae B2-DHA	Cr (VI)	(Khan, 2024)
Pseudomonas putida	Cr (VI)	(Kurella *et al.* 2024b)
Bacillus subtilis	Cr (VI)	(Kurella *et al.* 2024b)
2. Fungi		
Aspergillus fumigatus	Pb	(Rengarajan *et al.* 2024)
Gloeophyllumsepiarium	Cr (VI)	
Aspergillus versicolor	Ni, Cu	
Rhizopus oryzae (MPRO)	Cr (VI)	
3. Yeast		
Sacharomyces cerevisiae	Pb, Cd	(Rengarajan *et al.* 2024)
4. Algae		
Hydrodictylon, *Oedogonium* and *Rhizoclonium* spp.	As	(Rengarajan *et al.* 2024)
Spirogyra spp. and *Spirullina* spp.	Cr Cu, Fe, Mn, Zn	
Spirogyra spp. and *Cladophora* spp.	Pb (II), Cu (II)	

Conclusion

The uncontrolled release of hazardous heavy metals from many sectors is causing significant degradation of aquatic habitats. Consequently, dangerous heavy metals originating from this polluted environment have built up in several vital organs of fish and disrupted their regular processes. The buildup of these hazardous metals in the bodies of fish has significantly impacted their normal physiological functions, leading to decreased fish growth and reproduction. Bioremediation can effectively address and transform current contaminations in aquatic systems using a sustainable manner. In addition, bioremediation enhances fish well-being by modifying the detrimental impacts of several heavy metals. Not only does it provide benefits for aquatic creatures, but it also enhances the productivity of aquatic ecosystems. Through the effective implementation of this bioremediation process, we may greatly reuse the water, hence minimizing water wastage.

Additionally, the breakdown of organic materials in the water reduces the presence of harmful organisms, thus improving the overall biosecurity of our ecosystems. In addition to present bioremediation approaches, the future implementation of genetically engineered microorganisms (GEM) should be considered to enhance the effectiveness of bioremediation strategies in addressing harmful heavy metal pollution. It is important to evaluate the public acceptance of GEM and the environmental safety in this situation.

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