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UNDERSTANDING THE DETRIMENTAL EFFECTS OF HEAVY METAL POLLUTION IN SHRIMP FARMING AND TREATMENT METHODS – A REVIEW

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Abstract

High levels of heavy metals in the environment pose a significant risk to the aquatic ecosystem and its organisms. The non-biodegradable nature and lengthy persistence of heavy metals in the environment lead to toxicity in shrimp. Using aquatic animals as bio-indicators of metal contamination provides valuable data on acute and chronic toxicity in aquatic species and environmental quality. This review aims to provide insights into the sources, impacts, diseases and mitigation strategies related to heavy metal pollution in shrimp farming and the dangers to humans. Shrimp growth and development at each stage exhibit distinct responses to toxicity, which can vary depending on the species, types of metals, their mechanisms of action, as well as the concentration of heavy metals and duration of exposure. While several heavy metals are considered essential nutrient elements that enhance shrimp growth and feed efficiency, exceeding the maximum tolerable limit threatens shrimp health, human consumers, and ecological systems' stability. Shrimp species subjected to lethal toxic metal concentrations experience significant effects on accumulation in histopathology. Heavy metal toxicity has been linked to high mortality rates, malformation rates, oxidative stress, moulting issues, and decreased reproduction with increasing concentrations in shrimp. Various methods have been reported for removing heavy metal ions from aquatic environments, including filtration, adsorbents, removal efficacy, operating conditions, and the pros and cons of each technique. Therefore, this review provides an overview of how heavy metals can affect shrimp physiology and dangers to consumers. It aims to increase awareness about the importance of preventing and regulating their contamination in aquatic environments.

Key words: heavy metals, shrimp, bioaccumulation, acute toxicity, chronic toxicity

Aquaculture, as a rapidly expanding sector in agriculture, plays a significant role in meeting the increasing demand for fish consumption. It currently provides around half of the fish directly consumed by humans and contributes to 43% of the seafood production (Anderson et al., 2017). However, despite its promising growth, aquaculture faces various constraints that hinder its progress. These constraints include the scarcity of suitable locations, concerns regarding its adverse environmental impact (Frankic and Hershner, 2003), the risk of bacterial contamination, and the toxicity associated with heavy metals. Among these challenges, metal pollution stands out as a critical issue affecting estuaries and coastal areas. The presence of metals in aquatic habitats is particularly concerning due to their potentially harmful effects and their ability to accumulate over time (Censi et al., 2006).

Aquatic habitats are increasingly burdened by heavy metal pollution, which has far-reaching consequences for the environment and its inhabitants (Mahmuda et al., 2020; Sarkar et al., 2016). The toxic nature of heavy metals not only disrupts the delicate balance of aquatic ecosystems but also poses a direct threat to the survival of shrimp populations, which play a crucial role in maintaining the ecological equilibrium. The sources of heavy metal contamination in marine ecosystems can be traced back to human activities. Agricultural practices, including the use of chemical fertilizers and pesticides, contribute to the accumulation of heavy metals in water bodies. Additionally, the improper disposal of waste in landfills leads to erosion, releasing heavy metals into nearby water sources. Docking and embarking operations and industrial and domestic sewage further exacerbate the problem by introducing heavy metals into aquatic environments. Furthermore, certain natural processes, such as weathering and erosion, also contribute to the presence of heavy metals in marine ecosystems (Ezemonye et al., 2019; Sarkar et al., 2016).

Extensive agricultural operations, unchecked population growth, and heavy industrialization contribute to the production of various contaminants. These factors are ultimately responsible for causing severe damage to aquatic environments (Sarkar et al., 2022; Shahjahan et al., 2021). Heavy metals pose a significant threat to shrimp among these contaminants due to their toxicity,

bioaccumulation, and lack of biodegradability. Extensive research has been conducted to understand the harmful effects of heavy metals, as they endanger humans, the environment, and aquatic species (Iwuozor, 2019; Nyamete et al., 2022). Moreover, these metals have been linked to various health issues, including liver problems, cardiac disorders, renal dysfunctions, and even cancer in extreme cases. Aquaculture sustainability is particularly vulnerable to heavy metals such as copper (Cu), chromium (Cr), iron (Fe), nickel (Ni), cadmium (Cd), manganese (Mn), lead (Pb), and zinc (Zn). When present in inadequate amounts or at excessive concentrations, these metals can have detrimental effects on the environment. Essential metals like Fe, Cu, Zn, Co, Cr, and Ni, which play crucial roles in biological functions, can also become harmful under certain conditions. While these essential metals are beneficial for species development and feed utilization, exceeding the maximum tolerable limit disrupts the standard physiological and ecological systems in aquatic environments. This poses a threat to both organisms and humans, as these metals can have harmful effects. Several studies (Akter et al., 2021; Dawood et al., 2020; Ghazi et al., 2022; Rohani et al., 2022) have highlighted the positive impact of essential metals, while others (Mokarram et al., 2020; Okoye et al., 2015) have emphasized the dangers associated with exceeding safe limits. The harmful effects of these metals on organisms and humans have been extensively documented (Fernandes et al., 2008; Sarkar et al., 2016).

Shrimp accumulate heavy metals in their bodies through various sources, including their diet, water, inedible particles, and even skin absorption (Choi et al., 2016). These metals enter the aquatic environment primarily through integrated agricultural wastes (Ajewole et al., 2021). Industrial wastes and runoffs also contribute significantly to the presence of heavy metals in the environment, with a large portion of these metals ultimately settling and becoming incorporated into sediments. As a result, sediments serve as the primary repository for heavy metals in aquatic ecosystems (Iwuozor et al., 2022 a; Iwuozor and Gold, 2018; Wang et al., 2014). Once ingested, heavy metals travel through various tissues within the shrimp's body, including the gills, kidneys, and hepatopancreas, before being either stored or excreted (Choi et al., 2016). Shrimp, in particular, are highly susceptible to the physiological effects of heavy metal pollution, which can have detrimental impacts on their overall well-being (Islam et al., 2020; Suchana et al., 2021). Studies have shown that metals can undergo biomagnification in food chains, leading to sub-lethal effects or even mortality in shrimp populations (Jiang et al., 2014). Furthermore, these metals interfere with crucial developmental and growth-related processes in shrimp embryos, ultimately affecting their reproduction and survival rates (Jezierska et al., 2009).

Unlike fish, which have distinct eating habits, shrimps are scavengers that feed on various leftover materials and organisms found on the ocean floor (Canli et al., 2001). Crustaceans' most prevalent respiratory pigment, hemocyanin, contains approximately 0.17% Cu (Mangum, 1983). Depending on the moulting stage, this respiratory pigment can constitute up to 95% of the total haemolymph protein, enabling the tissue to retain about 40% of the organism's entire Cu load (Rao et al., 2008). Shrimp producers often use excessive amounts of copper sulphate in pond management (Chen and Lin, 2001). Consequently, Cu can accumulate in water due to excessive sewage discharge or residual algaecide, leading to toxic effects on aquatic animals (Qian et al., 2020). The contamination of shrimp with heavy metals has thus emerged as a significant global problem, posing non-cancerous health risks and endangering shrimp populations. For instance, the presence of Pb in animal feed can have detrimental effects on the kidneys and liver (Lee et al., 2011), while prolonged exposure can lead to severe cognitive impairments and even death (Al-Busaidi et al., 2011). Similarly, cadmium has been found to induce chronic toxicity symptoms in the kidneys, including liver dysfunction, infertility, hypertension, and the development of tumours (Rahman et al., 2010). Additionally, chromium can potentially harm proteins and membrane lipids, leading to disruptions in cell structure and function (De Mattia et al., 2004; O'Brien et al., 2003).

The significance of marine shrimp as bioindicators of heavy metal pollution in environmental monitoring studies has been highlighted by numerous researchers (Pourang and Dennis, 2005; Yılmaz and Yılmaz, 2007). The mounting evidence from various sources underscores the global attention directed towards heavy metal contamination in crustaceans. The detrimental effects of heavy metals on the growth and development of shrimp and other aquatic species cannot be overstated. These impacts manifest in a range of problems, including elevated heart rates, heightened mortality rates, physical deformities, and abnormalities in the vertebral column throughout different stages of embryonic development. Furthermore, there have been observations of reproductive compromises, such as a decrease in hatching rate and abnormal shape of reproductive organs, as documented by Wang et al. (2020), Witeska et al. (2014) and Zhang et al. (2012). However, despite the existing literature, there is a lack of comprehensive reviews that exclusively focus on and address the impacts of heavy metals on shrimps. Given the limited availability of research on the growth performance, physiology, biochemistry, immunity, and metabolism of aquaculture organisms, this review aims to primarily compile current information regarding the effects of heavy metal contamination on shrimp species. Additionally, it will explore potential approaches to remediate heavy metal-contaminated aquaculture. This review aims to provide valuable insights into the sources, impacts, diseases and the most advanced and efficient mitigation strategies related to removing heavy metal pollution in shrimp farming. By doing so, it seeks to contribute to understanding this issue and offer practical solutions for the aquaculture industry.

Heavy metal sources explored in aquaculture

The presence of heavy metals in the environment can be attributed to both human actions and natural processes. Heavy metal contamination is primarily caused by human activities, such as discharging domestic and industrial waste, leaching from landfills, storm runoff, shipping, and port operations (Marcovecchio, 2004). Humans typically come into contact with heavy metals through the consumption of contaminated food, drinking water, and polluted air (Sankhla et al., 2020). Toxic heavy metals like mercury, lead, arsenic, chromium, and cadmium are commonly found in the environment. On the other hand, heavy metals like zinc and copper are essential for human metabolism, but excessive concentrations can also have adverse effects on the human body. Heavy metals in surface water systems and aquatic environments are primarily the result of natural or human activities. Natural factors include rock weathering, erosion, and volcanic eruptions, while human activities encompass agricultural practices, mining, and municipal sewage runoff. Since the industrial revolution, most heavy metals found in the environment can be attributed to human activities such as sewage, agricultural production, and industry. Heavy metals typically exist in the form of hydroxides, oxides, phosphates, sulphides, sulphates, silicates, and organic compounds. These metals are released into the aqueous environment through both natural processes and human activities (Herawati et al., 2000). The diagram presented in Figure 1 visually represents the detrimental effects of heavy metals on aquatic ecosystems.

Domestic sewage

Domestic sewage contains numerous pollutants, including nutrients, radionuclides, pharmaceuticals, microorganisms, heavy metals, and personal care products. These can infiltrate natural water bodies and cause irreversible damage to aquatic ecosystems and human health. The soil transports heavy metals from effluent sludge, phosphate fertilizers, and municipal compost to groundwater (Boularbah et al., 2006). A significant number of households utilise chemical cleaners that include heavy metals, namely iron, and manganese. However, sewage treatment plants have a restricted capacity to handle these heavy metals effectively. As a result, these heavy metals enter aquaculture ponds, lakes, and other water environments via surface runoff or atmospheric subsidence, resulting in excessive heavy metal concentrations and negatively impacting the biodiversity of aquaculture ecosystems (Cao and Wang, 2017).

Agriculture production

In agricultural production, crop yields are increased using large amounts of fertilizers and pesticides, often containing pollutants such as heavy metals. For example, arsenic has been detected in glyphosate preparations. These pollutants enter aquatic ecosystems through soil infiltration or surface runoff, threatening aquatic animal health and entering the human body through the food chain, seriously endangering human health and forming a vicious circle in the long run (Verma et al., 2020). Aquaculture farms use fertilizer to boost phytoplankton growth,

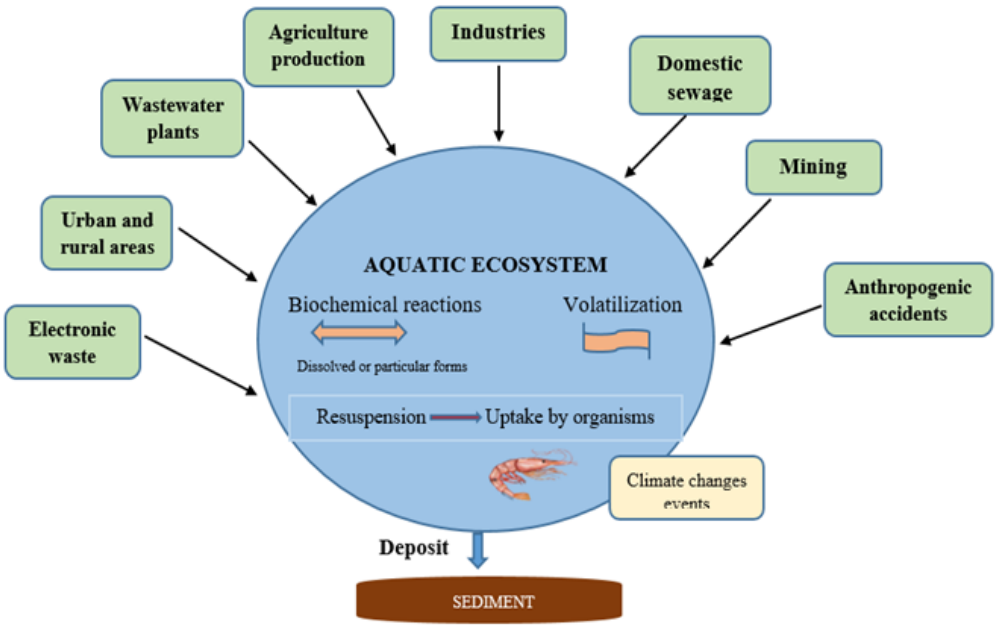

Figure 1. Sources of heavy metal pollution impacting aquatic ecosystems

enhance plant nutrient concentrations, and ultimately improve the yield of fish or crustaceans. Heavy metals, which are nitrogen- and phosphorus-based compounds, may be included in these fertilizers (Boyd and Massaut, 1999). Another consequence of contemporary agricultural techniques, which involve the application of fertilisers and pesticides to enhance crop productivity, is the enduring presence of these substances in farmed soils. Subsequently, these residues are carried into the aquatic environment through rainfall or irrigation water (Ouyang et al., 2018). Also, crops produced on soils polluted with heavy metals are fed to animals whose waste products are utilized in aquaculture. The metals enter the system in this manner through sediments (Nyamete et al., 2022). Discharging sewage from fish farming is an additional contributor of heavy metals in aquaculture. This approach, commonly referred to as sewage-fed aquaculture, enables the utilisation of sewage-treated wastewater, which may contain heavy metal residues, for aquaculture purposes in areas with limited water supplies (Azanu et al., 2016). Additionally, there is a chance of composite exposure when certain organochlorine pesticides and heavy metals are present together, which might result in a doubling of toxicity.

Industrial activities

The wastewater and waste gas from the mining process contains a high concentration of toxic and harmful heavy metals such as lead and zinc, causing heavy metal pollution in the soil, water, and other environments surrounding the mining area (Mei et al., 2021). The electroplating sector is responsible for the discharge of heavy metals into water and the environment, including lead, nickel, and iron, which may present carcinogenic risks to human health (Wenping et al., 2017). Many species at lower trophic levels die when hazardous heavy metals like arsenic, lead, and mercury are released into aquatic environments. These heavy metals are found in coal ash produced by coal-fired power plants (Jebakumar et al., 2018). The ingestion of heavy metals by crustaceans is another potential route of accumulation. Aquaculture relies on formulated feeds, yet some commercial feed manufacturers fall short of shrimp feed regulations and employ heavy metal-contaminated ingredients during production (Kundu et al., 2017).

Different types of heavy metals and their effects on shrimp

Heavy metals can be divided into essential metals (copper, zinc, nickel, iron, manganese, etc.) and nonessential metals (cadmium, arsenic, lead, mercury, chromium, tin, etc.) (Ghafarifarsani et al., 2024) (Figure 2). After heavy metals pollute shrimp environment, they can penetrate the waxy layer of their epidermis or tissues, enter the cell, and cause reactive oxygen species to reduce their defence ability. The damage to the body is mainly lipid oxidation, proteins, enzymes, and DNA, and ultimately leads to biofilm damage, protein denaturation, enzyme inactivation, and DNA replication errors, which are incredibly harmful to cells.

Table 1. Anthropogenic sources of some toxic heavy metals

Heavy metals	Sources
Fe	Metal refining, engine parts
Zn	Rubber industries, paints, dyes, wood preservatives and ointments, batteries, electroplating industries, phosphate fertilizers, detergents
Ni	Galvanization, metal refining, paint and powder battery processing facilities, and superphosphate fertilisers
Cu	The electroplating industry, plastic industry, metal refining, and industrial emissions are a few examples
Cd	Refined petroleum products, paint pigments, pesticides, galvanized pipes, plastics, polyvinyl and copper refineries
Cr	Chrome plating, petroleum refining, electroplating industry, leather, tanning, textile manufacturing, and pulp processing units. It exists in both hexavalent and trivalent forms
As	Automobile exhaust/industrial dust, wood preservatives and dyes
Pb	Petrol-based materials, pesticides, leaded gasoline and mobile batteries

Source: Gautam et al., 2016.

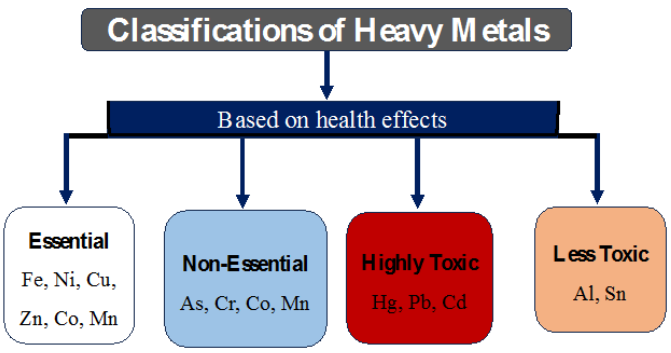

Figure 2. Classifications of heavy metals based on their health effects in humans and animals

Copper (Cu) is an essential element of heavy metal used in industry and agriculture for the average growth and development of living organisms. It is present in the blood of crustaceans like shrimp, crabs, and lobsters in the form of oxygen transporters and enzymes (Olaifa and Omekam, 2014). Haemocyanin is the predominant respiratory pigment found in crustaceans, constituting around 0.17% of copper content (Mangum, 1983). Depending on the moult stage, this respiratory pigment can constitute up to 95% of the total haemolymph (HM) protein, allowing this tissue to hold around 40% of the organism's total Cu burden (Rao et al., 2008). Cu has a role in several enzyme structures, including lysyl oxidase, cytochrome c oxidase, ferroxidase, tyrosinase, and superoxide dismutase, which are important for crustacean respiratory function (Lee and Shiau, 2002). Cu was utilized in feeds to enhance shrimp immune systems, antioxidant capacity, and growth performance (Wang et al., 2018; Yohana et al., 2023; Yuan et al., 2019). According to Olaifa and Omekam (2014), Cu in the form of Cu2+ has the ability to create complexes with both organic and inorganic compounds, which is responsible for its toxicity to aquatic life at high concentrations. Reduced development, a shorter lifespan, lower fertility, and behavioural changes are some of the chronic impacts of Cu on aquatic life, whereas mortality might be one of the acute effects (Olaifa et al., 2010). Zinc (Zn) exists in water in three forms: as a standalone element, as soluble complexes of Zn, and as part of dispersed matter (Olaifa and Fabusoro, 2017). It is an essential microelement for the vast majority of living organisms, including fish and crustaceans. According to Zheng et al. (2008), it performs crucial roles in various metabolic processes involving DNA and protein synthesis, transcriptional regulation, and cellular signal recognition. The metabolism of an organism, which is closely tied to the physiological processes of survival, growth, and reproduction, is one area in which Zn plays a significant role. Zn that has been assimilated into the body is carried to the liver via albumin, and globulin, which builds up before being disseminated to other tissues (Olsson et al., 1998). As an essential metal for organisms, Zn concentrations in the body may be maintained reasonably constant within a small range regardless of the significant variations of Zn concentrations in the ambient environment (10^{-8} to 10^{-5} M). At low concentrations, Zn is required for the regular growth and reproduction of plants and animals, including humans (Goyer and Clarkson, 2001). In animals, excessive Zn intake can be toxic and even fatal. Zn is a neurotoxic metal that has been linked to metabolic malfunction and behavioural challenges, according to earlier research (Senger et al., 2006). It is possibly toxic to shrimp and adversely affects their survival (Salvaggio et al., 2016; Si et al., 2019). Zn homeostasis failure impaired growth performance and produced significant metabolic problems (Song et al., 2017; Zheng et al., 2015). Nickel (Ni), an essential microelement, is required for several physiological activities. High amounts, however, disrupt gastrointestinal function while boosting red blood cell and lung function (Akoto et al., 2014). According to aquatic ecotoxicity studies, $NiSO_4 \cdot 6H_2O$ and $NiCl_2 \cdot 6H_2O$ are dangerous substances whose excessive concentrations can be harmful and interfere with an animal's homeostasis (Ololade and Ogini, 2009). Iron (Fe) is an essential element required for the formation of red blood cells (RBC). According to Björnerås et al. (2017), several geographic areas have begun to notice the rising level of Fe in freshwater ecosystems as a new environmental issue of concern. The concentration of dissolved Fe in an aquatic ecosystem is generally low, although it can vary depending on the pH of the system and the presence of an oxidizing environment (Yılmaz et al., 2017). Iron (Fe) toxicity stems from its capacity to catalyse the class of radicals that target and demolish cellular macromolecules, hence amplifying cellular death and tissue damage (Yllmaz et al., 2017). The whole-body contents of these ions were not altered by chronic exposure to various dietary Fe levels. To create a model that more accurately predicts the physiological consequences of dietary metals, it is vital to understand the interactions between metal exposure, physiological function, and control of metal transporters.

Cadmium (Cd), which is the most toxic heavy metal discovered in both the Earth's crust and marine environment, is classified as a non-essential element (Farid et al., 2014). It damages aquatic ecosystems over time and destroys aquatic animals (Chen et al., 2013; Liu et al., 2018; Yuan et al., 2017). The World Health Organization identifies Cd enrichment in food as a major carcinogen, typically Cd^{2+}. Cd is one of the most mobile heavy metals in the environment and can move in both aerobic and acidic conditions (Kubier et al., 2019; Zhang et al., 2017). The metabolism, growth, and reproduction of marine fish, shellfish, and other species are changed by high levels of Cd^{2+} exposure (Kim et al., 2016), and immunological and oxidative stress are produced in bivalves (Chen et al., 2020; Shi et al., 2018). Cd can limit aquatic animals' survival, growth, and reproduction rate (Ogendi et al., 2014). Cd is primarily concentrated in the liver and kidneys of animals (El-Boshy et al., 2015). Prolonged Cd exposure causes accumulation in organs, particularly the liver, kidneys, and gills, that serve as Cd storage sites (Al-Asgah et al., 2015). According to Cheng et al. (2013), the occurrence of arsenic (As) in aquatic environments is associated with anthropogenic sources, even though arsenic is a naturally occurring metalloid. Because of the apparent link between heavy metals and environmental toxicity it is sometimes classed with heavy metals (with other metalloids) (Farrell et al., 2018). The chemical form has a role in determining the substance's level of toxicity. Arsenobetaine, regarded as largely innocuous, is the primary chemical compound found in aquatic environments (Amlund et al., 2012; Krishnakumar et al., 2016). Lead (Pb) is a common toxic element, and its ingestion can cause haemolysis of red blood cells in animals, as well as injury to the kidneys, liver, nervous

system, and blood vessels. It is not known to provide any metabolic advantages to aquatic organisms. Alvarado et al. (2020) found that the levels and build-ups of it in marine species are influenced by environmental conditions, including temperature, pH, and dissolved oxygen. Due to its generally limited bioavailability, it does not appear that Pb has a significant impact on freshwater ecosystems under normal conditions. However, higher Pb concentrations from a discrete source, such as mining operations, might impact the ecosystem.

Additionally, Pb can harm aquatic organisms even in deficient quantities since it is non-essential for biological functions. Pb causes high blood concentrations and nervous system alterations in aquatic organisms such as crustaceans. Mercury (Hg) is prevalent in the marine ecosystem, primarily as methylmercury. It is a highly toxic, detrimental element without positive effects on organisms. In the presence of certain bacteria, the inorganic form is rapidly converted into very poisonous methylmercury (Yaghmaeian et al., 2015). According to Yaghmaeian et al. (2015), when shrimp are exposed to high levels of Hg, they experience significant harm to their kidney and liver, central nervous system impairment, and neurological disorders, damage to the blood, cardiovascular, and respiratory systems and renal reproductive system immunity. Chromium (Cr) exists in a wide range of oxidation states, from Cr^{2}+ to Cr^{6+}, with the trivalent and hexavalent forms being the most stable and frequent in terrestrial ecosystems (Chandra and Kulshreshtha, 2004). Although Cr is a beneficial element, only moderate levels are helpful for higher animals; excessive doses are highly toxic. Cr (VI) is a metallic ionic species that can be extremely hazardous depending on its degree of oxidation (Singh et al., 2021). Shaheen and Akhtar (2012) reported that oxygen facilitates the oxidation of Cr (III) to Cr (VI), a form that is both hazardous and more soluble in water compared to other forms. In fish and shrimp, Cr damages the gills above a particular level and, in some species, results in alterations, including anaemia, eosinophilia, lymphocytosis, bronchial lesions, and renal lesions (Farid et al., 2014).

Multiple studies have been conducted on the impact of a specific heavy metal on the performance of different shrimp species. Given that a significant portion of the aquatic environment is polluted with a combination of heavy metals originating from human activities and natural sources, it is imperative to assess the collective impact of these heavy metals on factors such as growth performance, embryonic and larval development, and other related aspects. The combined impact of Pb-Cd and Zn-Hg has been investigated in oriental river prawn *Macrobrachium nipponense* (Tavabe et al., 2019) and ridgetail white prawn *Exopalaemon carinicauda* (Zhang et al., 2017) juveniles respectively, revealing increased necrosis, lumen size and increased mortality. Studies have indicated that exposure to Cu in environments with high alkalinity might cause notable oxidative damage, apoptosis, damage to the antioxidant defence system, destruction of gill and hepatopancreas, inhibits respiratory metabolism and shifts energy utilization in *Macrobrachium nipponense* and *Cambaroides dauricus* (Bao et al., 2020; Wang et al., 2022). Moreover, the presence of Zn contamination had a detrimental impact on the enhancement of muscle biochemical compositions, digestive enzyme activities, growth, and survival in various species of shrimp. It also hindered the proper development and pigmentation of multiple organs (Muralisankar et al., 2015; Zhang et al., 2017). Table 2 summarizes the various observations of impacts made in several shrimp species as a result of exposure to other metals at various exposure periods.

Table 2. Effects of heavy metals on the performances of different shrimp species

Shrimp species	Heavy metal	Dose	Exposure period (days)	Effects observed	References
1	2	3	4	5	6
Litopenaeus vannamei	Cd	2.58, 1.30, 1.14, 1.07 mg/L	4	Elevations in ammonium excretion	(Wu and Chen, 2004)
Cambaroides Dauricus	Cu	2.06, 4.12 mg/L	14	*C. dauricus* mainly inhibits respiratory metabolism and shifts energy utilisation from adapting to Cu stress. higher concentration-dependent accumulation ability of Cu	(Bao et al., 2020)
Macrobrachium nipponense	Pb	0.072 and 0.12 µM/L	60	Increased large granular haemocyte (LGH) and cHH, increased mortality	(Tavabe et al., 2019)
Litopenaeus vannamei	Zn	3.98, 2.14, 1.75, 1.35 mg/L	4	Inhibition in oxygen consumption of 91.3% and 75.9% lower	(Wu and Chen, 2004)
Macrobrachium nipponense	Cd	0.08 µM/L	60	Increased necrosis, lumen size, melanisation, vacuolisation, and abnormal lumen shape	(Tavabe et al., 2019)
Exopalaemon carinicauda	Zn	76.4, 44.0, 30.2, and 17.2 mg/L	4	Decreased the oxygen consumption by 51.4% and increased ammonia-N excretion by 129%	(Zhang et al., 2017)

Table 2 – contd.

1	2	3	4	5	6
Exopalaemon carinicauda	Hg	0.212, 0.096, 0.084, and 0.065 mg/L	4	Inhibition of oxygen consumption by 48.1% and increment of ammonia-N excretion by 161%	(Zhang et al., 2017)
Palaemonetes argentinus	Cd	3.06, 12.24 µg/L	15	Haemocytic and connective infiltrations in the intertubular space, erosioned microvilli, a ripple of the basal lamina, atrophied epithelium, and necrosis, increased LPO	(Chiodi- Boudet et al., 2015)
Litopenaeus schmitti	Cd	0.98, 0.54, 0.32, and 0.18 mg/L	4	Elevations in ammonium excretion	(Barbieri, 2007)
Litopenaeus vannamei	Zn	0.05, 0.2, or 0.6 mg/L	28	Atrophy and necrosis of tubules, melanisation, alterations and unavailability of biochemical and nutritional materials within the hepatopancreas and, consequently, growth retardation	(Wu et al., 2008)
Macrobrachium nipponense	Pb	13.13 and 26.26 µg/L	60	Reduced growth, increased accumulation in muscle, impaired intestinal morphology, induced oxidant stress, increased MDA, decreased SOD	(Ding et al., 2019)
Litopenaeus schmitti	Zn	1.64, 1.22, 0.86, 0.31 mg/L	4	Inhibition in oxygen consumption of 55.92 and 44.09%	(Barbieri, 2007)
Palaemon macrodactylus	Cd	0.37 mg/L	4	Decrease in T-AOC and an increase in MDA content, which indicated damage to the antioxidant system	(Zhang et al., 2021)
Litopenaeus vannamei	Cd	0.1, 0.2, or 0.4 mg/L	28	Vacuolization of epithelial cells, loss of the star shape of the lumen, a thickening of the basal lamina, an increased distance between adjacent tubules, the appearance of a scraggy lumen surface, and infiltration of haemocytes	(Wu et al., 2008)
Sinopotamon henanense	Cd	7.25, 14.5, and 29 mg/L	5	Inhibit moulting by inhibiting the secretion of the moulting hormones	(Luo et al., 2015)
Macrobrachium rosenbergii	Zn	10, 20, 40, 60, and 80 mg/kg	90	Improvement in survival, growth, digestive enzyme activities, and muscle biochemical compositions	(Muralisankar et al., 2015)
Exopalaemon carinicauda	Cd	0.66, 0.379, 0.343, and 0.258 mg/L	4	Increase in mortality	(Zhang et al., 2014)
Macrobrachium nipponense	Cu	0.05, 0.1, 0.15 mg/L	4	Induce oxidative damage, apoptosis, damage to the antioxidant defence system, destruction of gill and hepatopancreas	(Wang et al., 2022)
Macrobrachium nipponense	Cd	0.01, 0.02, 0.04 mg/L	4	Induce oxidative damage, apoptosis, damage to the structure of gill and hepatopancreas	(Wang et al., 2021)
Litopenaeus vannamei	Zn	3 mg/L	2	Sloughed off epithelium filaments, hyperaemia	(Wu et al., 2009)
Exopalaemon carinicauda	Cu	0.932, 0.748, 0.725,0.712 mg/L	4	Inhibition in oxygen consumption of 34.8% and a decrease in the O:N ratio of 23.9%	(Zhang et al., 2014)
Penaeus indicus	Pb	72.23 µg/L	2	Decrease in metabolic rate and ammonia-N excretion	(Chinni et al., 2002)l
Litopenaeus vannamei	Cd	3 mg/L	2	Hyperaemia, blackened gills, epithelial oedema and cell proliferation	(Wu et al., 2009)
Litopenaeus vannamei	Zn	0.05 or 0.2, 0.3 mg/L	84	Higher metallothionein (MT) induced in the gills	(Wu and Chen, 2005)

Ecotoxicology of heavy metals in shrimp production

Heavy metal bioavailability to shrimp

Acute toxicity tests of heavy metals in shrimp are a simple and fast way to determine the toxicity of pollutants. The acute toxicological experiment refers to the experiment in which large doses of poison are given to the test animal multiple times within 24 hours to observe the specific poisoning effect and even death of the test

animal in a short period. The toxicity of metal to experimental organisms is determined by measuring the metal's half-lethal amount (LD_{50}) and half-lethal concentration (LC_{50}). The relative toxicity of metal pollutants can be studied, and the ratio of the actual intake of heavy metals to the health tolerance of experimental organisms can also be determined; that is, the safety threshold of heavy metal pollutants can be sought. The larger the safety threshold of the contaminant, the less harmful it is, and vice versa. Unlike other organic chemicals, metals are non-biodegradable and cannot be easily degraded into less harmful molecules. Metals are either absorbed by biota or redistributed throughout the water column after being added to an aquatic environment (Frémion et al., 2016). Metal bioavailability is the percentage of metal concentration that can accumulate in the body. The bioavailability of metals to organisms is influenced by various factors. These include the biology of the organism, such as its reproductive stage, size or age, feeding strategies, and its ability to efficiently assimilate metals. It is also affected by the geochemistry of the environment, including the distribution of metals in water sediment, suspended matters, and the speciation of metals (Roosa et al., 2016). Additionally, physical and chemical factors such as pH, salinity, temperature, dissolved organic carbon concentration, total suspended solids, and ionic strength play a role in determining metal availability (Bonnail et al., 2016; Fu et al., 2014). The bioavailability of metals determines their accumulation in shrimp. If metals are in dissolved form, they are absorbed through the porous epidermis; if metals are in particle form, they are ingested through the feed. The ingestion uptake also depends on feeding pace, intestinal transit duration, and digestion efficiency. According to Chapman et al. (1998), the organic molecules of the metals may be more bioavailable than their ionic forms. For instance, compared to mercuric chloride, which is not lipid-soluble, organic mercurial compounds are lipid-soluble and quickly infiltrate lipid membranes, enhancing their toxicity. Further study is required to understand the dynamics of various metal forms in the shrimp environment and assess the bioaccumulation and accumulation pathways depending on whether the metal forms are dissolved or suspended. Generally, metal binding decreases the bioavailability of metals from sediment (Rosado et al., 2016).

Heavy metals such as Hg, Pb, and Cd have a minimal safety threshold, increasing harm to organisms and humans. Heavy metals are a type of contaminant in aquaculture that are problematic due to their tendency to persist and build up in the ecosystem (Farrell et al., 2018; Mehjbeen and Nazura, 2013). Although there is no clear definition of heavy metals, they are classified as elements having a density of more than 5 g/cm^3 (Farrell et al., 2018). Amosu et al. (2016) identified iron (Fe), manganese (Mn), zinc (Zn), mercury (Hg), cobalt (Co), nickel (Ni), lead (Pb), copper (Cu), arsenic (As), and cadmium (Cd) pose the greatest risk of contaminating aquaculture products. Some of these metals are necessary elements that are required for the metabolism of the organisms. In contrast, other metals are non-essential and always contend with the essential ones for accessible enzyme sites (Serviere-Zaragoza et al., 2021). According to the US Agency for Toxic Substances and Disease Registry (ATSDR), Pb, Hg, As, and Cd are listed first, second, third, and sixth on the list of dangerous wastes, respectively (Rai, 2009 a).

Different stages of shrimp growth and heavy metal species are different in their toxicity to shrimp. Cui and Liu (1987) found that the toxicity of heavy metals to fish egg hatching was $Cu^{2+} > Zn^{2+} > Cd^{2+} > Cr^{6+}$. The toxicity order for larvae survival was $Cu^{2+} > Cd^{2+} > Zn^{2+} > Cr^{6+}$; the toxicity of the same heavy metal in different water quality is also different, and its toxicity law is non-ionized water > fresh water > brackish water > seawater. The order of embryotoxicity to flounder reported by Wu et al. (1990) was $Cu^{2+} > Zn^{2+} > Cd^{2+} > Cr^{6+}$, and the toxicity of tooth-fish was $Cu^{2+} > Cd^{2+} > Zn^{2+} > Cr^{6+}$. Nan-Xuyang (2009) examined the lethal effects of the heavy metals Zn, Cu, and Cd on loaches and discovered that these effects become more severe as poisoning time and toxic dosage increase with specific time effects and dose effects. By statistically analysing the test data collected after a 96-hour acute toxicity test on juvenile spinnaker mussels in three different water temperatures, it was discovered that temperature significantly correlated with the lethality rate of heavy metal stress and the test mass concentration of juvenile mussels, and that the toxicity of heavy metals increased with temperature. When examining the response of fish and shrimp in water to heavy metals in the water environment, researchers found that in low-concentrated heavy metal environments, shrimp ingest heavy metal pollutants through bait or water bodies, which manifests as the enrichment of heavy metals. On the contrary, shrimp exert their detoxification function to release heavy metals outside the body to maintain the stability of their intercellular concentration. In an environment with a high concentration of heavy metals, the enrichment of heavy metals by fish and shrimp is substantially more significant than their degradation, resulting in toxicity and mortality (Rashed, 2001). Additionally, research has shown that the heavy metal enrichment capacity of the internal organs of juvenile crucian fish and crayfish is significantly higher than that of the muscles and that the enrichment of the liver is more than ten times that of the muscles. This is because animals' liver, pancreas, and kidneys are their primary detoxification and excretory organs.

Metal toxicity effects

Following ingestion, metal is transported by lipoproteins to different parts of the body, such as blood, organs, or other tissues. It can then be directed to various centres, including (i) action centres. In these action centres, the toxic metal interacts with a macromolecule (protein) or cellular structure within the body, causing harmful effects for the entire shrimp; (ii) metabolism centres, where

detoxified enzymes process the metal; and (iii) storage centres, where the metal is stored. According to Bere et al. (2012), heavy metal over exposure reduces the growth of crustaceans, fish, phytoplankton, and other aquatic animals. Crustaceans and fish have gill necrosis and liver fatty degeneration (Sevcikova et al., 2016). Cellular assessments reveal how toxic metals affect marine organisms' enzymatic metabolism and function.

The lethal effects of metals in crustaceans were induced by inhibiting enzymes involved in cellular respiration. After chronic metal exposure, the histological alterations observed in crustaceans result from antioxidant enzyme inhibition (El Basuini et al., 2016; Jiang et al., 2016). The suppression of enzyme systems involved in protein synthesis and cell division resulted in consequences on the growth and development of organisms. Triebskorn et al. (2008) reported that the metal type can have toxic or nontoxic effects on bioaccumulation and enzymatic systems. Research on reproduction, accumulation, growth, survival, behaviour, impact on the enzyme system, and other aspects of acute and chronic metal toxicity are included.

Bioaccumulation of heavy metals and its effect on shrimp

Heavy metals refer to a class of metal elements with a density greater than 5 g/cm^3, with about 45 kinds of environmental pollution. The heavy metals mentioned, in fact, mainly refer to Hg, Cd, Pb, Cr, metallometalloid As, and other bio-toxic heavy metals, but also include general heavy metals with specific toxicity, such as Zn, Cu, Co, Ni, Sn (Wang et al., 2005). The accumulation rate of these metals is determined by their concentration in the water. When the concentration of metals in shrimp exceeds their concentration in the water, bio-concentration results. However, bioaccumulation occurs when the rate of assimilation exceeds the excretion rate (Nyamete et al., 2022). Therefore, the bioaccumulation of a pollutant is dependent on its absorption and elimination (Olaifa and Ayodele, 2004). Heavy metals do not immediately affect aquaculture unless the concentration is beyond the organism's retention capacity (Ju et al., 2017). Bioaccumulation is influenced by various physical and biological parameters, including dissolved oxygen levels, sex, temperature, age of the organism, salinity, alkalinity, pH, species, and developmental stage (Mziray and Kimirei, 2016; Xu et al., 2019).

External interactions between metals and shrimp include metals adhering to the skin or exoskeleton, which cause direct surface injury. Since metal particles are smaller and have a greater specific surface area than bulk materials, they adhere to the surface of organisms more readily. The accumulation of heavy metals in various aquatic products varied, and fish-fed phytoplankton had increased Cr and As concentrations. Shrimp and fish fed on debris and algae had higher Cr and Cu levels, while those fed on benthic invertebrates had higher Zn levels. Ni and Pb levels are higher in omnivorous fish. Omnivorous benthic organisms primarily feed on marine substrates and have a greater heavy metal concentration than fish (Long and Jing, 2002). The cumulative Cu concentration present in various aquatic organisms is different and follows the order fish < shellfish < crustaceans < cephalopods. The typical concentration of heavy metals in most aquatic animals follows the order Cd < Cu < Pb < Zn according to WHO standards. While trace amounts of Cu are necessary for crustaceans, elevated levels of this metal can lead to the build-up of Cu in various organs such as exoskeleton, muscle, gills, and hepatopancreas, resulting in osmoregulation disorders (Soegianto et al., 2013). Copper sulphate application rates range from 0.025 to 2 mg/L and are proportional to total alkalinity (Boyd, 2002). Several studies have investigated mortality, accumulation, and other impacts in crustaceans exposed to Pb (Santos et al., 2014), Cd (Barbieri et al., 2017), and Cu (Frías-Espericueta et al., 2015) as a result of increased metal burdens in coastal regions. In shrimp pond management, excessive amounts of $CuSO_4$ are frequently used (Chen and Lin, 2001). In such instances, Cu can build in water due to excessive sewage discharge or leftover algaecides, causing toxicity in aquatic organisms (Qian et al., 2020). According to Zhao et al. (2009), the concentration of heavy metals in sediment and water determines the majority of the heavy metal content in benthic animals. The concentration of heavy metals in aquatic organisms living in surface and middle water is influenced by the following two factors. First, the amount of heavy metals in the water. The quantity of heavy metals collected in water-producing items positively correlates with the amount of heavy metals in water bodies. The second is when the water product contains heavy metals when the heavy metal concentration in the water body is higher than the heavy metal content in the water-producing object. The accumulation of heavy metals in the organism is proportional to the length of exposure.

Under the same conditions, the accumulation of heavy metals in different organs in the same organism is also different. The different degrees of accumulation of heavy metal elements in various tissues and organs are due to their different affinity for endogenous substances in the body. Heavy metals are most likely to accumulate in the liver and kidneys of organisms, mainly because the liver and kidneys are able to synthesize a large number of metallothionein, which can quickly accumulate heavy metals in large quantities. Zhi-guo et al. (2010) studied the hepatopancreatic and occlusal muscles of the clam and found that these two parts are essential organs for heavy metal enrichment. Also, according to Zhao et al. (2009), the internal organs of purple mussels have the most apparent ability to accumulate and enrich Mn, Fe, and Cu. Hg is found in higher amounts in the liver of striped dolphins than in other tissues and organs. The four metals Cu, Mn, Cd, and Pb were the highest in the liver, oesophageal gland, visceral sac, and foot of the yellow-yellow sickle snail.

Table 3. Standards of water guidelines and permissible limits of heavy metals by different countries and organizations (mg/L)

Countries/ Organizations	Permissible limits (mg/L)									References
	As	Fe	Cu	Cd	Cr	Mn	Zn	Pb	Ni	
China	0.01	0.3	1	0.005	0.05	0.1	1.0	0.01	–	(Ando, 2004)
Canada	0.01	0.2	2	0.005	0.05	0.12	–	0.005	0.02	(Health Canada, 2019)
Australia	0.01	0.3	2	0.002	0.05	0.5	–	0.01	0.02	(NHMRC and NRMMC, 2011)
Japan	0.01	0.3	1	0.003	0.05	0.05	1	0.01	–	(Mehjbeen and Nazura, 2013)
India	0.05	0.3	1.5	0.01	0.1	0.1	15	0.05	0.02	(BIS, 2012)
New Zealand	0.01	0.3	2	0.004	0.05	0.5	-	0.01	0.08	(Ministry of Health, 2018)
USA	0.01	0.3	1.3	0.005	0.1	0.05	5	0.015	–	(WHO, 2017)
WHO	0.01	–	2	0.003	0.05	0.5	–	0.01	0.02	(WHO, 2017)
EU	0.01	0.3	1	0.005	0.05	0.05	5	0.015	0.02	(US EPA, 2023)

Source: BIS, Bureau of Indian Standards; US EPA, United States Environmental Protection Agency; WHO, World Health Organization.

Table 4. Comparison of metals concentrations in muscle of different shrimp species belonging to *Penaeidae* (µg/g)

Species	Hg	Cd	Pb	Zn	Cu	Fe	Mn	References
Fenneropenaeus merguiensis	–	0.07	–	40.20	17.86	17.77	0.15	(Pourang and Amini, 2001)
Penaeus semisulcatus	0.037	0.021	0.059	–	–	–	–	(Madany et al., 1996)
Penaeus semisulcatus	–	–	–	27.75	–	18.69	–	(Firat et al., 2008)
Penaeus semisulcatus	0.08	0.68	1.1	-	2.4	–	–	(Kureishy, 1993)
Penaeus semisulcatus	–	–	–	41.76	–	–	–	(Pourang and Dennis, 2005)
Penaeus monodon	–	0.25	–	13.03	3.56	5.17	0.17	(Mokhtar et al., 2009)
Penaeus semisulcatus	–	–	–	68.73	–	288.0	25.43	(Heidarieh et al., 2013)
Fenneropenaeus merguiensis	0.02	ND	-	-	9.1	0.61	1.09	(Darmono and Denton, 1990)
Penaeus monodon	–	0.72	32.12	1184.68	–	191.78	–	(Guhathakurta and Kaviraj, 2000)
Penaeus notialis	0.027	ND	0.29	15.7	4.81	4.99	–	(Biney and Ameyibor, 1992)
Fenneropenaeus indicus	–	1.27	3.3	–	60.5	–	–	(Joseph et al., 1992)
Litopenaeus vannamei	–	0.57	–	–	23.3	180.1	7.07	(Páez-Osuna and Ruiz-Fernández, 1995)
Penaeus kerathurus	0.038	0.03	0.34	13.2	7.4	3.1	–	(Balkas et al., 1982)
Fenneropenaeus merguiensis	0.032	0.175	0.414	13.8	1.26	15.13	0.1	(Javaheri Baboli and Velayatzadeh, 2013)

ND: not determined.

Heavy metal cycle from shrimp to the potential health risks for humans

Shrimps are considered one of the most nutritious aquatic organisms, serving as a reliable and valuable protein source that provides all essential amino acids in the global human diet (Domingo, 2016; Pandion et al., 2022). Research by Ra et al. (2023) has shown that shrimp is rich in omega-3 polyunsaturated fatty acids, which can help reduce the risk of diabetes, heart disease, stroke, and other health issues in humans (Smith and Guentzel, 2010). It is crucial to delve deeper into the presence of heavy metal pollution in aquatic species to ensure the safety of shrimp and public health (Yang et al., 2023). Various pathways exist that allow heavy metals from the environment to enter the bodies of shrimp, leading to their accumulation within the organisms. Shrimp can be contaminated with heavy metals through three main pathways: water, sediment, and their diet. The concentration of these metals in a shrimp's organs can vary, posing potential harm to aquatic organisms and leading to their accumulation in sediments. The food chain is widely recognized as the primary means by which heavy metals build up in aquatic environments. Consuming contaminated aquatic foods can present significant health risks to humans (Fernandes et al., 2008). The duration of exposure and the concentration of heavy metals can impact

shrimp embryos and larvae at each stage of development. Additionally, the toxicity of heavy metals can result in increased mortality rates, decreased fertility, lower fertilization success, changes in the gonadosomatic index (GSI), abnormalities in reproductive organs, muscle tissue, spawning rates, and ultimately, a lack of reproduction in shrimp (Raeeszadeh et al., 2023). Therefore, the presence of hazardous substances resulting from the accumulation of heavy metals can impede the positive effects on the health of shrimp. It is essential to identify heavy metals in commonly consumed farmed shrimp and evaluate any potential health risks (Yu et al., 2020).

Previous research has shown that the safety limit regulation of 2.0 mg/kg for chromium (Cr) in the tissues of *L. vannamei* was exceeded, with levels reaching 20.9±5.27 mg/kg at a farm in Guangdong, China, posing a significant risk to consumers (Wang et al., 2023). Additionally, the lead (Pb) concentration in *L. vannamei* collected from the Persian Gulf coast surpassed the recommended threshold of 2.0 mg/kg set by the Ministry of Agriculture Fisheries and Food (MAFF, UK), with levels reaching 2.54±0.32 mg/kg (Dadar et al., 2014). Studies have also shown that the mean Cr concentration in the shell and tissue of *P. monodon* at Botiaghata farm was 1.03 mg/kg and 0.68 mg/kg, respectively Sarkar et al. (2016), while *P. semisulcatus* from Turkey had cadmium (Cd) and Pb levels of 6.52±0.90 and 25.0±1.85 mg/kg, respectively, exceeding the FAO limits (Cd: 0.5; Pb: 2 mg/kg) (Arisekar et al., 2022). Despite the potential health benefits of consuming shrimp, concerns have been raised about the presence of chemical pollutants in these food products, particularly for individuals who consume shrimp regularly due to the harmful effects on shrimp health and the associated carcinogenic and non-carcinogenic risks (Martorell et al., 2011; Sarkar et al., 2016 b). The FAO and WHO have established the maximum recommended limits for each heavy metal (Table 5) to mitigate the potential health risks associated with heavy metal contaminations.

Table 5. Maximum recommended limits for each heavy metal for human consumption (mg/kg)

Heavy metals	Maximum amounts advised for human consumption (mg/kg)
Cd	1
Fe	100
Ni	1
Cr	0.05
Pb	2
Zn	100
Mn	1

Source: from Biswas et al., 2021.

Humans are most exposed to heavy metals through their diet, particularly seafood, although other sources such as water, air, and soil can also play a significant role (EFSA, 2010). The recommended daily allowance (RDA) for heavy metals such as Zn (8.0 mg/day for females, 11.0 mg/day for males), Cu (1.0 mg/day for children, 10.0 mg/day for adults), Cr (VI) (0.035 mg/day), Pb (0.005), and Cd (0.025 mg/day) is relatively low for humans (Sarker et al., 2023 a). These heavy metals play a crucial role in supporting various oxidation-reduction reactions in animals, as well as other biochemical and physiological activities (Latif et al., 2020). Heavy metals can enter the human body through various pathways, including respiration, skin contact, and intestinal absorption. Excessive intake of heavy metals, leading to abnormal human metabolism, can be attributed to their interaction with diffusing ligands and macromolecules, resulting in bioaccumulation, biomagnification, and eventual integration into the marine food chain (Sarker et al., 2023). While the absorption of heavy metals in elemental forms is limited, organometallic forms exhibit lipophilicity and can easily pass through membranes, including the blood-brain barrier (BBB), which acts as a protective barrier for the nervous system (Missel et al., 2016). Once heavy metals are absorbed into the body, they can be distributed extensively throughout various organs, including glands and the central nervous system (CNS). Some heavy metals are known as "bone seekers" and can accumulate in dental and skeletal structures (Pandey and Madhuri, 2014). The accumulation of heavy metals in the body's tissues can lead to chronic illness and have harmful effects on public health (Amirah et al., 2013). These metals have the potential to cause toxicological harm to various organs in both humans and animals (Fu and Xi, 2020). While some metals are essential for life, others can be highly toxic or become toxic in high concentrations. Prolonged exposure to heavy metals above safe levels, such as aluminium, copper, chromium, nickel, iron, arsenic, cadmium, lead, and zinc, can have serious consequences for both humans and animals. These effects may include osteomalacia, headaches, increased red blood cell production, liver damage, reduced lung function, neurological issues, renal tumour formation, kidney dysfunction, gastrointestinal problems, impaired cognitive development, hypertension, and reproductive issues (Hashempour-Baltork et al., 2023; Jaishankar et al., 2014). Heavy metals can also disrupt enzyme systems, leading to the production of harmful free radicals and competing with essential components of metallo-enzyme complexes, which can hinder the absorption of vital minerals (Mukherjee et al., 2023). Overall, heavy metals cause cellular toxicity and can render essential minerals inaccessible to the body, resulting in illness and disease. Figure 3 illustrates the cycle of heavy metals through the food chain, highlighting the health risks posed to both humans and animals.

Treatment and removal of heavy metal pollution in shrimp production

Shrimp have high edible and economic value, but the problem of heavy metal pollution has become a bottleneck in its development. They provide substantial harm and hazards for humans as well as aquatic

fauna and flora when they are released into the water environment. They also severely degrade and tend to accumulate in living organisms (Xu et al., 2019). As a result, the treatment of wastewater that heavy metals have contaminated has become essential, thus, the global concern for the treatment of wastewater containing heavy metals has led to the need for effective and efficient solutions. Heavy metals like Cd, Ni, Cu, Hg, and Pb cannot degrade; hence, the only way to eliminate them is to alter their modes of existence and forms of transformation (Gu et al., 2018). Two of the most crucial mechanisms for regulating the quantities of aquatic pollutants are accumulating contaminants present in the sediment of aquatic environments and remobilizing those compounds. It becomes very expensive and technically challenging to remove heavy metal contaminants from water and aquatic sediments (Ogemdi, 2019; Rai, 2009 b). There are several technologies available to reduce hazardous metal ions in water. Physiochemical techniques such as filtration, reverse osmosis, precipitation, ion exchange, and physical adsorption are often utilized to treat heavy metals (Khulbe and Matsuura, 2018). The development of affordable and environmentally acceptable techniques to successfully remove heavy metals from water is urgently needed in light of the drawbacks of conventional physiochemical approaches (Wołowiec et al., 2019). Bioremediation techniques, including phytoremediation, myco-remediation, bioaccumulation, bacterial bioremediation, bio-reduction, and biosorption, are regarded as cost-effective and environmentally friendly (Singh et al., 2022). Researchers have been trying to find a solution to this issue by improving the removal of industrial wastes, monitoring the pollution of water products by heavy metals, and temporarily purifying the water. However, these methods only alter the condition of the metals and do not have a substantial impact on enhancing the efficacy of their removal. The study of the technique for removing heavy metals is now a research hotspot because of the preliminary advancement in our understanding of the process by which heavy metal contamination occurs. The removal techniques include hydrolysate removal technology, *in vivo* removal technology and aquatic raw materials.

***In vivo* removal technology**

Shellfish water purification technology

Heavy metals substantially contaminate shellfish water products because of their poor mobility and filter-feeding characteristics. The live-weight metal purification device is now the most often documented method of temporary shellfish purification. The basic technique involves temporarily raising shellfish in a static clean water environment (Lee and Younger, 2002). Shellfish may excrete the heavy metals through their metabolic processes, decreasing the level of heavy metals in the body to comply with safety regulations. However, the outcome is poor if the loss rate throughout the holding process surpasses 50%. Relevant specialists have adopted the method of adding some bait to the temporary seawater, which is adding bait to remove heavy metals to limit the decline of nutrients in shellfish owing to metabolic losses and increase purifying efficiency.

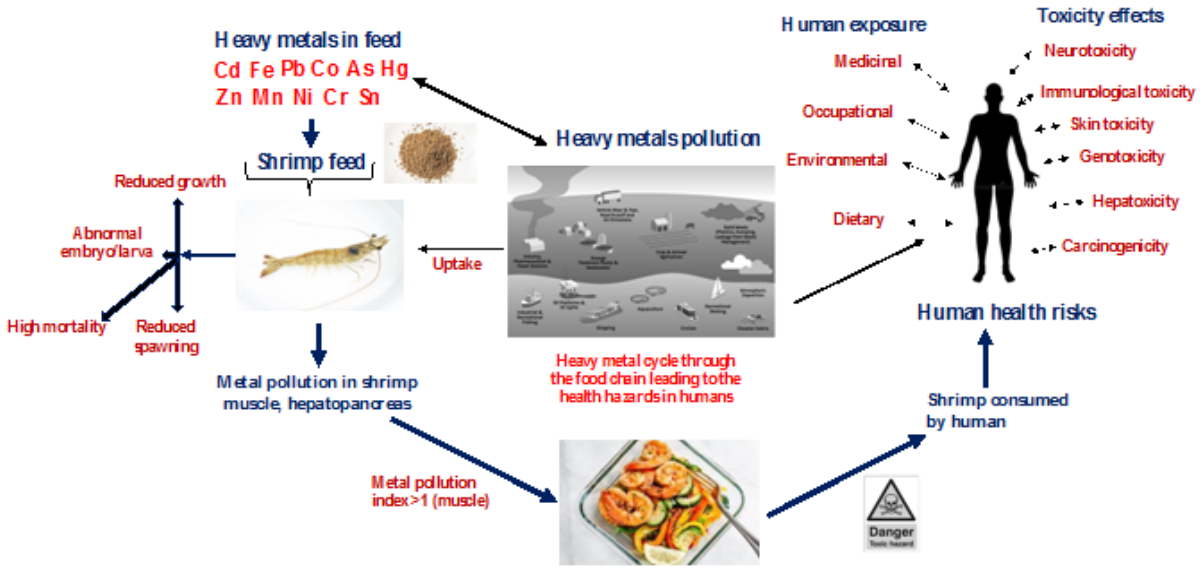

Figure 3. The potential risks associated with heavy metal contamination in the food chain, specifically from shrimp to consumers

Add bait removal technology

Single-celled algae, such as golden algae, flat algae, etc., are commonly used bait feeding shellfish (Wang et al., 1998). The cell walls of algae carry a certain amount of negative charge. They provide functional groups such as hydroxyl, carbonyl, imidazole, phosphate, and thiol. In addition to binding to metal ions, they can boost the vitality of crustaceans. Bere et al. (2012) investigated the accumulation capability of circumferential algae for Cr, Cd, and Pb storage. Seaweed adsorb Cu^{2+}, Pb^{2+}, and Cd^{2+} from wastewater (Feng and Aldrich, 2004). Cu had an adsorption capacity of 85–94 mg/g, Pb 227–243 mg/g, and Cd 83.5 mg/g. Jiang et al. (2006) developed a technique to purify heavy metals in bivalve shellfish. Microalgae were repeatedly added to the body of water where the bivalve shellfish were reared, and after a 2–31-day purification process, 38% to 52% of the heavy metals could be removed. Other related studies increased the amount of Vc in the input bait because Vc promotes the discharge of heavy metals such As and Pb in aquatic products (Huang et al., 2012). Therefore, heavy metals may be purified and eliminated by adding bait. However, relevant studies suggested adding specialized adsorbents due to this method's low efficiency and short purification time.

Adsorbent removal technology

Application of EDTA

According to Koen et al., 2023, the chelation of copper and manganese ions by ethylenediaminetetraacetic acid (EDTA) is likely responsible for its beneficial effects. Chelation decreases the free concentration of these ions, thereby diminishing their toxicity. In the absence of EDTA, concentrations of copper (0.2 μM) and manganese (2.0 μM) ions lower the proportion of nauplii that transform into protozoa. In the presence of EDTA, the proportion of nauplii that transform into protozoa increases for nauplii exposed to copper and manganese ions. In other research, seawater was treated with 0.5% EDTA to eliminate heavy metals from farmed oysters. Pb levels in oysters also showed a considerable decline after two days, indicating that EDTA salt may, to a certain extent, remove heavy metals from aquatic products and enhance saltwater quality. Studies have shown that when a certain quantity of EDTA is ingested, there is a minor irritation of the skin, eyes, etc., prompting some researchers to seek a healthier adsorbent.

Application of algin-metal complex

Algae are utilised as biosorbents to remove harmful heavy metals because they have a high capacity for biosorption (Ismail and Moustafa, 2016). Several types of cyanobacteria and algae can remove or degrade hazardous metals (Cirillo et al., 2012). The great photosynthetic activity of algae may be responsible for the enormous amounts of dissolved oxygen made available in aquatic environments, which led to the aerobic breakdown of several organic substances, including hazardous metals. Heavy metals and other harmful chemicals can be degraded, detoxified, and converted through various enzymatic and metabolic processes in algae's metabolism. Cell walls also play a big part in eliminating toxic heavy metals through a biosorption mechanism (Kumar et al., 2021). Other researchers used calcium alginate and synthetic calcium alginate/calcium pectinate (1:1) gel pellets to remove soluble copper and cadmium from aquaculture water. The results showed that the gel pellet mixture mixed with 2% alginate and 2% pectinate could remove 45.61% Cu and 40.55% Cd. The removal of heavy metals from shellfish is facilitated by the addition of algin, a metal complex, to the resting saltwater.

Addition of chitosan and its derivatives

Chitosan, also known as deacetylphthalein chitin, is a naturally occurring substance that is non-toxic and contains functional groups like hydroxyl and amino groups that may form complexes with metal ions to form one of the main structural components of the exoskeleton of crustacean shrimps. Chitosan may be easily changed to generate various chitosan derivatives that produce complex functional polymers with exquisite features that are significantly different from those of synthetic polymers because of free hydroxyl and amine groups (Kurita, 2001). Chitosan polymer flocculants that have been altered are utilised with specific methods, like grafting, to efficiently carry out the process of heavy metal chelation and capture (Yang et al., 2016). These techniques also enhance the hydrophilic characteristics of chitosan and its ability to bind and retain heavy metals. According to Mohammed et al. (2013), deproteinization with 5% NaOH and demineralization with 1% HCl may be used to successfully remove chitin from shrimp shells. There have been many reports on applying chitosan and its related derivatives to remove heavy metals where a nano-feed additive was used; the primary material contains chitosan, which effectively removes heavy metals and decreases the concentration of heavy metals in water-producing objects.

Research on the chelation and adsorption of heavy metals by naturally modified products suggests that the effectiveness of high molecular compounds in removing heavy metals can be significantly enhanced through carboxylation, hydroxylation, acylation, and other derivation reactions (Teh et al., 2016). Scallops are purified using COS-Mg and COS-Ca complexes, which lower the amount of Cd, COS-Ree, and COS-Zn. Additionally, Cd responds effectively to the two compounds (Liu and Wang, 2011). The need for chitin-chitosan increased, leading to the continuous processing of shrimp shells to become chitosan to avoid forming potential waste that could pollute the environment, as well as the potential for heavy metal contamination in the environment can be overcome by the use of chitosan modification or chitosan of activation for heavy metal ion absorption (Sarkar and Majumdar, 2011). The utilization of chitosan can drastically reduce the cost of synthetic source materials

because it is an easily accessible natural polymer resource.

Aquatic product hydrolysate removal technology

This technology makes aquatic product tissues into homogenate or enzymatic hydrolysate and uses chemical, biological, and physical methods to remove the heavy metals contained in the homogenate or enzymatic hydrolysate. The following describes four removal techniques: filtration removal, charge exchange, flocculation, and increased adsorption.

Filtration and removal technology

Heavy metals can be removed using various membrane filtering methods, each optimised for a specific particle size range. There are a few distinct categories, such as microfiltration (MF), ultrafiltration (UF), reverse osmosis (RO), and nanofiltration (NF).

Ultrafiltration (UF) is commonly employed at relatively low levels of transmembrane operating pressure (TMP). The size of UF membrane holes may exceed that of heavy metal ions, thereby necessitating the bonding of additives to metal ions to increase their size. Hence, polymer-enhanced ultrafiltration (PEUF) and micellar-enhanced ultrafiltration (MEUF) are suggested. Li and Wang (2013) ultra-filtered the enzymatic hydrolysate after sieving it repeatedly through 100 mesh and 300 mesh sieves at ambient temperature. The enzymatic hydrolysate's lead concentration was 3.917 ng/mL before ultrafiltration, and the atomic absorption graphite furnace did not detect the lead content after ultrafiltration. This indicates that ultrafiltration may significantly lower or even eliminate the lead content of an enzyme hydrolysate. Nanofiltration (NF) is employed to concentrate components that possess a molecular weight above 1000 Da and remove solutes with a size between 0.0005 and 0.007 μm, as long as their molecular weights are above 200 Da (Wang et al., 2011). Therefore, nanofiltration (NF) functions within the operational range bounded by reverse osmosis (RO) and ultrafiltration (UF) technologies. Microfiltration (MF) eliminates particles, including micron-sized particles, viruses, pollutants, bacteria, contaminants, protozoa, and other substances, from a solvent, fluid, or solution by means of a microporous membrane. The MF process is a membrane process that operates under low-pressure conditions, with membrane holes typically ranging from 0.1 to 10 μm (Wang et al., 2011). Reverse osmosis is a pressure-driven separation method that allows only smaller molecules to pass through a semipermeable membrane with a pore size of 0.5–1.5 nm. By providing pressure (20–70 psi) over the osmotic pressure of the feed solution, the RO process reverses the typical osmosis process. The solutes that are inhibited typically have molecular sizes between 0.00025 and 0.003 μm (Wang et al., 2011). Filtration may be employed as a more effective supplementary removal technique, thereby significantly increasing the removal rate of heavy metals.

Ion exchange removal technology

Ion exchange resin is a unit operation that belongs to the mass transfer separation process by using the ion in the resin to exchange with the metal ion in the dilute solution to extract or remove the relevant ions in the solution (Dąbrowski et al., 2004). Eliminating a heavy metal ion from a wastewater solution involves binding the ion to an immobile solid particle, therefore substituting the cation of the solid particle. Solid ion-exchange particles can consist of natural materials, such as inorganic zeolites, or manufactured materials, such as organic resins. The ion-exchange technique can eliminate specific heavy metal ions, including Cu^{2+}, Cd^{2+}, Cr^{3+}, Cr^{4+}, Zn^{2+}, V^{4+}, V^{5+}, Hg^{2+}, Pb^{2+}, and Ni^{2+}, from wastewater (Dąbrowski et al., 2004). Han et al. (2005) used a cross-linked cationic starch chelating agent to remove heavy metals in a dissolved state, and the results showed that the removal rate of Cu^{2+} and Pb^{2+} reached more than 95%, and it also had a good removal effect on Cd^{2+} and Cr^{3+}. Ion exchange allows for the separation of compounds or the removal of all ions from a solution. As a result, total deionization and selective ionic pollution removal may be differentiated. The decision between the two is mainly influenced by the solution's composition and the level of decontamination needed.

Flocculation removal technique

The main methods of flocculation removal involve destroying the system's stability through electrostatic adsorption, electrical neutralisation, bridging, adhesion, and cross-linking, which causes the particles to aggregate into large particles that are then separated by gravity settlement. The flocculation process involves adding one or more flocculants to wastewater that contains heavy metal contamination. This technique depends on flocculation agents, neutralisation, the adsorption bridging effect, or chelate precipitation (He et al., 2018). Flocculation is a popular, effective, affordable, and practical technique for removing heavy metals (Al-Saydeh et al., 2017).

Heavy metals cannot be degraded, in contrast to common contaminants that may be eliminated by oxidative breakdown. Through flocculation, dissolved heavy metal ions and compounds on the surfaces of suspended solids or colloidal particles may be removed using the right flocculants (Wang et al., 2016). Flocculants can be categorised as organic, inorganic, or microbiological. Some examples of common flocculants include cake acid, gelatine, and chitosan. Chitosan possesses surface groups in its macromolecular structures, allowing it to function as both a flocculant and absorbent for the purpose of eliminating heavy metals (Yang et al., 2016).

Adsorption removal technology

The physicochemical properties of the heavy metals and the adsorbent material, as well as a variety of operational factors like temperature, the amount of adsorbent employed, pH level, adsorption duration, and the initial concentration of metal ions, all influence the adsorption

mechanism. Adsorption using different types of adsorbents is widely recognised as a highly efficient and convenient approach for removing heavy metals in advanced wastewater treatment. This method is favoured due to its strong affinity for heavy metals and relatively low operational costs (Ighalo et al., 2021; Mou et al., 2021; Zhulquarnain et al., 2018).

The process of adsorbing heavy metal ions causes the wastewater's metal ions to stick to the surface of nano-porous adsorbents, which have a large surface area because of their porosity. One or more metals may be preferred over others during the adsorption process. A desorbing agent might be used to facilitate the regeneration process. Various adsorbents have been utilised to remove heavy metals from wastewater. These adsorbents include carbon-based compounds (Karnib et al., 2014), polymers and resins (Onyekachi and Iwuozor, 2019; He et al., 2017), clays and minerals (Tsai et al., 2016), as well as nanoparticles and nanocomposites (Iwuozor et al., 2022 b).

Physical and mineral adsorption

Physical adsorption includes the zeolite, silica, clay and activated carbon adsorption methods, which are considered viable water purification options due to their suitable attributes and cost-effectiveness (Gabaldón et al., 1996). Zeolite has a rack-like structure, and zeolite adsorption is mainly carried out by ion exchange or surface complexation for the adsorption of heavy metals (Li et al., 2017). Clay has remarkable characteristics such as exceptional cation exchange capacity (CEC), selectivity in cation exchange, hydrophilic surface properties, significant swelling and expansion ability, and surface electronegativity (Zhang et al., 2021). Activated carbon adsorption is through the exchange of ions and heavy metal ions on the surface of activated carbon; the second is the electrostatic interaction between the surface of activated carbon and heavy metal ions. The predominant processes governing wastewater treatment using mineral adsorbents have been determined to be chemical adsorption, physical adsorption, and ion exchange, as demonstrated by several research studies. In addition to the parameters previously discussed, the pH, temperature, adsorption duration, and adsorbent dose are all recognized as crucial factors governing the adsorption process. The effectiveness of adsorption removal is positively correlated with an increase in pH and a drop in starting concentration (Alshameri et al., 2019).

Chelating resin adsorption method

Chelating resin is a polymer material that can form a multi-coordination complex with a crosslinking function with metal ions. The underlying adsorption mechanism involves creating a chelate complex with a compact structure, achieved by coordinating functional atoms and metal ions present in the resin. The chelating resin has a high affinity for metal ions, resulting in binding solid interactions. Yu et al. (2011) examined the adsorption activity of superabsorbent resin towards a solution containing heavy metal salts. The researchers found that the resin exhibited varying adsorption capacities for different heavy metal ions, with the highest capacity observed for Pb^{2+}, followed by Cd^{2+}, Cu^{2+}, and Ni^{2+}. The corresponding adsorption capacities were measured as 331.80, 182.82, 165.79, and 23.89 mg/g, respectively. These results indicate the resin's effective removal capability for heavy metal ions.

Complexation involves using complexing agents to effectively eliminate heavy metals by using their chelating capacity. Succinic acid and citric acid are widely recognized as prevalent complexing agents. In Tao (2012) study, Cd components were extracted from clam flesh using citric acid. The results showed that the extraction rate of Cd from Martensian mother-of-pearl homogenate was determined to be 92.2%. In a study conducted by Al (2007), it was shown that adding humic acid to the mussel cooking liquid at a volume ratio of 0.7% to 1.0% resulted in a significant reduction in Cd level by 95%.

Conclusion and recommendation

This review evaluates the quality of aquatic systems concerning acute and chronic metal contamination. Toxic metals in marine environments are frequently documented as a prevalent contamination. It is of utmost importance to ascertain the consequences of these pollutants to safeguard both the ecosystem and human well-being. The aquatic ecology is most significantly threatened by heavy metal ions such as Fe, Cu, Cd, Pb, and Cr.

Heavy metals play a crucial role as essential ingredients in facilitating the regular growth and development of the human body. Population growth has led to increased pollutants such as industrial and medical waste, which often contains large amounts of heavy metals, the discharge of which contributes to water pollution that harms aquaculture. Excessive intake of heavy metals can lead to reproductive complications, physical deformities, and even threats to survival in shrimp, and relevant research on heavy metals should be continuously deepened. Bioaccumulation levels varied by species, metal type, and sampling site. It is concluded that the mortality rate, malformation rate, oxidative stress, moulting, and reproduction increase with increasing concentrations of toxic metals identified in this study. This review provides a comprehensive overview of the biological techniques employed in removing heavy metals, encompassing both metabolically dependent and independent approaches. It also examined the sources of heavy metals and their associated harmful effects. This work enhances our comprehension of the development of efficient biological wastewater treatment systems.

The presence of these heavy metals caused significant abnormalities in several aquatic organisms, which ultimately represent a significant danger to the organisms that consume them. To enhance the long-term viability of the aquaculture industry and ensure the production of safe shrimp for human consumption, the relevant

authorities at the local, state, and national levels must conduct regular monitoring of both the shrimp and their surrounding environment. An expedited development of a robust framework is needed to alleviate this significant issue. The heavy metals that have been extensively studied in the literature include Cd, Ni, Zn, Cr, As, Cu, and Pb. Only a limited number of studies have documented the impacts of other heavy metals, such as Fe, Sn, Se, Hg, and Co, on shrimp. Future studies should focus on closing this gap, particularly with non-essential metals that pose a threat to shrimp at any concentration.

Authorship contribution statement

Asare Derrick – original draft; conceptualization; data curation; writing; review and editing of the manuscript. Mpwaga Alatwinusa Yohana, Zheng Yudong, Li Gongyu, and Beiping Tan – review and editing. Shuang Zhang – conceptualization; supervision, review and approval. All the authors have approved the manuscript for publication.

Declaration of competing interest

According to the authors, this review has no conflict of interest.

Data availability

Data will be available upon request.

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