

IMPACT OF PATHOTOXICITY AND BIOACCUMULATION OF LEAD ON FISH HEALTH AND ECOSYSTEM DYNAMICS

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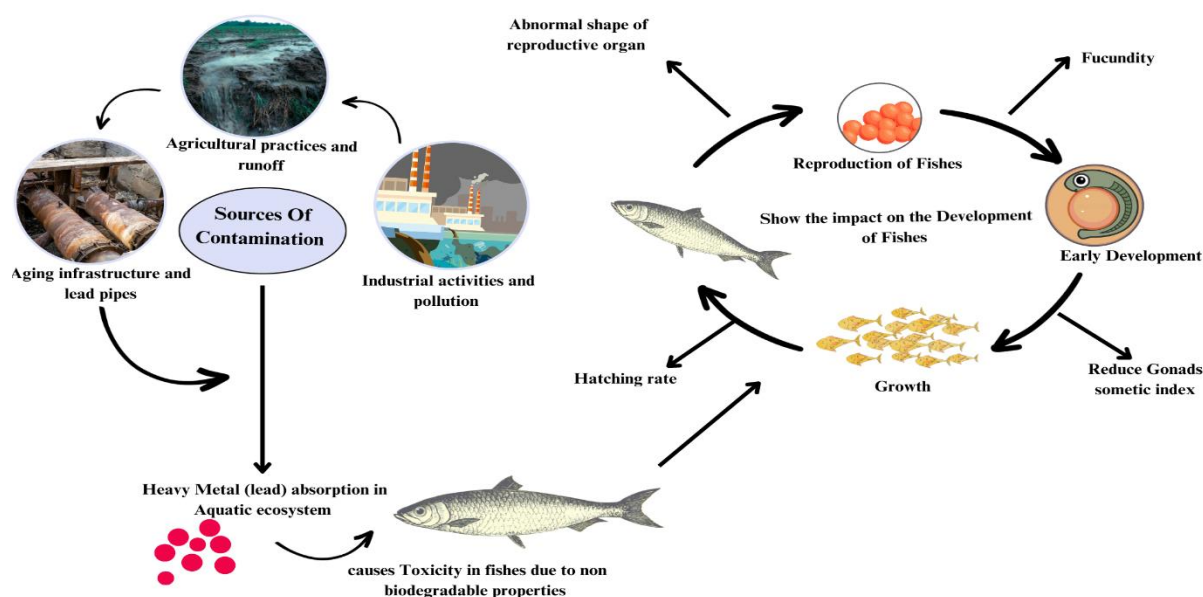
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Abstract

Heavy metal pollution in aquatic systems has become a major problem on a global scale. Many heavy metals are regarded as essential nutrients that aid in fish growth and more effective feed utilization. However, when these metal concentrations rise over the maximum amount that can be tolerated, they disrupt ecological processes and jeopardize human and fish health. Fish are dangerous due to lead contamination in their body. Lead causes toxicity because it is long-lasting and non-biodegradable in the environment. This review looked at the impact of heavy metals on fish early development, growth, and reproduction. Fish embryos and larvae, as well as each developmental stage of the embryo, react to intoxication differently and vary between species. Lead poisoning has been linked to decreased gonad somatic index (GSI), fecundity, hatching rate, fertilization success, aberrant form of reproductive organs, and ultimately loss of reproduction in fish. In summary, this review aims to increase awareness of the prevention and control of aquatic environmental pollution while shedding insight on how heavy metals manipulate fish physiology; the review also gives the valid concerns regarding potential impacts of deteriorating conditions of aquatic environment and their surroundings as well as impacts on fish species and from the food chain it invades ecosystem dynamics.



Graphical Abstract

Metal poisoning is a growing problem as it increases day by day. Given its vast ecology and the variety of impacts that toxic metal poisoning has on water bodies, the aquatic environment is a major area for the observation

of metal toxicity. The creatures that depend on these ecosystems for existence suffer when hazardous metals are present in water bodies. Aquatic life types, such as fish, are especially susceptible to metal poisoning. The ability

of these species to develop, reproduce, and maintain general health may be negatively affected by long-term exposure to high concentrations of hazardous metal such as lead. Additionally, as metals move up in the food chain, they can accumulate in the tissues of aquatic organisms, increasing the risk of poisoning. Major sources of heavy metals released into the environment include household and farm waste, industrial waste, fossil fuel combustion, mining, and wastewater treatment plants (Gheorghe et al., 2017; Garai et al., 2021). Elements with larger atomic weights such as chromium, lead, mercury, cadmium, and arsenic are called heavy metals. Certain metals, even in small doses, can be harmful to living species including plants, animals and humans. With the rapid development of industry in cities, toxic metals such as chromium (Cr), nickel (Ni), copper (Cu), lead (Pb), iron (Fe), and zinc (Zn) have polluted wastewater. Metals that are both biologically necessary and non-essential can be broadly classified (Taslima et al., 2022). Metal like lead has no known specialized biological activity, its toxicity increases with increasing concentration. The majority of metals are necessary for a variety of tasks and activities in small doses, but when their concentration exceeds a certain point they turn toxic and detrimental, necessitating the need for people to become more conscious of them as their effects worsen with time. The presence of lead spreads from one target to another, such as when chemicals are used in industries, those industries produce waste, which is released into the environment (such as aquatic ecosystems), which then affects aquatic life such as fish, which then affects humans, and so on and so forth to the next generation. Lead can cause serious health problems, such as heart, liver and kidney problems, and in the most severe cases, death. Exposure to lead can have significant negative effects on the physiology of many aquatic organisms, especially fish (Islam et al., 2020; Suchana et al., 2021; Sarkar et al., 2022 a; Taslima et al., 2022). Fish at the top of the aquatic

food chain can accumulate lead in soft and hard tissues (Mansour and Sidky, 2002). Fish can absorb lead pollutants through their skin, gills, food particles and oral drinking water. Lead contaminants are transported via the bloodstream to the liver for processing or, after absorption, to a different storage location of the body (Obasohan, 2008; Muneer et al., 2022). This clarifies the problems and impacts that lead has on fish health. As we previously said, the environment contains a number of hazardous heavy metals. However, lead toxicity is currently of greatest concern since it is rising steadily to a high peak.

The effects, causes, investigation of lead in aquatic ecosystems, and some significant remediation approaches will all be covered in this review article with an emphasis on the most economically important aquaculture species. The current study aims to gather the most recent information regarding the impact of lead on the growth, reproduction, immunity, and developmental processes of embryos and larvae of fish. Along with dealing with the ecological consequences of lead pollution in other ecosystems, it also contains information concerning the sources of contamination in order to assist in the problem-solving of lead contamination and to safeguard aquatic life and the life forms that depend on it.

Review methodology

Literature review

A comprehensive and all-encompassing search of scholarly databases is the approach used in this review paper. This method involved a broad variety of pertinent concepts being searched, including “toxicity”, “accumulation”, “fish health”, and “ecological impacts of lead”. In order to find and get pertinent papers and research on the subject of lead contamination’s effect on fish health and ecosystem dynamics, a literature search was done (Figure 1).

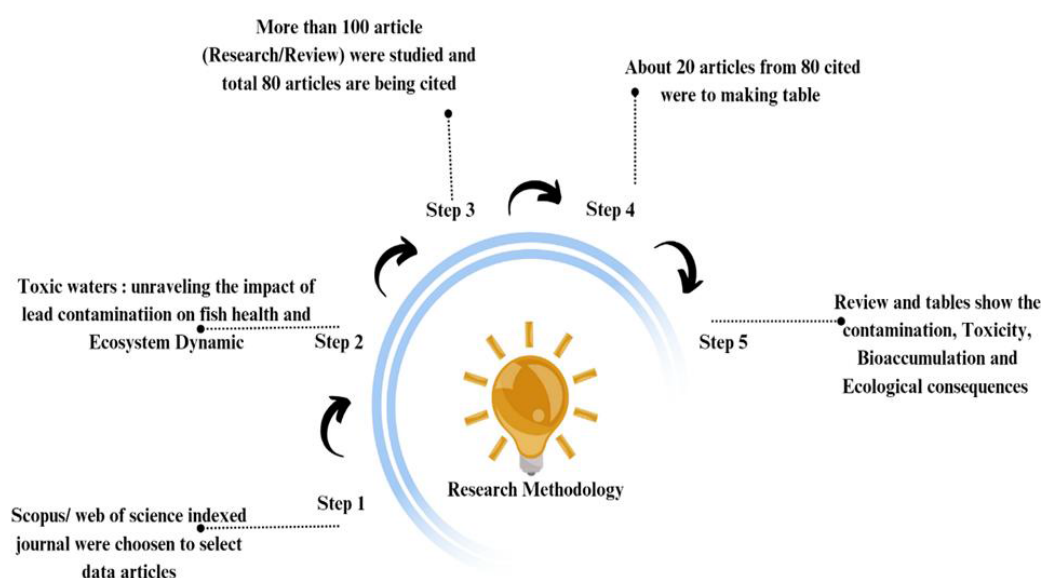


Figure 1. Graphical representation of review methodology

Article screening and inclusion criteria

“Toxic waters: unravelling the impact of lead contamination on fish health and ecosystem dynamics” is the title of the data article that was picked for the data screening and search using the Scopus/Web of Science Index journals. Twenty of these publications are utilised to create the table “Concentration and accumulation profile in different organs of different fish species” out of the total number of papers, of which 80 are cited. The identified academic articles underwent a thorough screening procedure to determine their relevance to the topic; only those that met the specified inclusion requirements were considered deserving of additional examination. The selected publications were carefully assessed in terms of their final conclusions, methodological framework, empirical data, and experimental design.

Data synthesis and presentation

The review article at hand employs a systematic and well-structured approach, encompassing multiple sections that elucidate the historical context of how lead contamination affects both fish health and the dynamics of ecosystem.

Sources and pathway of lead contamination

Lead in surface water can be found in a variety of natural or man-made sources, including industrial effluents, agricultural wastes, mining impacts, deteriorating infrastructure, sea salt sprays, forest fires, and other events that can release lead into various environmental areas from their endemic skies as shown in Figure 2. Lead may find its way into the environment either in its natural condition or in combination with a variety of inorganic and organic chemicals.

Industrial activities and pollution

The main sources of pollution include domestic sewage, industrial waste and municipal garbage, which are

discharged directly into natural water systems, causing water pollution due to discharge of untreated waste (Afzal et al., 2018). Wastewater entering surface water resources will reduce the aesthetic value of water and cause irreversible harm to aquatic ecology and humans. Wastewater is a complex mixture of microorganisms, heavy metals, nutrients, radionuclides, and pharmaceuticals and personal care products (Sonone et al., 2020). These pollutants can damage water resources, reduce available water, increase cleanup costs, and impact food supplies (Hussain et al., 2023). Lead compounds, including lead salts, oxides, and sulphides, as well as dissolved lead may be found in industrial effluents. Lead may enter aquatic and terrestrial environments through the inappropriate discharge of polluted wastewater to streams or wastewater treatment plants.

Aging infrastructure and lead pipes

Engineers define ageing infrastructure as any federal agency project that is more than 75 years old and involves the production, storage, irrigation, or use of water resources. Globally, utilities including electricity, water, and transportation are vulnerable to outages and noncompliance with environmental regulations. The danger of infrastructure ageing can be increased by a variety of physical and chemical environmental conditions, as well as by human interaction. Changes in subterranean pressure and construction over time may be included in the soil movement (Cooper et al., 2019). Lead and other heavy metals may pollute these old, abandoned construction materials. Lead can enter drinking water through chemical processes involving lead-containing plumbing parts. Corrosion refers to the dissolution or removal of metal from pipes and fittings (Ali et al., 2019). This reaction is stronger in water with low mineral content or high acidity. If lead tanks or pipes are present, the water supply may be contaminated.

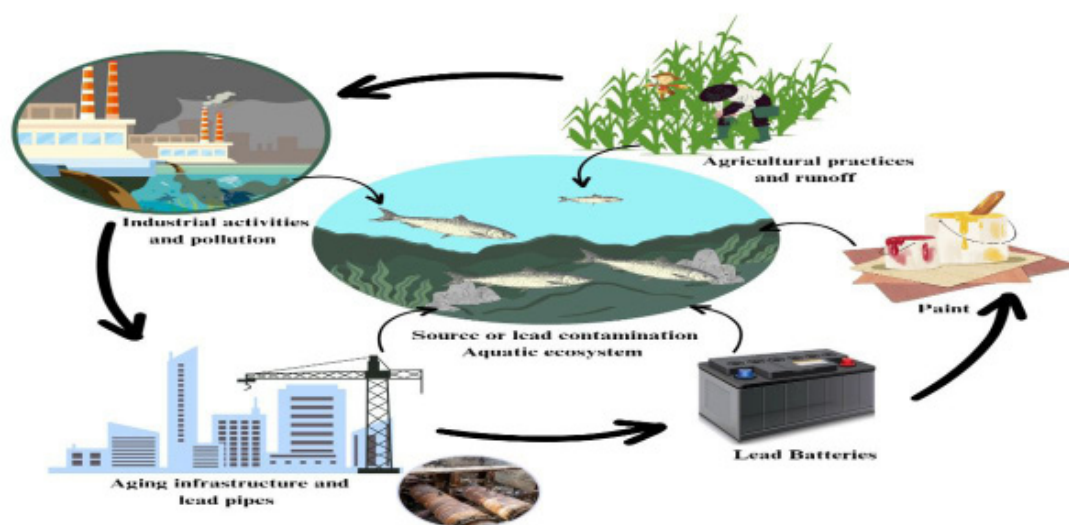


Figure 2. Different pathways of lead contamination in aquatic ecosystem

Agriculture practice and runoff

The ever-growing need for food has led to the expansion and intensification of agricultural systems. Rivers, lakes, aquifers, and coastal waterways are among the environments with greater pollution burdens due to the abuse and misuse of agrochemicals, water, animal feed, and productivity-boosting medications. Agricultural pollution also affects aquatic ecosystems. For example, eutrophication caused by bioaccumulation in lakes and coastal waters affects fisheries and biodiversity. The growing demand for food has led to the development and intensification of agricultural systems (Sonone et al., 2020). Agricultural operations discharge many agricultural chemicals, organic wastes, pharmaceutical residues, sediments and saline wastewater into water bodies. The resulting water pollution has been found to pose a threat to human health, aquatic ecosystems, and production activities (Manzoor and Sharma, 2019). When agricultural waste is deposited in aquatic ecosystems, many aquatic animals, including fish, are harmed as they accumulate toxins directly from the contaminated water and enter the food chain. Fungicides, herbicides and insecticides are widely used in agriculture in many countries. They may contaminate water sources with carcinogens and other harmful substances that may harm humans if not carefully selected and maintained (Bouida et al., 2022).

Lead contaminated paint

Lead was once used in paint because white lead gave exterior and interior paints a uniform base colour and improved the paint's durability and washability. In the US, lead was widely used in paint manufacture starting in 1884 and reached its peak in the 1920s (Gooch, 2005). Large amounts of lead are associated with old buildings and architectural debris because lead-based paint is persistent and tends to cover previous layers of paint rather than remove them. Paint peeling, physical wear, and degradation caused by atmospheric chemicals such as ozone and nitrogen dioxide (National Academies of Sciences, Engineering, and Medicine, 2017) can lead to the emission of particulate matter, aerosols, and gaseous lead from interior and exterior surfaces of residential, commercial, and industrial buildings. This was the main cause of lead contamination in the soil and water bodies nearby. Lead has also historically been included in paints used for road markings. High lead concentration road dust is produced as automobiles erode certain paints, and most of it ends up on the sides of the road (Murakami et al., 2007). Lead-based paints have the potential to cause significant harm to the human body, including central nervous system disruption, breathing and respiratory issues, and more such as harm both children's and adults' kidneys and neurological systems. Seizures, unconsciousness, and even death can result from extremely high lead levels (Ramírez Ortega et al., 2021).

Lead batteries

Lead is used extensively in the worldwide industrial

sector, primarily in the production of batteries. In the majority of cars, lead-acid (Pb-PbO_2) batteries are still the most common way to provide energy. Elevated amounts of environmental lead pollution can result from the unregulated and informal recycling of lead-acid batteries, which is frequently done in backyards or residences. These procedures often entail using an axe or hand tools to break apart spent lead acid batteries, which increases the risk of battery acid leakage into the surrounding area. After the batteries are opened, the lead is taken out and frequently melted in crude stoves that let lead dust fly and pollute the nearby land, water, and air. Additionally harmful impacts of this lead are shown in the health of humans and other environmental creatures. Lead gets discharged into the environment from several sources, such as lead bullets used in game bird shooting, obsolete plumbing systems, and acid batteries. Lead pollution is also a result of leaded petrol combustion. Despite being outlawed, several poor nations continue to use tetraethyl lead as an antiknock agent in petrol (Ali et al., 2019).

Uptake and accumulation of lead

Mechanism of lead bioaccumulation in fish

Fish are exposed to a variety of dangerous heavy metals that enter water bodies through natural and anthropogenic processes. Heavy metal pollution has become an increasingly important global issue as it harms fish and exposes fish consumers to health risks (Fatima et al., 2022). Typically, absorption, inhalation, and ingestion are how fish consume lead. The bioaccumulation of heavy metals in freshwater fish is influenced by many variables, including fish characteristics and external influences (concentration of toxicants, and the duration of exposure). Internal environmental parameters include fish age, size (weight and length), dietary habits and body physiology. External environmental factors include metal concentration and bioavailability in water bodies, physical and chemical properties of water, and other climatic conditions. Due to its ability to readily bind oxygen and sulphur atoms in proteins to create a stable complex, lead is one of the most accumulative hazardous metals (Verstraeten et al., 2008) and prior research has shown significant accumulations in a variety of fish tissues exposed to lead. Exposure to dietary lead caused a notable buildup in several organs, including the kidney, liver, spleen, gut, and gills, in young rockfish, *Sebastes schlegelii* (Kim and Kang, 2015). A notable buildup in the gills, liver, kidney, spleen, and intestine of starry flounders, *Platichthys stellatus*, subjected to dietary lead was also documented by (Hwang et al., 2016). The study of exposure routes is crucial to comprehending the mechanisms by which accumulation results from metal exposure; variations in dietary or waterborne metal intake can generate significant variations in accumulation patterns. Because the gill tissues are exposed to metal ions in the water during respiration and osmoregulation, rather large rates of accumulation may be seen in the event of waterborne exposure (Rogers et al., 2003; Alves and Wood, 2006). However,

when food exposure occurs, intestinal tissue exhibits substantial rates of accumulation (Alves and Wood, 2006; Castro-González and Méndez-Armenta, 2008). Its exposure to the aquatic environment negatively impacts reproduction, development, and behaviour in fish (Junejo et al., 2019). Lead toxicity arises from the interaction of lead with proteins. High-affinity metal-binding proteins, such as metallothionein's and Pb-binding proteins can disrupt the lead-enzyme interaction (Junejo et al., 2019). Pb poisoning in fish can cause hyperactivity, erratic swimming, loss of equilibrium, black tail, numbness, and degeneration of the caudal fin in addition to damage to all tissues, the central nervous system, and blood when the concentration of Pb is higher than what is considered safe (Junejo et al., 2019).

Accumulation and biomagnification of lead in aquatic food chains

A significant portion of a human diet includes fish. Fish is favoured in diets because it is higher in protein, has less saturated fat, and has enough omega-3 fatty acids. However, because of the numerous anthropogenic activities covered in the previous sections, the water that fish consumes and uses is contaminated with a lot of pollutants and heavy metals. Lead is a heavy element that accumulates and intensifies in fish, reaching higher trophic levels through the food chain shown in the Figure 3. There are three possible ways for lead to enter the fish body: gills, digestive system and body surface. It is

well known that gills are the first important site for absorbing metals from water (Al-Kshab and Yehya, 2021). Lead exposure and accumulation in bodily organs varies among fish species as shown in Table 1. When metals enter the body through the intestines, they are excreted and detoxified by the liver. The liver is considered an important part of the excretion system of fish exposed to lead because it binds the metal to steroids in the bile. Bile metal complexes (Pb) are then absorbed by the intestinal wall or excreted in the faeces (Lee et al., 2019). Contaminated water entering the body through the gills and liver can be absorbed into the circulatory system (Zhai et al., 2017). Pb is one of the most accumulative hazardous metals owing to its skills to easily bind oxygen and sulphur atoms in proteins to produce a stable complex in the tissues of fish and its excretion rate is low; this approach is known as bioaccumulation. Although biomagnification is a disputed subject in metal ecotoxicology, multiple studies have documented biomagnification of heavy metals in particular food chains. Higher trophic level species in the food chains are more vulnerable to the biomagnification of these metals. Because of biomagnification, creatures at higher trophic levels may have larger quantities of trace metals, which might be harmful to these species' health or the health of humans that consume them (Ali and Khan, 2019). In this case when lead contaminated fish are eaten by higher fishes or directly by humans the concentration of lead increases that high risk.

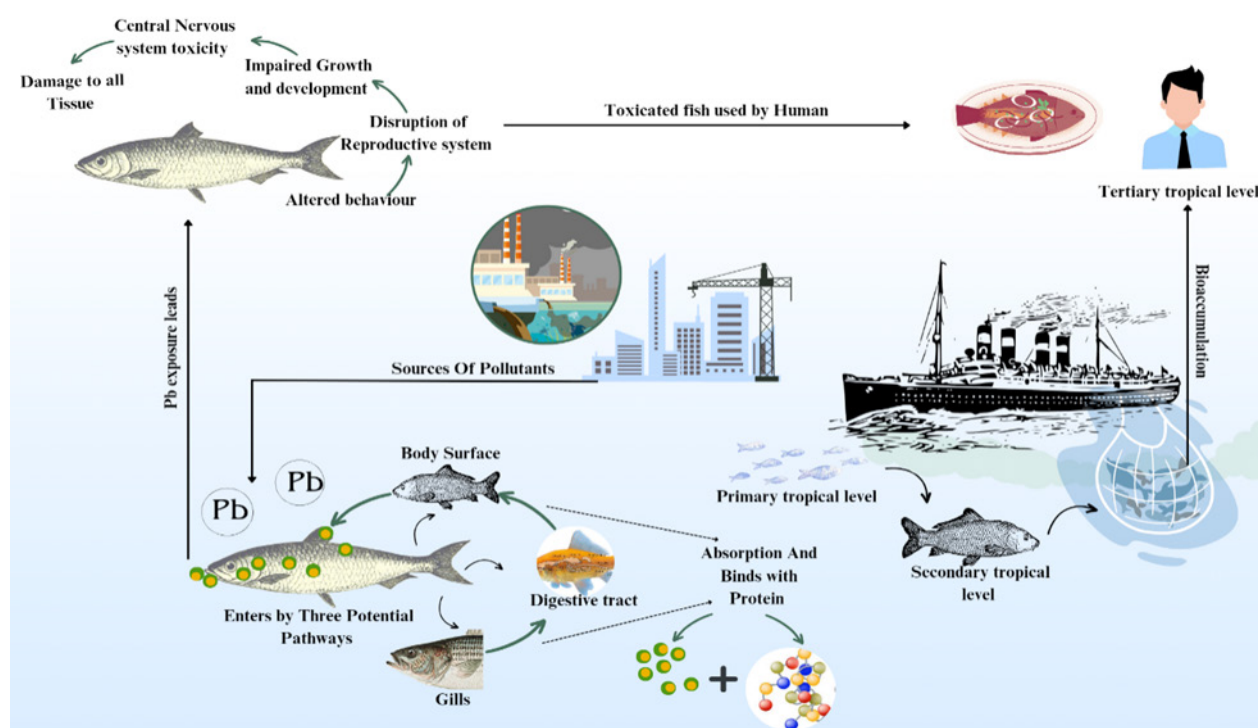


Figure 3. Bioaccumulation and effects of lead in fish through different pathways and their uptake on different trophic levels

Table 1. Concentration and accumulation profile in different organs of different fish species

No.	Fish species	Habitat	Concentration	Accumulation profile	Month of breeding	Reference
1.	<i>Labeo rohita</i>	Freshwater	0.23–1.84 µg/g	Kidney > Liver > Gills > Skin > Muscle > Scales	April – September	(Maurya et al., 2019)
2.	<i>Tenualosa ilisha</i>	Marine	0.562 ml/g	Gills > Muscle > Liver	Complete year except 7–28 October	(Sarker et al., 2021)
3.	<i>Ctenopharyngodon idella</i>	Freshwater	0.237 µg/g	Muscles	October – January	(Chatta et al., 2016)
4.	<i>Mystus tengara</i>	Freshwater	0.24–0.84 ml/g	Liver > Gills > Muscle	May – September	(Tabrez et al., 2021)
5.	<i>Labeo calbasu</i>	Freshwater	0.115 µg/g	Muscle tissue	July – August	(Sahu et al., 2023)
6.	<i>Cirrhina mrigala</i>	Freshwater	2.4 mg/L	Liver > Muscle > Gills	May – September	(Javed, 2012)
7.	<i>Cirrhinus reba</i>	Freshwater	3.4 mg/L	Gill > Muscle > Liver	June – August	(Shivakumar et al., 2014)
8.	<i>Channa marulius</i>	Freshwater	0.02	Mostly in muscles	July – September	(Chatta et al., 2016)
9.	<i>Catlacatla</i>	Freshwater	2.7 mg/L	Liver > Gills > Muscle	June – July	(Sahu et al., 2023)
10.	<i>Crossocheilus latius</i>	Freshwater	1.816 mg/L	Liver > Gills > Muscle	April – July	(Maurya et al., 2019)
11.	<i>Mystus seenghala</i>	Freshwater	0.04	Gills > Liver > Kidney > Muscle	June – September	(Tabrez et al., 2021)
12.	<i>Clupisoma garua</i>	Freshwater	2.72 mg/L	Liver > Gills > Muscle	March – August	(Maurya et al., 2019)
13.	<i>Oreochromis niloticus</i>	Freshwater	12.7	Muscles	August – September	(Tole and Shit-sama, 2003)
14.	<i>Clarias gariepinus</i>	Freshwater	14.9 µg/g	Gill > Liver > Kidney > Muscle	September – March	(Tole and Shit-sama, 2003)
15.	<i>Synodontis schall</i>	Freshwater	1.05 µg/g	Gills > Tissues > Intestine	July – October	(Nnaji et al., 2007)
16.	<i>Cyprinus carpio</i>	Freshwater	250 µg/L	Gill > Intestine > Muscle > Kidney > Liver	January – March July – August	(Tripathi et al., 2003)
17.	<i>Sparus aurata</i>	Marine	0.75 mg/kg	Liver > Gill > Intestine > Dorsal muscle	October – December	(Bat et al., 2022)
18.	<i>Long tail tuna</i>	Marine	0.22 µg/g	Liver > Muscles	May – October	(Ahmed et al., 2015)
19.	<i>Gillichthys mirabilis</i>	Marine	50 µg/kg	Intestine > Vertebrae > Fin > Gill > Skin > Liver > Muscle	December – April	(Somero et al., 1977)
20.	<i>Sebastes schlegelii</i>	Marine	240 mg/kg	Kidney > Liver > Spleen > Intestine > Gill > Muscle	October – February	(Kim et al., 2017)
21.	<i>Etiopis maculatus</i>	Freshwater	0.79 µg/g	Intestine > Kidney > Gills > Brain > Muscles > Liver	Throughout year	(Shivakumar et al., 2014)
22.	<i>Hypophthalmichthys molitrix</i>	Freshwater	0.325 µg/g	Intestine > Muscles	February – May	(Chatta et al., 2016)
23.	<i>Ompok bimaculatus</i>	Freshwater	0.54 µg/g	Brain > Liver > Gills > Kidney > Muscles > Intestine	May – August	(Shivakumar et al., 2014)

Physiological effects of lead on fish health

Embryonic hatchery and development

Consequences of lead exposure, such as immunological reactions, oxidative stress, neurotoxicity, and bioaccumulation, and to find markers to gauge the degree of lead toxicity depending on exposure levels. It can damage the central nervous system, peripheral nervous system and cardiovascular system, thereby limiting the growth and development of fish and fish larvae (Tavares-Dias, 2021; Han et al., 2022). Fish go through different larval stages

during their existence, such as segmentation, hatching, blastula and gastrula. Much of the research involves the effects of lethal and sublethal lead concentrations on embryonic and larval survival, delayed hatching, developmental retardation, and morphological abnormalities (e.g., skeletal malformations, circulatory abnormalities, hypo pigmentation, eye abnormalities, etc.) (Gárriz and Miranda, 2020; Yan et al., 2020). Lead expression may have different effects depending on the fish species and the extent and duration of lead exposure.

Altered behaviour and neurological effects

Fish with long-term Pb exposure have toxic central nervous system (CNS) impairments that impair behaviour and cognition (Nabi and Tabassum, 2022). Fish neurotoxicity and oxidative damage brought on by Pb exposure are intimately connected. Pb is a neurotoxicant that affects brain and cognitive function by morphological changes in the brain, leading to neurodegenerative disorders, cell signalling dysregulation, and impairment of neurotransmission (Ezemonye et al., 2019). By disrupting calcium flow and calcium-regulatory functions, lead causes neurotoxicity; further potential routes might affect the biophysics of cell membranes, leading to oxidative stress and death of the cells (Abbas et al., 2021; Ishaque et al., 2020). Lead binds to the calcium transport machinery of the nervous system and competes with calcium by mimicking the calcium cation, an ion essential for neurotransmitter release and regulation. Therefore, lead exposure alters calcium homeostasis and affects neurotransmission (Sarkar et al., 2022 b). Many proteins found exclusively in the brain are controlled by the largest family of transcription factors, zinc finger proteins, which bind to nucleic acids to regulate transcription. These proteins are affected by lead exposure because lead ions displace zinc. Fish whose nervous systems are weakened by lead exposure also exhibit erratic movements and hyperventilation (Malik et al., 2020). Fish exposed to lead develop neurological and behavioural problems due to synaptic damage and neurotransmitter alterations. Furthermore, adenosine triphosphate (ATP) and neurotransmitter systems were found to be highly correlated with each other (Paduraru et al., 2023). After liberating extracellular nucleotides, the essential messenger ATP is catabolized into adenosine diphosphate (ADP), adenosine monophosphate (AMP), and adenosine. Of them, adenosine possesses the most potent neuroprotective properties. Ecto-nucleotidase is an essential enzyme for the control of purinergic signalling, and exposure to lead modifies its activity (Sarkar et al., 2022 b). Consequently, exposure to lead can change how genes are expressed, interfere with DNA repair and transduction processes, and change the structural or functional characteristics of proteins (Malik et al., 2020).

Disruption of reproductive and endocrine system

All creatures must reproduce, and the ability to do so successfully is one of the key factors determining an animal's ability to survive as a species (Milla et al., 2021). Fish reproductive health is severely impacted by heavy metal pollution, which leads to low-quality gametes that may have an impact on the success of fertilization, hatching, and offspring survival rates (Bera et al., 2022). Lead and other heavy metals can cause abnormalities in the development of reproductive cells or organs. It prevents spermatogenesis and oogenesis, which results in decreased number and quality of eggs and sperm, as well as decreased hatching and fertilization. Uneven oocyte production, partially adhering gametes, unfilled folli-

cles, increased follicular atresia, decreased GSI (gonad somatic index), loose follicular lining, steroidogenesis, gametogenesis, and other symptoms can all be caused by lead poisoning (Ando et al., 2018). Overall, there will be destruction of reproductive system of fishes and hormonal imbalance resulting in a declining rate of production of new and healthy offspring (de Almeida Rodrigues et al., 2022).

Effects of lead on fish immune system

Exposure to lead as an environmental immunological toxin modifies fish immune responses (Tang et al., 2023). Pb also affects how animals' immune systems operate, which can lead to neurological, physiological, and metabolic dysfunctions (Kumar and Singh, 2024). One study found that fish exposed to lead have decreased hematopoietic and phagocytic activity in the spleen, as well as decreased antibody production. It has been shown that immune system activation and tissue damage in fish exposed to lead increase lymphocytes; however, long-term exposure causes immune system injuries that lead to a reduction in lymphocytes and white blood cells (Nayak et al., 2024). Due to the stress response's elevation of cortisol production, which decreased lymphocyte lifespan and promoted its apoptosis, fish exposed to Pb had noticeably lower white blood cell and lymphocyte numbers (Witeska et al., 2023).

Studies have shown that Pb affects an immune response by controlling cytokine expression (Zhao et al., 2020). Interleukin (IL), tumour necrosis factor (TNF), and other cytokines are proteins that govern messages between various cells that initiate an immune response that are vital in managing the immune system (Savan and Sakai, 2006; Dai et al., 2018). Interleukin 10 (IL-10) and tumour necrosis factor are two of the cytokines that play a role in the immune system's cellular inflammation and response. Pb exposure increased the expression of TNF-mRNA and IL-10 in some fish, and Pb concentrations up to a certain point can significantly compromise the health of the fish immune system (Kim and Kang, 2016).

Ecological consequences of lead contamination

Lead bioaccumulation in freshwater fishes has significant effects on the environment and human society and ecosystems which is described in Figure 4. Because aquatic ecosystem depends on metals in many ways, both directly and indirectly, it suffers greatly when there are notable ambient concentrations of lead metal that cause lead to be biomagnified in the food chain and accumulate in higher amounts in the species. It also affects other species that depend on aquatic food sources directly or indirectly in their food chains. Heavy metals like lead have a variety of effects on aquatic environments, some of which have already been studied. These effects include those on plants and animals such as aquatic, birds and mammals, as well as changes to their development, behaviour, and neurological systems. The repercussions also had an influence on humans and other creatures.

Every food chain becomes intertwined as fish accumulations expand to humans and other animals that rely on aquatic life for sustenance, and this eating of one species by another has an influence. After being absorbed by red blood cells (RBC), lead is distributed throughout the body. Pb is mostly connected to haemoglobin after it enters the cell, not the RBC membrane (Zulfiqar et al., 2019). Serious Pb poisoning can cause anaemia because the haematological system is susceptible to Pb (Flora, 2002). Histopathological evidence indicates that Pb ions are transported to the liver, where they have the potential to induce chronic liver damage. Furthermore, Pb poisoning decreases protein synthesis while increasing blood enzyme levels (El-Neweshy and El-Sayed, 2011; Yuan et al., 2014; Cobbina et al., 2015). Pb damages the kidneys structurally and modifies their excretory function, both of which have harmful consequences (Abdou and Hassan, 2014; Yuan et al., 2014; Cobbina et al., 2015). The additional organ and tissue systems affected by lead exposure include the neurological, cardiovascular, and reproductive systems (Flora, 2002; Carocci et al., 2016; Zulfiqar et al., 2019). Lead toxicity causes teeth and bones to mineralize, which puts a significant lot of stress on the body. Compared to adults, children absorb more lead than do adults. Adults are predicted to absorb 3–10% of an oral dose of Pb that is soluble in water, however children may absorb up to 40–50%. Pb levels in blood are greater in children with low Fe or Ca levels than in children with acceptable levels of these elements. Over 95% of lead phosphate is deposited as insoluble phosphate in skeletal bones, and pregnancy may enhance the absorption of lead (Kabata-Pendias and Szeke, 2015). According to autopsy studies, 90–95% of the body's lead burden is accounted for by teeth and cortical bone combined. In

adults, the total Pb body load in the bones is 80–95%, but in youngsters, it is around 73% (Kabata-Pendias and Szeke, 2015). Breastfeeding mothers have the potential to transmit lead to both the foetus and the newborn (Concha et al., 2013). Higher trophic levels that eat polluted fish may also be impacted by lead contamination.

Humans basically lie at the highest trophic level (not in all cases) and due to biomagnification, the level of lead contamination is here found to be high in higher trophic level and thus, the ecosystem can be affected by such contaminations.

Mitigation and management strategies for prevention of lead contamination

A precondition for aquatic environments and further lead buildup in the food chain is the use of lead remediation technology for the effective cleanup of polluted water sources. Several strategies are proposed to combat this threat. The removal of heavy elements like lead from wastewater is said to be possible and affordable using the chemical-biological integrated treatment approach. It is advised to weigh the benefits and drawbacks of both therapies. Chemical cleanup is one of the most popular repair methods since it is easy to apply and produces results quickly. Yet toxic byproducts and metal precipitates have seriously impeded this process (Crini and Lichtfouse, 2019). Conversely, biological treatment is gaining popularity due to its high return on investment and little impact on the environment. Sludge formation, a long acclimatization period, and changes in the isolate's biodegradability are among the disadvantages (Marzuki et al., 2021). These are some of the most successful approaches for lowering lead levels in water; other approaches include microbial and phytoremediation.

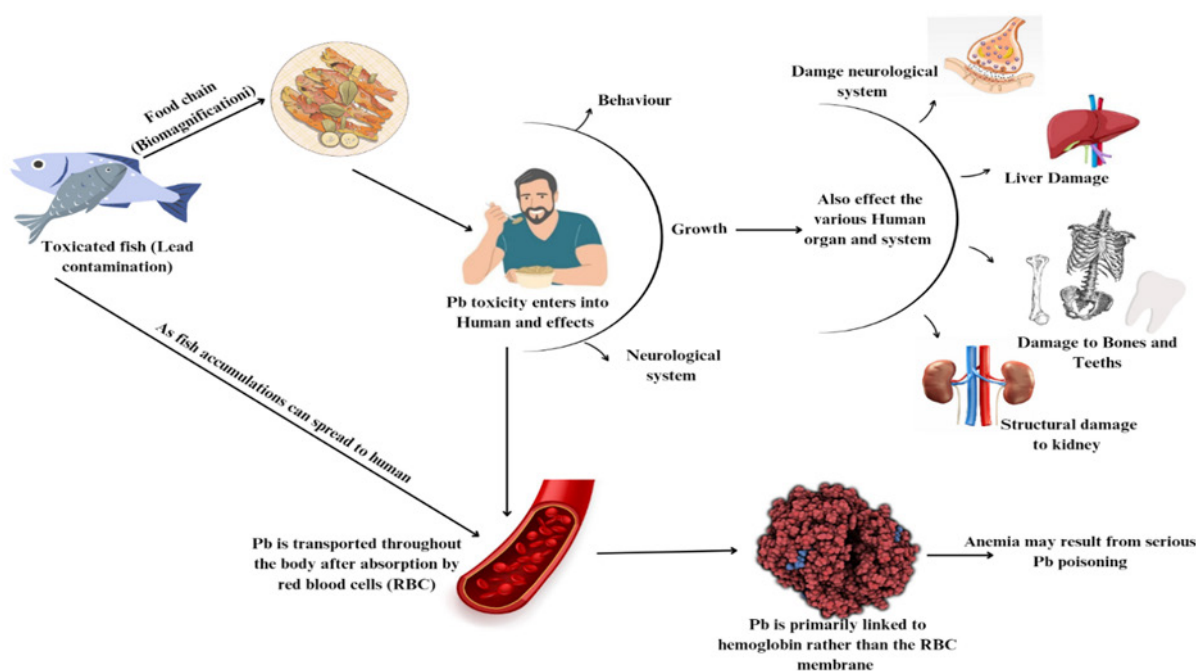


Figure 4. Ecological effects of lead-contaminated fish on higher trophic level

Environmental standards

In order to safeguard aquatic habitats against lead-containing compounds and the hazards associated with chemical use, it is critical to adhere to environmental regulations. Holistic resource planning should ensure that the relationships between land use, development, water flow, water purity, and aquatic ecosystems are taken into consideration before any land use designation is made (Isangedighi and David, 2019). In order to prevent the direct or indirect release of lead-containing compounds into aquatic environments – from homes, hospitals, farms, building sites, etc. – anthropogenic activities have to be controlled. The academic curricula of schools and colleges should incorporate environmental sustainability education, and environmental pollution awareness-raising should receive the serious attention it requires. Additionally, compensatory actions like operating fish hatcheries can generate young fish that are no longer able to be produced by heavy metals like lead-contaminated environments (Sankhla et al., 2022; Alsafran et al., 2023). To find out how much lead is consumed by fish on a daily basis and how much of it is consumed by higher trophic levels that eat contaminated fish and fish products, regular studies should be carried out. Such data will be valuable for a more accurate and reliable human and ecological risk assessment (Ali et al., 2019; Singh et al., 2022; Chopade et al., 2023).

Conclusion

The review highlights how dangerous lead is and how it might harm fish health and different ecosystems. Industrial processes, agricultural practices, and several other lead sources, including lead paint, lead batteries, and petroleum products, are the causes of lead pollution, bioaccumulation, and health risks. The paper provides detailed information on the bioaccumulation and biomagnification of fish contaminated with lead, from these sources to various ecosystem trophic levels. Several remediation techniques are available to lower the concentration of heavy metals in water and the food chain, hence minimising these Pb-based health concerns. To create effective remediation techniques, nevertheless, integrated approaches that are particular to the site and the source need to be implemented. Remediation methods that reduce Pb toxicity in systems that are moderately polluted can be economical and ecologically beneficial. Examples of these methods include phytoremediation and various physical and chemical methods. As a result, Pb exposure in fish has detrimental impacts on a variety of systems. The indicators impacted by Pb toxicity may be utilised as a crucial parameter to assess Pb toxicity in aquatic environments, and this article discusses potential remediation options.

Future research directions

Continuous study is crucial due to the intricacy of lead pollution in aquatic ecosystems. Researchers can study and develop creative solutions to problems like

lead poisoning in fish and aquatic environments, such as using advanced imaging techniques, toxic genomics, and nanotechnology.

The long-term impacts of lead contamination and bioremediation techniques involve research on how exposure to pollutants and changes in genetic diversity and adaptations over time affect these changes. The development of integrated risk assessment frameworks and management strategies can be pursued for further research studies and sustainability and resilience of the critical environment. This approach to multi-stressor study includes contamination study along with climate change, nutrient pollution, habitat loss, and development of integrated risk assessment frameworks and management strategies.

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