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Impact of heavy metal pollution on the growth and reproduction of marine fish

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Abstract

Marine ecosystems are highly sensitive to human activities, and growing industrial shipping practices has exacerbated the risk of heavy metals inflicting even more damage on the already weakened habitats. Heavy metals adversely affect the reproductive functions of marine fish species which leads to a staggering impact on the ecosystems. The objective of this research is to understand the level of bioaccumulation of the noxious heavy metals like mercury, cadmium, lead, and arsenic within marine fish and analyze their impact on the reproductive physiology and functions of the fish. Environmental studies have shown that chronic exposure of these metals to the environment causes dysregulation of endocrine systems, impaired gonad morphogenesis, and decreased embryo and larval survival resulting in significant risks to global fish populations and biodiversity. The analysis provided through the mentioned techniques outlines the clear implications for fisheries and consumer safety due the imbalanced vulnerability to different species at various tissues and levels of bioaccumulation. The ramifications suggest immediate modification of maritime policies like alteration of industrial emission zones adjacent to coastal ecosystems and decommissioning of shipping lanes in close proximity to industrial ports. By channeling these efforts, sustainably integrating them into maritime ecological evaluation through strategic frameworks can exponentially assist in the preservation of biodiversity and establishing a steady economy.

Keywords: Heavy metals, Marine pollution, Fish reproduction, Growth inhibition, Bioaccumulation, Marine ecosystems, Ecotoxicology

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Introduction

Heavy metal pollution involves the contamination of the environment due to the presence of harmful elements in metals that are toxic even in small quantities. The heavy metals that are most frequently found in marine ecosystems include mercury (Hg), cadmium (Cd), lead (Pb), and arsenic (As) which stem from industrial discharges, mining runoff, agricultural activities, and maritime activities (Ali *et al.*, 2019). These pollutants are persistent, non-biodegradable, and have the ability to bioaccumulate in marine sediments and organisms (Wuana and Okieimen, 2011). In marine ecosystems, heavy metals have considerable toxicological effects as a result of their incorporation in the food web through the capture and ingestion of plankton and benthic organisms by predatory fish (Shridhar and Udayakumar, 2024). These metals inflict oxidative stress, cellular injury, and disruption of metabolic activity in fishes (Rajeshkumar and Li, 2018; Hussain and Taimooz, 2024). With time, chronic exposure causes diminished biodiversity, imbalance and alteration of population dynamics, and disruption of equilibrium in the ecosystem (Zheng *et al.*, 2008; Sharma and Maurya, 2024; Ngu and Amran, 2018). The ecological repercussions of marine contaminants pose significant threats to the health of coastal communities and the enduring sustainability of fisheries worldwide. There is a sea of changes that needs to be implemented in pollution control policies based on ecotoxicology studies for effective strategy building in resource management, particularly to combat the alarming decline of fish populations (Roy *et al.*, 2024; Ismail *et al.*, 2016). Accumulated toxins in contaminated seafood through bioaccumulation can have dire repercussions for human health, especially considering that a plethora of species is harvested commercially (Burger and Gochfeld, 2005). Understanding the ecological risks is crucial to protect marine-based economies and food security. Throughout the years, researchers have documented the impairments in reproductive health-related to toxic metal accumulation such as hormonal imbalance, severe gonadal degeneration and offspring viability issues, as Atli and (Canli, 2008) describes. Furthermore, mercury and cadmium accumulation is associated with reduced sperm motility and oocyte developmental capabilities, leading to degenerative embryotoxic impacts (Gupta and Rajbanshi, 2020; Ikechukwu *et al.*, 2019). This not only reduces the vitality of larvae, but also disrupts the nutrient assimilation process, increasing mortality during development. Prolonged exposure at any stage is detrimental to growth rates (Pane *et al.*, 2004). Heavy metals are absorbed through the skin, gills, and even the gastrointestinal tract, severely affecting marine fish.

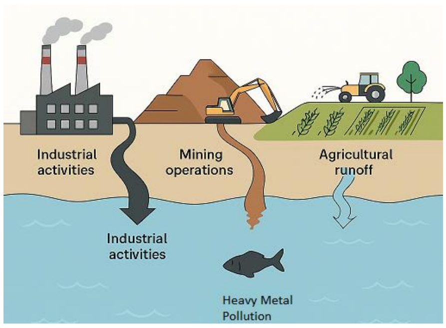

Figure 1: Sources of Heavy Metal Pollution in Marine Environments

Figure 1 provides a detailed snapshot of the human-induced activities and processes which act as profound sources of heavy metal pollution found in coastal and marine ecosystems, namely industrial processes, mining systems, and agricultural activities. Industrial plants are represented on the left side of the figure with a smokestack on the facility's roof capturing belched pollution, alongside oil refineries waiting to discharge liquid industrial waste into the sea through pipes. These wastes invariably contain lethal metals as cadmium, lead, and mercury. In the center, mining disciplines are depicted with retaining walls on a plateau above the water body, and enormous bulldozers pouring heavy metal-rich sands into water bodies in surface runoff. During precipitation and erosion events, processes of this sort tend to transport deadly metals like arsenic and nickel into water bodies. The right side of the figure depicts agricultural fields with a tractor applying chemicals, signifying the application of fertilizers and pesticides that indiscriminately wash into streams and rivers. Such compounds conspicuously contain metalliferous residues copper and zinc that invade water bodies from irrigation or seisures of precipitation. All three sources funnel their sluices into the sea where metals accumulate to form a dangerous concentration to life in the sea. It also features a fish cartoon inside the water body to show how these heavy metals are incorporated into the food chain and consequently topical marine ecosystems. This illustration also highlights the multi-faceted nature of human activities on land within a given region as well as their cumulative effects on the marine environment, thereby underscoring the necessity for comprehensive pollution management and environmental surveillance.

Sources of Heavy Metal Pollution in Marine Environments

Like other types of pollution, the pollution of the marine environment with heavy metals stems from many different human activities. They include industries, agriculture, and mining, which happen to be the most important ones. These undertakings introduce metals such as cadmium (Cd), mercury (Hg), lead (Pb), arsenic (As), and chromium (Cr) into the oceans and sea coasts, where they accumulate and remain. Industrial processes comprise some of the heaviest sources of contaminants for marine ecosystems: metal industrial waste have been identified in most coast near ecosystems. Coastal factories are a major source of this pollution because they tend to dump awful lot of polluting sewage water into rivers and seas (Ali *et al.*, 2019; Hartmann and Wendzel, 2022). Shipbuilding and repairing industry, textile industry, oil refineries, paint manufactures or upholstery leather industry are just a few examples of heavy metal polluters (Zhou *et al.*, 2008). In particular, the tanning and electroplating industries introduce chromium and cadmium while chemical and paint industries have mercury and lead to offer. Ultimately, shipyards and ports make other significant contributions to pollution as they discharge ballast water and use antifouling paints. Those substances become trapped in the sediment and may remain biologically accessible for long period of time, causing severe damages to ecosystems (Pan and Wang, 2012; Khyade, 2018). Such regions are coastal cities that are not strictly regulated environmentally. These cities are especially sensitive to pollution issues.

Mining activities both offshore and on the shoreline are significant sources of heavy industrial marine pollution. The erosion products of the shore, the mining overburden and mineral waste products, tailings and slurries, as well as acidifying wastewater all poison coastal waters and rivers (Ogunkunle and Fatoba, 2014). For instance, in the" Market" gold nuggets", on the blade gold mining and small gold mines (ASGM) mercury bowls and pipes oceans rivers mercury polluted abundant (Driscoll *et al.,* 2013; Chandravanshi and Neetish, 2023). Acid mine seepage resulting from sulfide minerals oxidation increases metal form and material mobility, further amplifying the existence of downstream coastal waters ecosystem pollution (Lottermoser, 2010; Vijay *et al.,* 2022). Research in regions such as Papua New Guinea and the Philippinein documented substantial for marine ecological destruction from copper and gold umming (Kocsis *et al.,* 2020).

The agricultural sector adds to the pollution of marine areas with heavy metals indirectly through industrial fertilizers, chemicals, livestock waste, and herbicides. Such products tend to contain heavy metals like arsenic, lead, and cadmium which find their way into water bodies via surface runoff, particularly during rainfall (He *et al.,* 2005; Abdullah, 2024). These pollutants eventually get transported and concentrated in the rivers, estuaries, and coastal regions. The expansion of coastal intensive farming poses direct risks to the pollution of marine ecosystems. Moreover, aquaculture facilities that apply medicated feeds and other supplements are potential sources of heavy metal pollution to nearby marine waters (Chen *et al.,* 2013; Choudhary and Reddy, 2025). The chronic exposure to such metals by marine organisms can compromise food safety and harm the ecological balance (Zakaria and Zaki, 2024; Kavitha, 2023). The Figure 2 shows the cascaded resultant effects of heavy metals on marine living wonders, depicting the entire sequence from exposure to ecological repercussions. Initially, toxins are discharged from industrial activities, agriculture, and atmospheric pollution, enabling heavy metals to infiltrate the water bodies. Marine fish become susceptible to these impairments through gill respiration, feeding, and marginally through the skin.

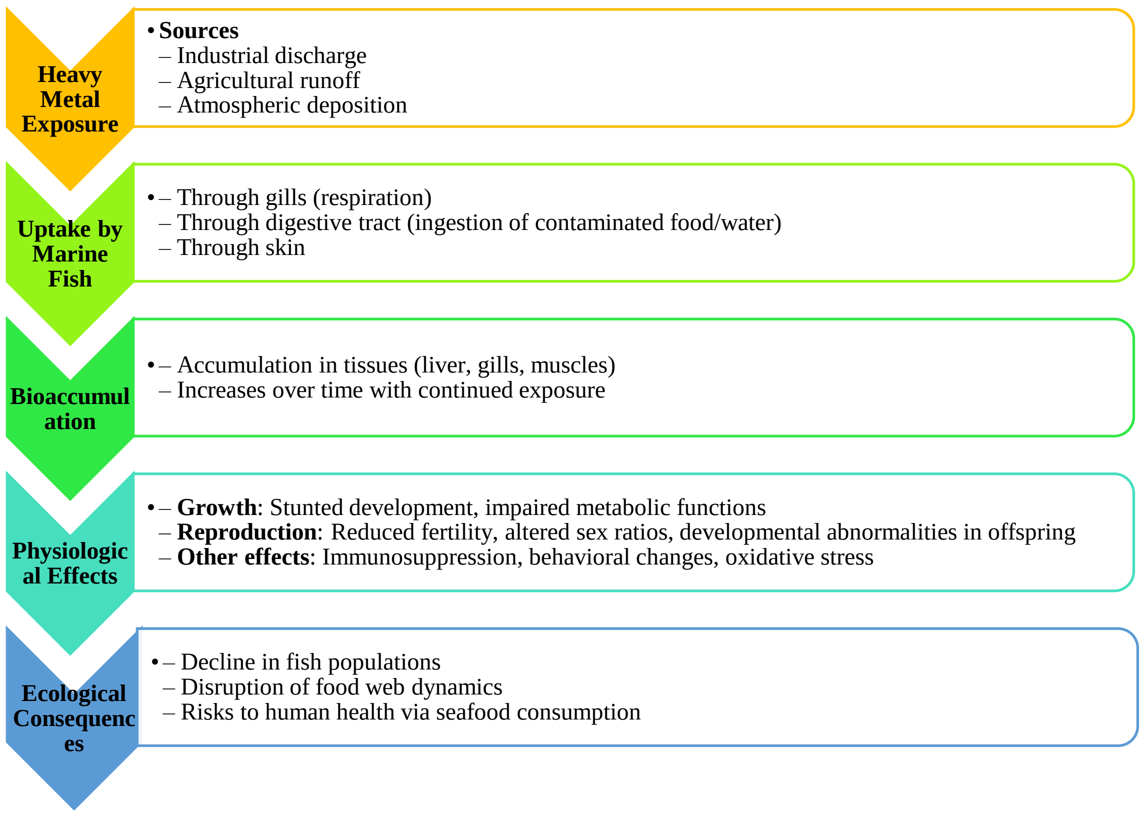

Figure 2: Impact pathways of heavy metals on marine fish.

Once these metals breach the biological barriers, they infiltrate the myriad of soft tissues such as the liver and gills, and even the muscles and slowly undergo the process of bioaccumulation. The metals eventually build up in an increasingly more toxic form with time. The metals will also induce many diverse detrimental physiological effects, some of which stunted growth, reduced and even negative fertility, copulatory skewing, and heritable morphological and functional correction deformities. Fish can be subjected to an array of other disabilities including immune suppression, active and passive behavioral alteration, and heightened oxidative stress. The invasive growth of these heavier burdens, will in the end is predicted to spell doom for the humans eating the marine fishes, biosystem equilibrium, and fish population drastically multiplies all along disrupting the marine ecosystem alongside human life, danger heavy contaminating metals.

Uptake and Accumulation of Heavy Metals in Marine Fish

Mechanisms of Uptake in Gills and Intestines

Little fish that are still forming their gills to the lungs undergo metals absorbtion in the delta and ocean areas. Skin seems to be the most productive part, surface area gaining oxygen on is borderline skin but for baby fishes. The main point the alive water organisms gether oxygen is water is concentrated is hyper salt water. Absorbation can occur through various means both active by propulsion, Calcium, sodium, or lighter metals. As concentration goes higher and higher. Ion increase absorption also pushes lungs stimulation pumps oxygen and blood increase, fully synchronized. Currency getting more extracted and goes lower circulates becomes shock goes into hyperactive stage. The intestines become a major route of entry when contaminated food or sediment gets ingested by fishes. Metals are passed through the intetstinal wall and infiltrated into the bloodstream as the fish processes food through the digestive system. Heavy metals may associate with proteins and amino acids within the intestines, thereby assisting in their transcellular transport. The degree to which metals are assimilated into the body is proportional to their chemical form, solubility, and interaction with other dietary constituents. After penetrating the body of the fish, heavy metals are transported throughout the body via the blood and primarily stored in the liver, kidneys, muscles, and brain. Considered the primary detoxifying organ, the liver usually harbors the greatest levels of metals, due to the active synthesis of metal-binding proteins like metallothioneins, which occurs in the liver.

Determinants of Tissue Build-Up

The extent and rhythm of heavy metal accumulation in marine fish is influenced constantly and differently by some biotic and abiotic factors. The most striking one is the species and age of the fish. A selection of species can control the intake of metals more effectively than others which leads to the variation in intake. Additionally, younger fish tend to absorb metals more readily than adults due to an increased metabolic rate and softer tissues. The feeding behaviors and trophic level of the fish in question are also important factors to consider. For example, carnivorous fish feeding on contaminated prey tend to accumulate more metals than herbivorous or omnivorous fish. Benthic feeders that eat sediment-dwelling animals as well as the sediment itself tend to be more exposed to metals in sediment. Accumulation also depends on environmental parameters such as metal concentration in the water or sediment, temperature, pH, and salinity. For instance, heavy metals in lower pH (acidic) waters are likely to be more soluble and therefore bioavailable. Moreover, changes in salinity are known to affect the form and ionic nature of metals, impacting the permeability of biological membranes. Another important consideration is the speciation or chemical form of the contaminating metal. Free ionic forms of certain metals tend to be more toxic and bioavailable than in organic or particulate bound forms. On the one hand, some metals that form complexes become more readily absorbed, whereas others may become less accessible for uptake.

Bioaccumulation and Biomagnification in Food Chains

An example of bioaccumulation is the gradual increase in concentration of heavy metals in an organism through its respiratory and dietary metals ingestion. Since heavy metals are so difficult to break down or excreted, their concentration is increased in a fish’s tissues especially in organs associated with detoxification and storage. Heavy metals tend to accumulate in an organism, sometimes in large amounts, thus increasing the risk of dysfunction within physiological processes. Biomagnification refers to the increase of heavy metal concentration at the higher trophic levels of a food chain. The heavier contaminated organisms undergo transference of metals to be accumulated in a larger predator's tissues. Usually predatory fish which sits at the top of the food chain, tend to accumulate the highest concentration of heavy metals in their bodies. This is not only a worrying process because of the ecosystem workings but also with regard to people consuming the seafood posed possible threats. Methylmercury formed in aquatic systems is an example of biomagnifying mercury is toxic for not only humans but when ingested by fish will severely alter the way it functions. Biological membranes are prone to being crossed easily so the mercury excreted proves harmful and results in severe neurotoxic effects for the fish and even higher organisms. As a whole, the absorption and accumulation of heavy metals in marine fish is a multifaceted combination of physiological, ecological, and environmental factors. Comprehending these processes is critical for evaluating ecological hazards and managing risks associated with marine life as food.

Effects of Heavy Metal Pollution on Growth of Marine Fish

An observable impact of heavy metal pollution in oceanic ecosystem is the reduction in fish growth rate. Heavy metals slow the growth of marine organism by interfering with the fish's capability to dissect and adequately utilize nutrients. Sublethal doses of metals over prolonged periods deplete energy that would otherwise facilitate developmental processes. In stressed environments, detoxification consumes growth potential. The result is clearly visible in juvenile fish in mid-growth phases who exhibit weight stagnation, shortened body length, and considerable delays in attaining growth milestones. Extreme cases of chronic exposed can render stunted growth which drastically reduces survival-fish's reproductive capabilities.

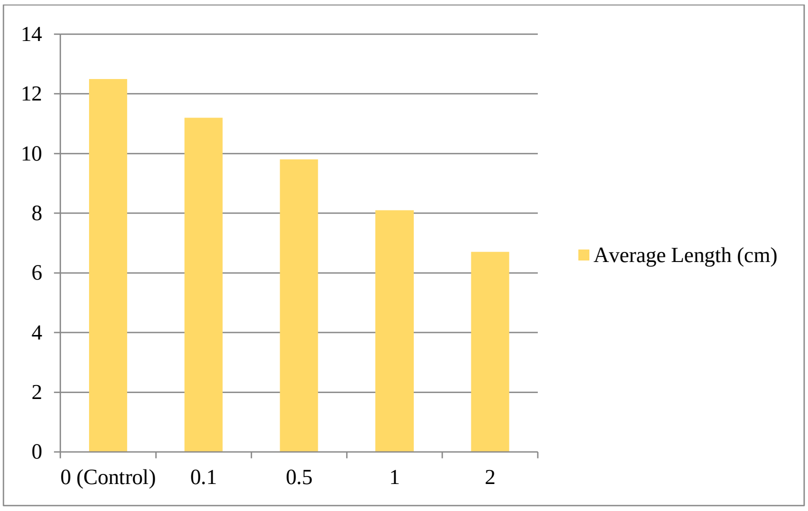

Figure 3: Average length of marine fish after 30 days of cadmium exposure.

The figure 3 shows the reduction in average length of marine fish after 30 days of exposure to increasing levels of cadmium (Cd) concentration. There is an apparent dose-dependent suppression of growth as the control group of fish reached an average length of 12.5cm, while those exposed to 2.0mg/L Cd only averaged 6.7cm. This measurement clearly indicates the somatic growth inhibition cadmium exerts on the animal, probably through perturbation of protein synthesis, nutrient uptake, cellular energy metabolism, and cell division. The data also suggests that even small concentrations of cadmium would severely undermine the physical growth of marine fish, which is alarming for their wild population as well as those cultivated in affected environments with deteriorating water quality. Figure 4 illustrates the activity of ATPase enzymes in different fish tissues at varying concentrations of cadmium. ATPase activity in the control group was already low, at 2.45 µmol/min/mg of protein, but at the highest exposure level it dropped to 0.41 µmol/min/mg. This ATpase activity drop of 2.04 is particularly alarming because it decelerates the work done by the enzyme to 1.8 USD per minute. This decline evidences severe energy exacerbation which is overwhelmed by the toxicity cadmium exerts on the biological system. Cadmium is known for clogging the energetic pathways of enzymes, respiration ladened mitochondria, and thus ATP yielditure. The drop in activity is suggestive of ATP responsiveness along with a strangle-hold on energy dependent processes that is poised to counterbalance heavily elevated metal intrusion, atlbsdueest needed fuel. The stage where bio energetics is outmatched daedtrically spelled doom for skeletal osseous power. Subsequently, immunodeficiency, stunted growth, and lack of physical activity drive fish behind osseous metal stress.

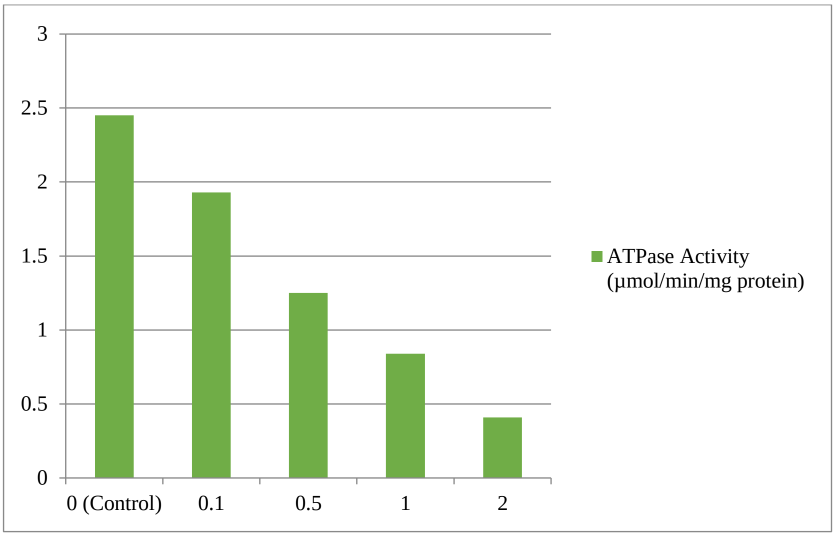

Figure 4: ATPase enzyme activity in fish tissues under cd exposure.

The Condition factor (K) or overall health of fish measured against their weight with respect to length is illustrated in the graph (Figure 5). With increasing cadmium concentration, the K value decreased from 1.55 within control conditions to 1.05 at maximum exposure. The cadmium exposure greatly reduces the fish growth, robusticity, and strength. Poor health, inadequate fat stores, and diminished growth are some of the aspects elaborated in declining K values. Condition factor is reduced is signifying adverse impacts. Prolonged exposure to cadmium may reduce food accessibility—fasten metabolism which causes body energies to be redirected from growth to detoxification activities and stress management. The graph (Figure 6) depicts the impact of cadmium exposure on the survival rate of marine fish over a thirty-day period. The control group exhibited full (100%) survival while, with increasing exposure, mortality increased steadily with progress, attaning only 58 percent survival at 2.0 mg/L. This trend unmistakably highlights the toxic and often fatal consequences cadmium drives most certain to inflict at higher concentrations. The reasons for the decline in survival rate is more than likely the result of overwhelming cumulative physiological stress, organ system disruption, and osmoregulative failure. Bypassing the rampant growth stagnation and metabolism depression wrought by cadmium mockery reveals true cadmium pollution reality, bringing forth the dire existence threatening plausible fish viability and population constancy in marked oceans.

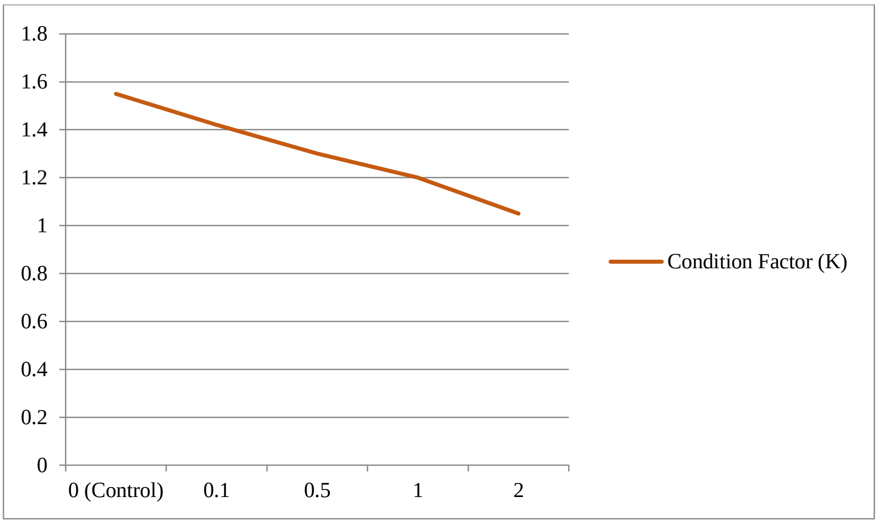

Figure 5: Condition factor (k) of fish after 30 days of cd exposure.

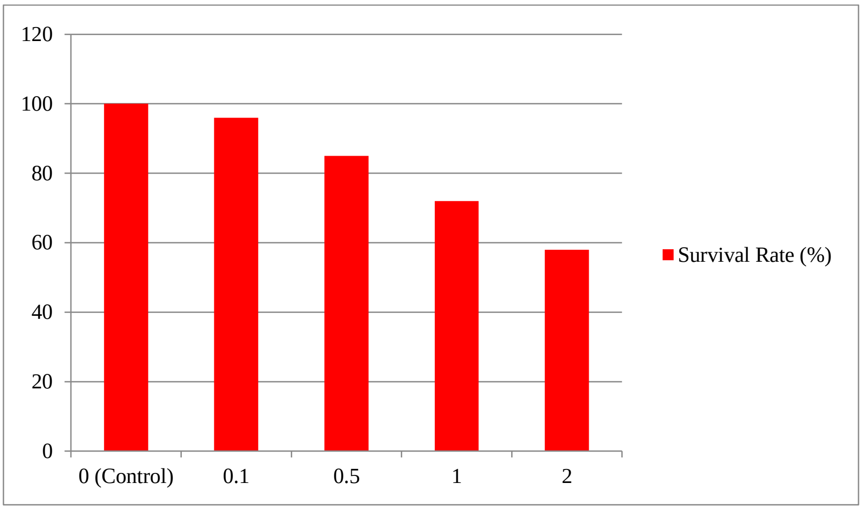

Figure 6: Survival rate of marine fish under varying cd concentrations.

Metals that are heavy interfere with multiple metabolic functions by hindering enzyme activity and physically damaging important organs like the liver and kidneys. Metals might block or make nonfunctional enzymes responsible for protein synthesis, energy generation, and ion regulation.

Decreased cell energy caused by reduced ATP production from mitochondria due to certain metals binding with cell structures will eventually lead to energy crisis on several levels. Reduced metabolic efficiency affects physiological performance, thereby reducing the capacity of the fish to grow, swim, and feed. Also, heavy metals can interfere with the regulation of some hormones, particularly those associated with growth such as Growth hormone (GH) and Insulin-like growth factor (IGF). Since these pathways are intermingled, endocrine suppression severely limits tissue development and protein synthesis, compounding the negative impact of growth. Metal induced oxidative stress due to excess production of reactive oxygen species (ROS) also inflicts damage on several components of a cell, like DNA, proteins, lipids leading to permanent changes in metabolism.

Heavy metal pollution has specific impacts related to growth and not only compromises the specific effects on growth but also affects the overall health and condition of marine fish. The poses individuals Showcases signosos of poor body condition suchpoor body condition as emaciation, discolored skin, fin erosion, and organ abnormalities, to mention but a few. Detoxifying metals may damage or enlarge internal organs, such as the liver, impairing various functions like digestion, immune response, and reproduction. Weakened immune systems render these fishes Vfirtered to more diseases, effectively eliminating their abilityto retreat with infections, as well as environmental stressors. Altered social interactions are combined with reduced predator evasion and feeding activity resulting from poor health. Taken as a combined phenomenon, and using desired fitness levels as a benchmark, these health declines reduce determined fitness and erode individual survival in polluted habitats. In our finishing, chronic and multi faceted cataclysm caused by heavy metal pollution with undermining essential metabolic activity allied to depleting, general health shipiac influence marine fish growth. The concentration of growth hindering, heavy metals is injurious to fish population dependent on marine biodiversity, food security, and fisheries posed significant challenges to global wide.

Effects of Heavy Metal Pollution on Reproduction of Marine Fish

Diminished Reproductive Functions

Heavy metal contamination on marine fishes by cadmium, mercury, lead and arsenic results into functional and structural deficiencies of the reproductive organs. These metals highly disturb the endocrine system which is responsible for secretion of hormones critical for gamete formation and maturation. With this, there is observable varied gonadal development with observable degeneration or underdevelopment of ovaries and testes, and intersex development where the fish exhibit both male and female sex organs. Metal contamination interrupts the normal balance of hormones causing heavy disruption in the delicate cycle of reproduction. Such endocrine disruptive activities might lead to underdeveloped sexual characteristics, subpar spermatogenesis or ovulation cycles resulting in decreased reproductive activity including the courting rituals and the physical act of spawning. In extreme situations, enduring elevated concentrations of metal over a longer period of time can lead to complete incapacity for reproduction.

Reduced Reproductive Activity

Both the ability to create usable sperm—fertility—and the quantity of eggs produced—fucndity—are directly inversely proportional to the existing levels of heavy metals in the ecosystem. In the case of female subjects, exposure to metals significantly decreases the number as well as the quality of eggs and in the case of male subjects, the motility and the overall morphological structure of sperms are adversely affected. The most troubling factor in all this is that these changes take place when the fish are in prime condition health wise, making detection extremely difficult. Annually, drops in the previously stated values combined with other factors leads to dips in the reproductive outcome of offspring and weak population resilience. The steady availability of resources in some areas aids to increase recruitment rates over time but poses a problem in commercial fisheries and conservative sensitive predatory species pushing further population decline.

Deformities and Death During the Larval Stage

The risk associated with heavy metal pollution now applies to baby fish. Metals ingested by the adult fish with the water significantly reduces their reproductive potential as their fishy head gets stuck permanently in a penny jar infested with water laced with toxic substances. These metals reach the eggs either through the yolk sac or the ambient water in close proximity to the egg. This water not only maintains the fish's body temperature but serves as a growth medium. This direct exposure has the potential to bring about changes in the skeletal structure and soft tissues, including but not limited to, the fins, vertebral column, head, heart, and nervous system. Fetal forms of life subjected to heavy metals tend to drown right after being “born”, faster than their sisters, but retaining unparalleled power to self-drown at alarming rates. Out of those who manage to “overcome” this challenge, many tout a spectacular demise waiting for them when they leave the confines and “soar” into the vast expanse due to impaired vision, reproductive prowess, and lack of motor skills. Overwhelming population demise during this initial phase of life is exceptionally detrimental towards maintaining stable ecosystems, creating striking disadvantages for population stability as the fathomless number of changes desired from nature in the generational cycle take immense time to translate reality with ease.

Mitigation and Management of Heavy Metal Pollution in Marine Environments

Management of Pollution from Industrial Activities

Implementing stringent regulations on industrial discharge systems is fundamental in controlling heavy metal pollution. Industries like metal processing, ship building, mining, and manufacturing heavily contribute cadmium, and other heavy metals into oceans and sea waters. Governments of countries with an ecological conscience need to enforce limits on discharges, which means industries need to treat their wastewater and make sure it is free from heavy metals before discharge into rivers, estuaries, or even the costal oceans. Permits along with environmental compliance audits will assist in monitoring whether industries are complying with discharge standards or not. Furthermore, adoption of "cleaner production techniques" wastes minimization aids in reducing toxic byproducts on creation. Holistic approaches of converting to non-toxic substitutes along with creating closed loop systems ensures wastes are recycled which aids greatly in aiding pollution.

Management of Historically Contaminated Datasets

In terms of areas historically contaminated by heavy metal pollution, each requiring a site specifuc remediation technique to effectively restore its ecological value while minimizing the threat posed to marine organisms, so, remediation could be physical, chemical or biological in relation to the level and type of contamination present. Dredging is an example of a physical method employed to lift sediments from the sea floor, and care must be exercised so that pollutants are not disturbed during removal. Chemical processes like the use of binding or stabilizing agents that treat metals to immobilize and limit their bioavailability in organic sediments pose less risk. In some situations, clean sediments or clays are placed atop contaminated areas in a cap type formation to walls off the contamination. Using microorganisms or plants to detoxify or sequester metals, also known as bioremediation, is an example of an emerging ultra-green technology. The use of seaweeds and seagrasses to sequester heavy metals phytoremediation is a promising development regionally. Using multiple methods can be very advantageous in areas with complex, heavily polluted settings.

Environmental Health Assessment Monitoring Programs

Emerging pollution threats must be detected, and mitigation efforts evaluated and monitored consistently to measure their effectiveness. Regular water, sediment, seawater, and marine organism sample collection for heavy metal quantification constitutes monitoring programs. They assist in pollution hotspot identification, tracking, assessing management needs, tracking over time, and ultimately leading to informed decisions. Mussels, oysters, and certain fish are some of the indicator species which can be used for biomonitoring. Such species help in understanding bioaccumulation patterns and ecological risk. Moreover, remote sensing, satellite data, and GIS tools allow for large-scale marine area monitoring, in combination with aforementioned methods, tailored towards biomass monitoring. Sharing monitoring data publicly enhances transparency and fosters accountability. By engaging the public with researchers and policymakers, a proactive and informed environmental management system can be constructed.

Conclusion

To summarize, the consequences of heavy metal pollution relating to the health risks and sustainability of marine fish species are extremely detrimental and concerning in maritime sectors and ecological balance. The destructive processes directed at nature by industries, for example, industrial wastes, mining, and agricultural activities are the main cause of dangerous metals like mercury, lead, cadmium and arsenic being present in oceans. These pollutants restrain development because of disruption of nutrient absorption and metabolism and reproduction due to hormonal disturbances, infertility, and deformities to the larvae. Physiological stressors of this nature increase the risk to the stability of marine food webs because they weaken fish populations and their resilience. Marine sectors like commercial fishing and aquaculture which greatly rely on productive marine ecosystems are at grave risk. The reduction in fish health and reproduction not only decreases the supply of fish from fisheries but also decreases food availability for coastal populations who depend on fish for sustenance. Therefore, urgent attention to the research that meets these needs for understanding the consequences that deal with time and species of fish with metal toxicity as well as the development of new technologies for the treatment of seawater and metals is needed. It is vital that conservation efforts concentrate on controlling the origin of the pollutants, reclaiming polluted areas, and establishing programs for ongoing monitoring of the environment. As previously mentioned, it is crucial for all maritime stakeholders, such as port authorities, the shipping industry, and coastal managers, to actively engage in resource preservation and pollution control. Pollution associated with shipping impacts flora and fauna, thus making it critical to combine maritime policies with ocean governance, to conserve biological diversity while enhancing the productivity of marine economy. Without prompt initiatives, pollution from heavy metals will further destroy marine ecosystems, jeopardize marine industries, and undermine efforts towards sustainable development within ocean-driven economies.

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