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Impact of Heavy Metals and Pesticide Contamination on Aquatic Environment and Fish Health: Challenges and Bioremediation Strategies

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Introduction

The environment is the space in which humans, plants, animals, and microorganisms live and operate. It consists of the land, the Earth's atmosphere, and water. The Earth's system is defined by four spheres: the biosphere (living things), the atmosphere (air), the lithosphere (land), and the hydrosphere (water), all of which function together in harmony. Environmental contaminants, often known as pollutants, are compounds that are found at higher levels than in any other part of the environment. (Masindi *et al*., 2018) Industrialization has increased rapidly during the last century. It has thereby raised the demand for reckless exploitation of the Earth's natural resources, exacerbating the global problem of environmental contamination (Gautam *et al*., 2016). Various pollutants, including inorganic ions, organic pollutants, organometallic compounds, radioactive isotopes, gaseous pollutants, and nanoparticles, have severely damaged the environment. (Walker, 2012) The term 'contaminant' broadly refers to any undesired alteration in the natural quality of water as a result of biological, chemical, or physical elements, including fertilizers, pesticides, plant diseases, microplastics, and toxic metals. (Bukola and Zaid, 2015).

Soil pollution

Soil plays a pivotal role in ecosystems (He *et al*., 2023). However, it is increasingly threatened by pollutants such as industrial and urban wastewater, solid waste, pesticides, fertilizers (Xue *et al*., 2020), livestock excretions, biological residues, and atmospheric fallout (Guan *et al*., 2019). Naturally occurring mineral deposits, as well as high concentrations of elements resulting from mineral disintegration and weathering, all contribute. These contaminants can cause diffusion zones in which the concentration of elements in the soil exceeds the natural background level, resulting in soil contamination (Cai *et al*., 2023). The 2030 Agenda for Sustainable Development, established at the United Nations Summit in New York, has 17 worldwide Sustainable Development Goals, several of which emphasize the importance of soil. For example, the "Zero Hunger" target emphasizes soil's role in supporting and regulating food security, nutrition, and sustainable agriculture. The "Clean Water and Sanitation" target acknowledges soil's critical role in managing the water cycle and sustaining water quality, and microplastics have been acknowledged as a significant environmental challenge.

Water pollution

Water is a critical resource for agricultural production and plays an important role in global food security (Food and Agricultural Organization of the United Nations, 2014). Waterborne pollutants in irrigation water can have a substantial impact on plant health, output, and operational efficiency. These concerns include lower growth, higher susceptibility to disease and plant mortality, loss of economic value, and increased treatment expenses. (Raudales *et al*., 2014). Within the agricultural sector, plant production nurseries are particularly at risk from waterborne contaminants due to their concentrated, polyculture production methods (Abdi and Fernandez, 2019). While many production nurseries use water treatment systems to eliminate contaminants, there is still a lack of understanding of the water quality dynamics, as well as the types and sources of contaminants found in recycled water, and how they affect plant health and productivity.

Water contamination is caused by two key factors: urbanization and industrialization. Metals are carried through runoff from villages, towns, cities, and industries, which accumulate in water bodies' sediments. Even if traces are carried to aquatic bodies, they may still be extremely harmful to humans and other organisms. Heavy metal toxicity is determined by a variety of factors, including the metal present, its nature, its biological role, the organism exposed, and the time period during which the organism is exposed. If one creature is harmed, the entire food chain suffers as well. Because humans are typically at the bottom of the food chain, this will have a greater impact on us because we will have accumulated more heavy metal as the concentration rises up the food chain. Both industrial and home pollutants are typically discharged into the sewage system.

Heavy metals

Heavy metals are regarded to be among the most harmful water contaminants. Still, 80% of untreated wastewater is discharged into aquatic bodies, including freshwater basins used for domestic purposes. This is causing global water stress as freshwater resources become increasingly scarce. According to a study, over 60% of the world's population will experience water stress by 2025. (Khalid *et al*., 2018). Heavy metals in wastewater are caused by a variety of naturally occurring events (such as volcanic eruptions) as well as manmade activities. Electroplating, textiles, dyes, mining, batteries, autos, and other industries all discharge heavy metals into the atmosphere. Heavy metals from these industries are discharged into the air, soil, and lastly into water bodies. Heavy metals such as mercury, lead, arsenic, nickel, chromium, titanium, cadmium, molybdenum, copper, zinc, nickel, manganese, iron, cobalt, boron, silver, and gold enter the food chain and accumulate inside the human body, causing negative effects on human health (Pacheco *et al*., 2020). Apart from human health, these pollutants have negative effects on flora and fauna. This environmental degradation increased the demand for remedial solutions.

Source of heavy metals

(Angon *et al.*, 2024).

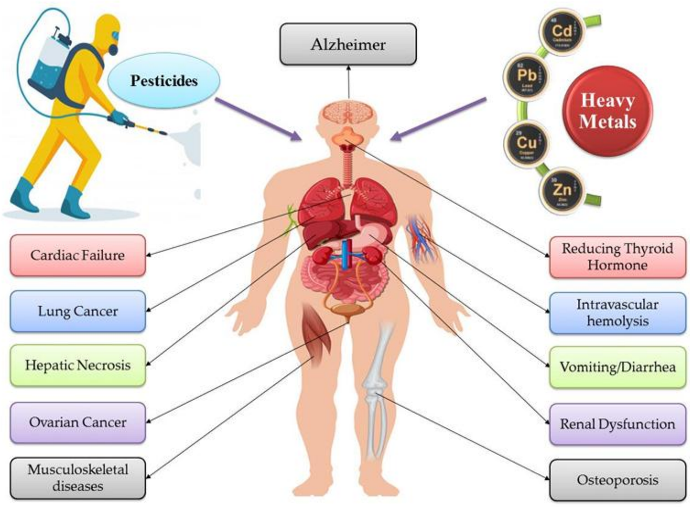
Heavy metals: sources and hazardous effects

Heavy metals are one of the most dangerous contaminants worldwide, causing environmental devastation. Heavy metals such as arsenic, lead, chromium, cadmium, mercury, nickel, silver, and uranium are released into the environment by industries such as batteries, automobiles, mining, and ore smelting, as well as agricultural waste such as fertilizers and pesticides. Recently, barium was added to the list. (Usmani *et al*., 2020). These are not biodegradable and have a negative influence on the entire environment. Heavy metals are utilized indiscriminately for anthropogenic purposes, altering biogeochemical cycles. The presence of excessive amounts of heavy metals in the soil, air, and water has a negative impact on the planet's natural diversity. Their accumulation in the environment promotes biomagnification. Heavy metals are also known to cause respiratory, renal, mental, and cardiovascular diseases, as well as cancer. In this section, we discussed the four most fatal heavy metals: arsenic, chromium, cadmium, and mercury.

Effect of pesticide and heavy metal toxicants on fish and human health

Fisheries and aquatic resources (ponds, rivers, streams, canals, seas, and oceans) provide people with long-term advantages. These are direct financial benefits that give employment, profits, and the ability to save money. Fish is an important human food source, as well as a crucial component in many natural food webs. Fish protein is higher quality than beef and poultry protein and is therefore healthier for human health. Fish is composed of 15-24% protein, 1-3% carbohydrates, 0.1-22% fat, 0.8-2% inorganic compounds, and 66-84% water (Ackman *et al*., 2012). Fish is an important part of the diet because it contains trace elements and calcium. It also contains calories and nutrients such as fat, vitamins, and minerals such as phosphorus, sodium, and trace elements. The aquaculture sector poses industrial dangers and raises safety concerns. Some practices have resulted in environmental damage. The public perceives farmed fish as "cleaner" than comparable wild fish. Some farmed fish have a far higher body load of natural and man-made harmful chemicals, such as antibiotics, pesticides, and persistent organic pollutants, than wild fish. The rules and international oversight for the aquaculture business are exceedingly complicated, with multiple agencies regulating aquaculture operations, including site selection, pollution control, water quality, feed supply, and food safety. (David *et al*., 2009).

Negative effects of heavy metals and pesticides toxicity on human health



Source: Alengebawy *et al*., 2021

Pesticide

The agriculture sector serves a critical role in sustaining human existence, but the ever-increasing global population is putting immense strain on the food supply based on the practice. (Sadowski *et al*., 2018). One of the most stringent agricultural operations is the use of insecticides to control pests and undesired plants and increase food yield (Alletto *et al*., 2010). They are necessary in agriculture to protect crops, but their use can have serious consequences for human health and the environment. Pesticides are chemicals used to exterminate a variety of pests that threaten crops, livestock, and overall farm productivity (Rani *et al*., 2010). Furthermore, they have versatile applications, serving as plant growth regulators (to stimulate or hinder growth), defoliants (inducing leaf or foliage shedding), desiccants (accelerating plant tissue drying artificially), and nitrogen stabilizers (inhibiting nitrification, denitrification, ammonia volatilization, or urease production by affecting soil bacteria). (Sabarwal *et al*., 2018). They include more specific herbicides, insecticides, weedicides, rodenticides, fungicides, piscicides, and so on. Pesticide contamination causes roughly 25% of worldwide soil deterioration and 30% of biodiversity loss in agricultural settings. (Midler *et al*., 2022).

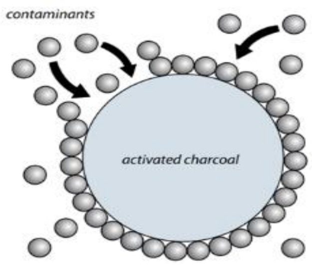
Classification of pesticides

Pesticides can be categorized into three categories based on their principal chemical constituents, namely, 1. Organochlorines 2. Organophosphates. 3. Carbamates. The main characteristics of them are summarized. Organochlorine pesticides (OCP), along with organophosphates (OP), carbamates, and synthetic pyrethroids (SP), account for 40% of all pesticides used in India. They are extremely bioaccumulative, resulting in biomagnification in the food chain and eventually in the food web. The biological toxicity induced by these chemicals is a major concern. Some noteworthy examples of such pesticides include dichlorodiphenyltrichloroethane (DDT) and its derivatives, dichlorodiphenyldichloroethane (DDD), dichlorodiphenyldichloroethylene (DDE), aldrin, dieldrin, polychlorinated biphenyl (PCB), hexachlorocyclohexane (HCH), etc.

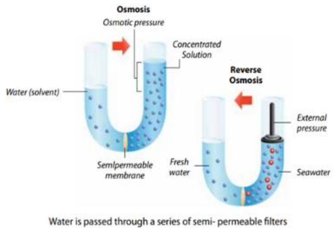
Environmental fate of the pesticides

Pesticides are found everywhere, including water (surface and ground), soil, sediments, air, and the tissues of species such as fish, birds, plants, and humans. Their entry, transport, and destiny in diverse environmental components such as soil, water, and air are influenced by several circumstances. Pesticides wind up in many sections of the atmosphere or in living creatures. Pesticides can wind up in sediments and aquatic creatures via water, causing bioaccumulation and later biomagnification in the trophic level. Pesticides can infiltrate surface or groundwater through the soil, and even plants or crops take up pesticide residues, which are eventually received by the many organisms and humans that come into contact with these items, causing toxicity and harm to the population.

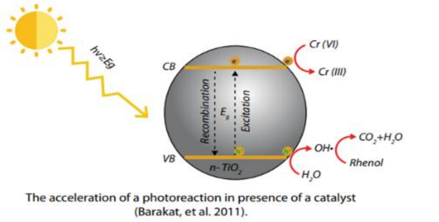
Mitigation Measures to Manage Contamination of Heavy Metals



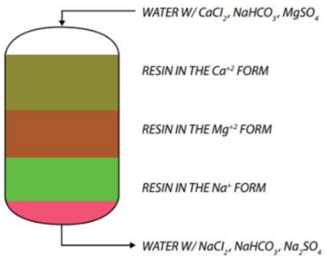
Adsorption



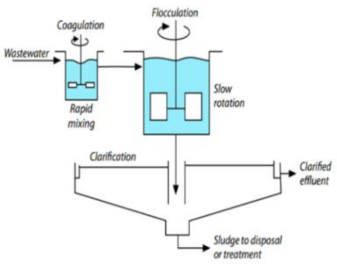
Reverse osmosis



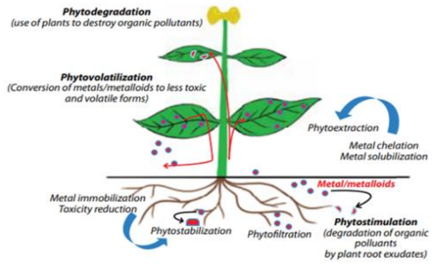
Photocatalytic reduction



Resin- based water treatment technology



Chemical Clarification



Phytoremediation

Bioremediation of pesticides and heavy metals

Fungi

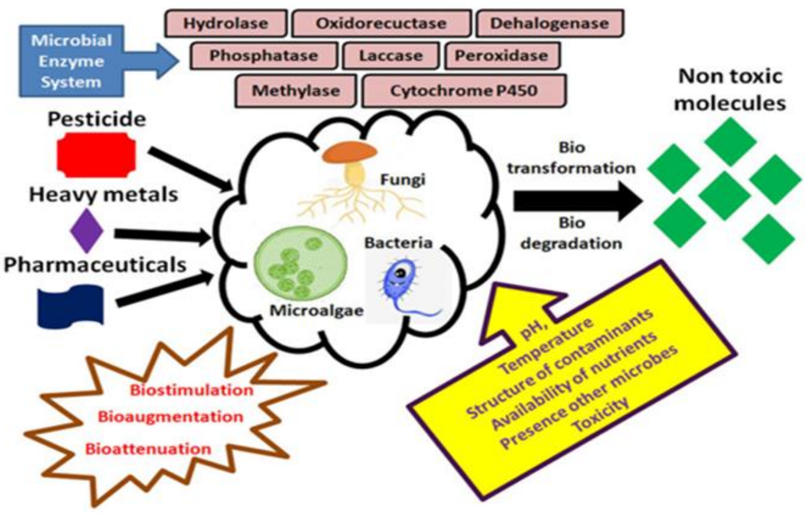
Fungi biotransform pesticides by making tiny changes to their structures, rendering them non-toxic and releasing them into the environment for further degradation (Gianfreda and Rao, 2004). Fungi use their numerous enzymes to break down complex refractory materials such as lignin and cellulose, which have low substrate specificity (Gendi *et al*., 2021). Laccase, oxidase, and peroxidase are extracellular and intracellular enzymes utilized to break down diverse complex inorganic and organic contaminants (Dashtban *et al.,* 2010). The fungal breakdown of pesticides consists of three phases. In the first process, the initial pesticide molecule is reduced, hydrolyzed, or oxidized into a non-toxic and soluble chemical. This process relies heavily on a reducing or oxidizing enzyme released by a specific fungus. The second stage involves the creation of a conjugate, which increases the water solubility of the intermediate product. Finally, enzymes such as peroxidases and oxygenases converted intermediate metabolites into non-toxic molecules (Huang *et al*., 2018).

Fungi are promising candidates for heavy metal biodegradation because they have more mycelial biomass to adhere to the soil-heavy metal interface, metal chelation, bioaccumulation potential, and metal biotransformation capacity (Vaksmaa *et al*., 2023). Aspergillus, Penicillium, Cephalosporium, Rhizopus, Phlebia, and Stachybotrys are among the fungal genera known for heavy metal bioremediation. Fungi accumulate heavy metals intracellularly in two phases. First, metals are absorbed to the cell surface by forming complexes with functional groups on the cell wall and undergoing ion exchange processes. Later on, cellular absorption and compartmentalization of metals aid in their intracellular bioaccumulation. Notably, the biosorption capacity of fungi differs between species. (Dusengemungu *et al*., 2020)

Microalgae

They use bioremediation mechanisms such as bioaccumulation, biosorption, and biodegradation to degrade pesticides. Pesticides accumulate intracellularly primarily by bioabsorption. Pesticides bond to sulfated polysaccharides on their cell walls, facilitating the biosorption process. Several lipids, proteins, and other substances in their membranes serve as pesticide binding sites. The processes are regulated by many physical and chemical parameters, such as pesticide structure, pH, temperature, salinity, nutrients, light quality, and strength. (Verasoundarapandian *et al*., 2022)

Heavy metal bioremediation by microalgae, like pesticides and other developing harmful contaminants, involves a series of phases, including biosorption, bioaccumulation, and biodegradation. Heavy metals are first attached to the rigid, porous surface of the cell wall, where they interact with negatively charged carboxyl, hydroxyl, phosphate, thiolic, thioesteric, imidazolic, or aminic functional groups of cell surface proteins, lipids, and polysaccharides via either energy-dependent active or passive processes. Acidic pH aids in the biosorption process. In contrast, intracellular bioaccumulation of heavy metals is an energy-dependent process. (Mojiri *et al*., 2020)



Source: Chakraborty *et al*., 2025

Challenges and opportunities

Algae are regarded as great bio remediators due to their superior metal tolerance, ease of growth, strong metal binding affinity, huge surface area, and environmentally favourable nature. Even dead algal cells can be used for remediation, as there are no nutritional or other parameters that limit their suitability for metal removal. However, when it comes to phytoremediation of heavy metals, scientists confront several problems. During heavy metal phytoremediation, despite algae's metal tolerance capability, biomass production falls, as does the productivity of lipids, nanoparticles, pigments, and other useful products. To address this, more advanced systems such as biomimetic systems or pretreatment technologies should be utilized. (Leong and Chang 2020). Strains should be chosen not only for optimum heavy metal remediation but also for the ability to accumulate the most byproducts, such as lipids, proteins, pigments, etc. Bioremediation by itself is not an economically viable technique. Algae are collected in an open wastewater system, which reduces biomass since algae must share nutrients with other biological agents such as bacteria, fungi, and diseases that are naturally present in the wastewater. This can be solved by combining algal consortia with other biological agents, which not only shortens the repair period but also increases its efficiency. Another issue that is currently being addressed is that these bio remediators are grown in the waste stream in order to make the process more cost-effective. However, it has been discovered that this wastewater contains some nutrients in excess or in trace amounts, which affects the growth of the algae. So, it is critical to define the wastewater first, followed by nutrient balance. Another approach is to segregate and filter the algal bioremediatory from the waste stream. To address these challenges, pretreatment techniques like membrane filtration, acidification, chlorination, and UV irradiation might be used (Wu and Cheng 2018).

Conclusion

Long-term exposure of fish to pesticides poses a continual health risk to the human population. As a result, consuming these hazardous fish puts the human population in danger. Pesticide rationalization is regarded as the most important aspect in minimizing pesticide and other pollutant pollution in aquatic environments. To safeguard wildlife and water quality, pesticides must be used with prudence. Surface water pollution and aquatic life contamination can be avoided by using pesticides in conjunction with other pest control measures and applying them safely. Recent technological advancements have increased the effectiveness of bioremediation. This method is unique and successful since it does not require chemicals or complicated apparatus. The current investigation demonstrated bioremediation as a possible strategy for resolving or lowering the harmful impacts of environmental contamination. Because it employs living entities to regulate pollution, it cannot increase the problem of heavy metal buildup or ozone depletion. It is thought to be both environmentally friendly and economically viable, making it applicable to both emerging and developed nations worldwide.

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