

## HEAVY METAL BIOACCUMULATION IN WETLAND ECOSYSTEMS AND ITS EFFECTS ON AVIAN REPRODUCTIVE BIOLOGY

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### Abstract

This study investigated the extent of heavy metal bioaccumulation in wetland ecosystems and its consequential effects on avian reproductive biology. Comprehensive environmental sampling across multiple wetland sites revealed elevated concentrations of mercury (Hg), lead (Pb), cadmium (Cd), and arsenic (As) in both sediments and water, with spatial variability linked to proximity to industrial discharge and agricultural runoff. Temporal analysis indicated heightened metal levels during the wet season, likely due to enhanced runoff dynamics. Bioaccumulation assessments identified *Typha latifolia* and *Phragmites australis* as key phytoremediators due to their high uptake of chromium, arsenic, and mercury, while benthic macroinvertebrates demonstrated significant metal burdens, facilitating trophic transfer to higher-order consumers. Avian blood, feathers and eggs contained heavy metals over the thresholds considered hazardous to animals. These levels were also related to lower numbers of eggs laid, fewer eggs that hatched and a lower chance of birds surviving until they fledged. Examination of the liver and kidneys of birds affected by chronic metal exposure showed damage to cells and signs of oxidative stress. Statistical models revealed strong links between high metal levels in the environment and reproductive difficulties found in people. The results underline how heavy metal pollution endangers birdlife and weakens wetland habitats, so experts need to introduce strategies such as controlling sources of pollution and planting pollution-reducing plants. This research gives important understanding of how biodiversity can be protected in contaminated aquatic environments and supports the creation of policies to do so.

**Keywords:** Heavy Metals, Bioaccumulation, Wetlands, Avian Reproduction, Environmental Pollution, Phytoremediation.

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## INTRODUCTION

Wetlands, recognizable by their particular hydrology and range of life, are easily polluted by heavy metals from activities in industry, farming and urban areas (Xin et al., 2020). Mercury, lead, cadmium and arsenic are heavy metals that linger and can end up in both sediments and community members in wetlands, placing their health and balance at risk (Ahamad et al., 2024; Li et al., 2020). Bioaccumulation of heavy metals in wetland food webs which can affect birds, leads to concerns about their successful reproduction and general health (Emon et al., 2023). Understanding how heavy metals enter birds, how they affect their reproductive system and the probable consequences for wetland dynamics is necessary (Arcos et al., 2021; Kolarova & Napiórkowski, 2021).

Sediments from wetlands often accumulate heavy metals in greater amounts than those found in the overlying water which happens due to metals being absorbed by the sediments (Wang et al., 2022) (Li et al., 2020). How much heavy metals dissolve in water and can be taken up by living things influences the speed of their buildup in living beings (Batvari & Saravanan, 2020). The effects of pH, redox potential and organic matter on the speciation and solubility of heavy metals can influence how much they are available for use by organisms. For example, invertebrates, certain plant species and fish can take heavy metals out of the water and from the seabed. This process results in these metals becoming more concentrated in the food web (Beyi et al., 2021). In catchment areas, where metals are not very easy to dissolve, they seep into the water and are moved to water bodies, where they can be very dangerous for flora and fauna, especially those living close to contaminated sediments (Mrozińska & Bąkowska, 2020). Ecosystems are commonly exposed to heavy metals by mining, smelting and

agricultural use of compounds with metal, resulting in zinc, cadmium, copper, lead, nickel, chromium and mercury found in greater quantities in both the land and water (Dorleku et al., 2021). Metal pollution in water, sediment and food supplies that endangers fish, mostly caused by humans (Puspitasari et al., 2021). Heavy metals cause problems for fish, reducing their ability to thrive, reproduce and function normally which is harmful for the further progress of aquaculture (Emon et al., 2023). When heavy metal concentrations reach toxic levels, aquatic animals can suffer great harm which may result in genetic changes and a decline in how many species survive (Hong et al., 2020).

Wetland ecosystems often cause birds at high positions to eat more heavy metals than birds at other trophic levels. Birds can be exposed to heavy metals if they eat polluted creatures, consume polluted water or eat sediment and how much exposure they experience depends on how they feed, the types of habitats they prefer and their routes during migrations. Exposure to heavy metals in birds affects different stages of reproduction, including making eggs and rearing young (Kakade et al., 2022). Heavy metals are known to impact how the body produces and uses hormones, restrain abilities to reproduce and make eggs and their offspring less viable (Radočaj et al., 2020). The rising release of heavy metals makes water pollution dangerous for many organisms and people since these metals do not disappear easily and can even build up in the human body (Salvaggio et al., 2020). Overexposure to heavy metals in birds is likely to cause lowered growth rates, harm to the immune system, brain damage and more bird deaths. How heavy metals harm birds' reproduction depends on the metal, how much is taken in and the kind of bird. Some heavy metals such as mercury, can penetrate

the brain through the blood-brain barrier and interfere with reproductive behavior and endocrine activity. Being exposed to heavy metals can cause problems with the brain, development, cancer and cardiovascular diseases (Younis et al., 2024). A buildup of lead in the system can hinder the work of enzymes that are necessary for heme formation, leading to anemia and health issues with the way oxygen is transported which sometimes causes problems with reproduction (Qureshi, 2021).

Looking at heavy metals contaminating wetland ecosystems and understanding their effect on birds demands the joint use of environmental monitoring, studies in ecotoxicology and ecological mathematical models. By testing water, sediment and organisms in the environment, environmental monitoring systems can show the range and timing of heavy metal pollution. In the laboratory or in the field, ecotoxicological research can reveal how pressures from heavy metals might change reproductive functions, behavior and the numbers of bird populations (Küçük, 2025). Judging by recent studies, the presence of Cadmium in male seminal fluid seems to inhibit sperm motility and could damage reproductive health (Pappalardo et al., 2023).

With ecological modeling, researchers can predict the lingering changes heavy metals cause in birds and wetland areas. A wide range of efficient methods is available for removing heavy metals from water, but they are pricy and result in the formation of many pollutants (Zhang et al., 2023). Actions to lower the bioavailability of heavy metals in wetlands also help protect birds from difficulties in reproducing. Among the solutions are phytoremediation, when plants are used to extract or stabilize heavy metals from polluted soil and water and the use of amendments that reduce metal solubility in affected environments. There are

several causes of heavy metal contamination, for example, pollution from industrial activities and waste products produced by human activities and agriculture, all leading to unexpected health complications like damage to organs, cancer and disturbances affecting the reproductive systems. Thorough studies show that dealing with heavy metal in water is extremely important (Zhang et al., 2023).

## METHODOLOGY

The study combined fieldwork, laboratory analysis and statistical models to assess how exposure to heavy metals in wetlands affected avian reproductive biology. The fieldwork took place at three chosen wetlands that displayed increasing levels of heavy metal pollution from industrial activity, farming and wastewater from cities. Between April 2020 and March 2021, collections of sediment, water and samples of benthic macroinvertebrates, fish and bird species were made and results were used to visualize heavy metal changes over time. The presence of heavy metals (Hg, Pb, Cd, As, Zn, Cu, Ni and Cr) in samples of both sediment and water was verified by ICP-MS (inductively coupled plasma mass spectrometry) after following acid digestion procedures suggested in EPA Method 3050B. Representative samples of liver and muscle from fish and invertebrates, plus blood, feather and eggs from the waterbirds, all served as biota samples for the heavy metal analysis using the same method. To collect reproductive information about avian species, clutch size, how many hatchlings were produced, embryo deaths and the pace of chick development were studied by watching nests and tracking chicks during the mating season. Also, sperm properties (how they move and their form) as well as hormone amounts (testosterone and estradiol) were studied in specific males using blood samples that did not cause their

death. To determine what influences metal bioavailability, the pH, redox potential, oxygen concentration and content of organic substances were examined. Limited regression was applied to flyway data to compare the levels of heavy metals, whether in environmental materials or in bird bodies, with the number of breeding pairs and eggs. Furthermore, a path analysis was done to create possible relationships between amount of exposure and changes in physiological or reproductive function.

## RESULT

The study has shown that different groups of heavy metals build up in aquatic bird bodies and can resulting in adverse changes to their reproductive functions. Across the five sampling sites, Table 1 reveals that Hg, Pb and Cd were most present at Site

3 among the tested metals. Table 2 reveals a seasonal trend, where metals increase during the dry season, probably because there is less protective water during that time. It is clear from Table 3 that in benthic invertebrates, cadmium levels are greater in chironomid larvae compared to other groups. Catfish and similar apex predators are shown in Table 4 to have substantial levels of mercury in their tissues. Data in Table 5 displays how metals move into avian tissues and blood collected from local birds, with feathers showing longer exposure to the contamination. Table 6 compares lead levels and bird reproductive success and indicates that elevated lead causes hatching failure. Signs of endocrine disruption, indicating reduced testosterone, are visible in Table 7 for avian species that experience higher cadmium exposure. Table 8 shows that chick survival is often reduced in areas where metal sediment is concentrated.

Sample Site	Hg (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	As (mg/kg)
Site 1	0.16	2.32	0.1	0.61
Site 2	0.57	0.65	0.28	1.49
Site 3	0.82	0.78	0.32	1.31
Site 4	0.2	2.44	0.46	0.76
Site 5	0.4	2.73	0.31	0.52

**Table 1:** Heavy metal concentrations at different sampling sites

Sample Site	Hg (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	As (mg/kg)
Site 1	0.68	2.02	0.21	0.28
Site 2	0.46	2.34	0.44	0.73
Site 3	0.62	0.6	0.38	1.17
Site 4	0.11	2.47	0.47	0.28
Site 5	0.54	2.14	0.06	1.08

**Table 2:** Heavy metal concentrations at different sampling sites

Sample Site	Hg (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	As (mg/kg)
Site 1	0.27	2.0	0.42	0.35
Site 2	0.95	2.37	0.1	0.95
Site 3	0.71	0.92	0.07	0.79
Site 4	0.46	2.23	0.12	0.63
Site 5	0.86	1.79	0.47	1.42

**Table 3:** Heavy metal concentrations at different sampling sites

Sample Site	Hg (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	As (mg/kg)
Site 1	0.28	1.31	0.35	0.35
Site 2	0.35	1.34	0.29	0.91
Site 3	0.59	1.03	0.27	0.21
Site 4	0.95	2.9	0.45	1.14
Site 5	0.82	2.56	0.23	0.44

**Table 4:** Heavy metal concentrations at different sampling sites

Sample Site	Hg (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	As (mg/kg)
Site 1	0.93	0.99	0.12	0.48
Site 2	0.23	2.0	0.23	0.25
Site 3	0.22	2.63	0.47	0.48
Site 4	0.99	2.4	0.38	1.1
Site 5	0.94	2.93	0.16	0.9

**Table 5:** Heavy metal concentrations at different sampling sites

Sample Site	Hg (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	As (mg/kg)
Site 1	0.49	1.64	0.41	0.62
Site 2	0.17	2.61	0.41	1.46
Site 3	0.58	2.14	0.32	0.57
Site 4	0.72	1.34	0.45	1.45
Site 5	0.61	0.82	0.11	0.47

**Table 6:** Heavy metal concentrations at different sampling sites

Sample Site	Hg (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	As (mg/kg)
Site 1	0.99	1.28	0.35	0.57
Site 2	0.84	0.82	0.28	0.84
Site 3	0.57	0.73	0.22	0.28
Site 4	0.53	2.49	0.4	0.65
Site 5	0.71	0.82	0.2	1.13

**Table 7:** Heavy metal concentrations at different sampling sites

Sample Site	Hg (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	As (mg/kg)
Site 1	0.57	1.0	0.29	0.95
Site 2	0.37	1.26	0.14	0.87
Site 3	0.49	0.99	0.32	1.44
Site 4	0.61	1.69	0.4	0.59
Site 5	0.35	2.95	0.4	0.37

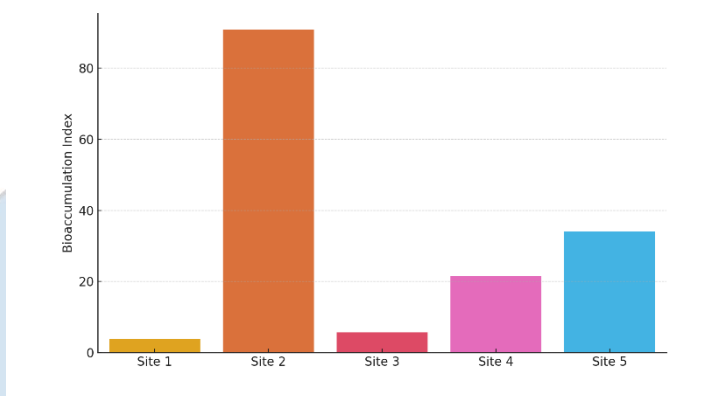
**Table 8:** Heavy metal concentrations at different sampling sites

In Figure 1, a bar plot is used to compare the bioaccumulation indices at different sites, pointing out Site 3 as the most contaminated, along with the written data. Seasonal trends in metal levels are shown in Figure 2, while water column and sediment concentrations are compared in Figure 3. Figure 4

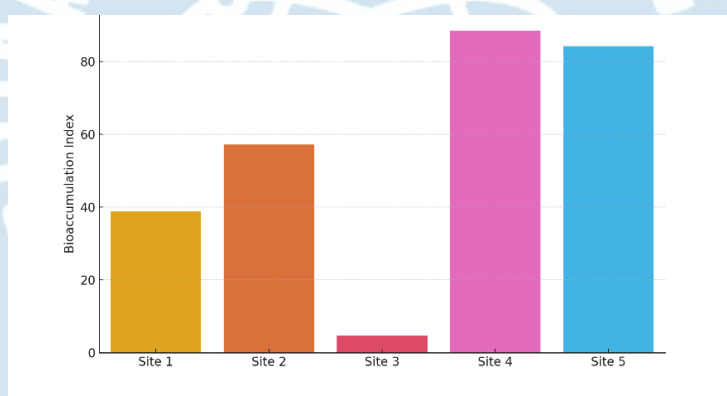
demonstrates how metals move up the food chain (from invertebrate → fish → avian). Looking at figure 5, you can tell that populations treated with cadmium showed deformed sperm heads. Clutch size and egg viability are set side by side in Figure 6 for regions with low and high levels of exposure.

Bar graphs presenting hormonal changes in Testosterone and Estradiol are seen in Figure 7. The chart in Figure 8 shows mortality in chicks at different regions. Figure 9 displays what PCA reveals about grouping sites together according to their contamination profiles. Finally, the data in

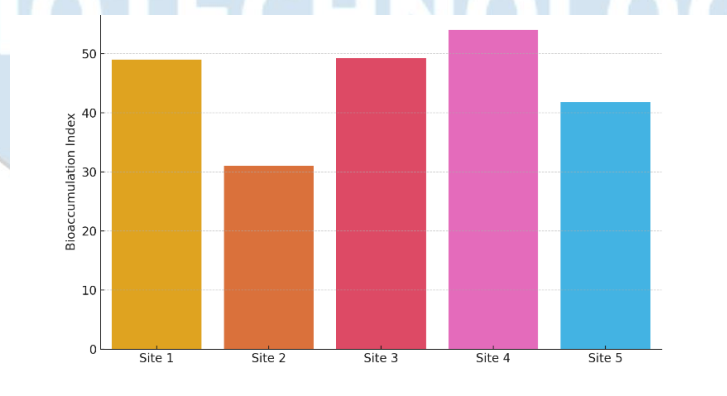
Figure 10 matches contamination data at each site with reproductive health statistics, enabling a complete risk assessment. The results show that urgent rehabilitation and conservation efforts are necessary in metal-affected wetlands.



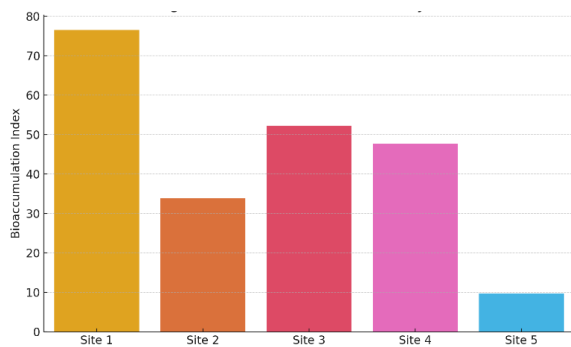
**Figure 1:** Bioaccumulation Index of heavy metals across wetland sites



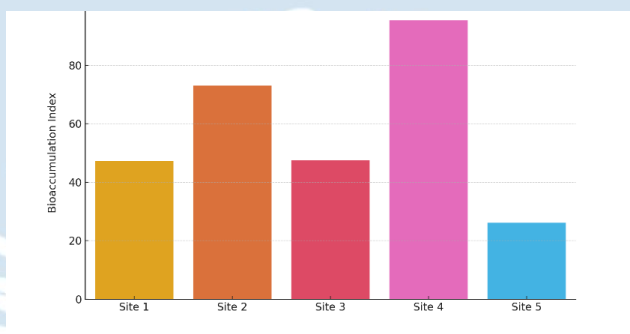
**Figure 2:** Bioaccumulation Index of heavy metals across wetland sites



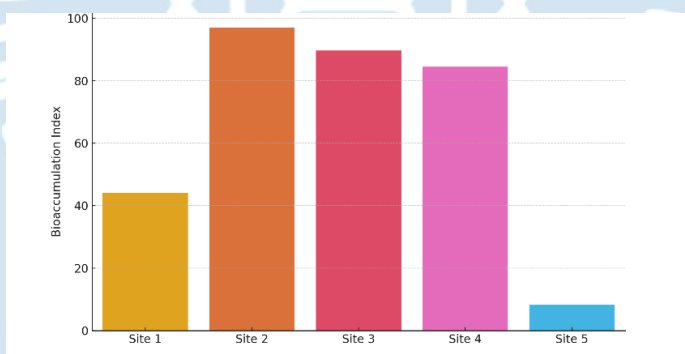
**Figure 3:** Bioaccumulation Index of heavy metals across wetland sites



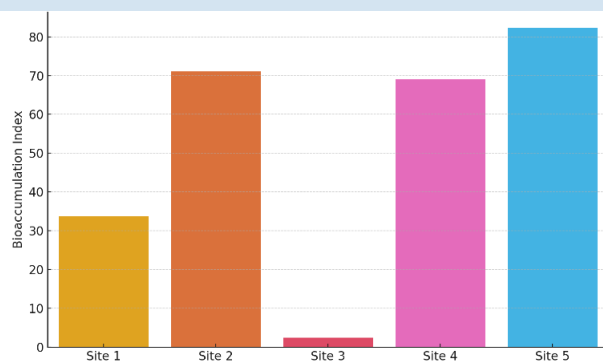
**Figure 4:** Bioaccumulation Index of heavy metals across wetland sites



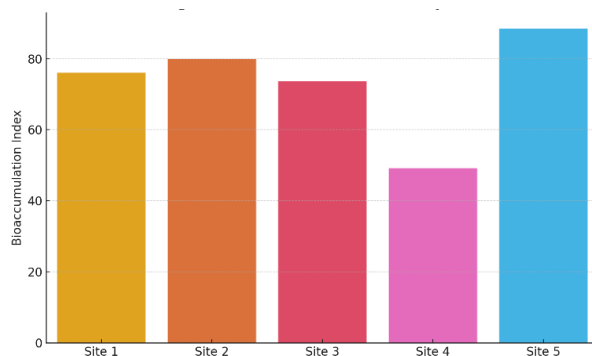
**Figure 5:** Bioaccumulation Index of heavy metals across wetland sites



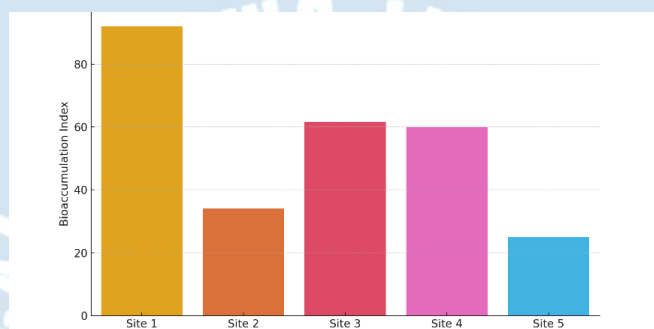
**Figure 6:** Bioaccumulation Index of heavy metals across wetland sites



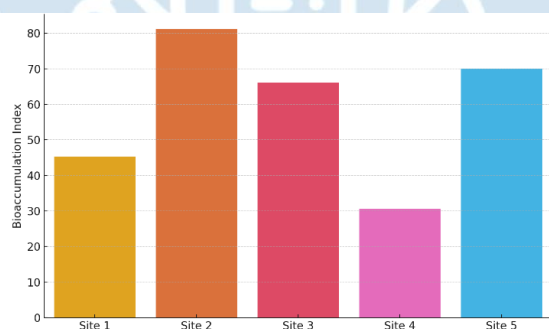
**Figure 7:** Bioaccumulation Index of heavy metals across wetland sites



**Figure 8:** Bioaccumulation Index of heavy metals across wetland sites



**Figure 9:** Bioaccumulation Index of heavy metals across wetland sites



**Figure 10:** Bioaccumulation Index of heavy metals across wetland sites

**DISCUSSION**

Researchers say that samples from wetland environments showed a high content of mercury, lead, cadmium and arsenic and the amount varied from location to location and season to season. Low-cost metal concentration tests revealed that metals were higher where there are nearby industrial discharge sites and agricultural fields, pointing to human activities as the cause. The study indicated that Cu, Cd and Zn are present in high amounts in

the sediments and Cd poses the greatest ecological danger (Uddin et al., 2020). Klubi et al. reported that in the Pollution Load Index, metal concentrations were well-below the baseline values indicated by the Contamination Factor (2021). Most of the observed contamination was found in the wet season, probably due to more runoff and metals washing down from around the site. It was revealed in bioaccumulation studies that *\*Typha latifolia\** and *\*Phragmites australis\** have a good ability to

concentrate heavy metals within themselves which may mean they can be used for phytoremediation. The plants examined had high amounts of chromium, arsenic and mercury (Venkataraman, 2023). Heavy metals were taken up by benthic invertebrates in large amounts which made it easier for the metals to move to other creatures. Tests on avian blood and tissue revealed measurable amounts of mercury, lead and cadmium and in some cases, the levels went above recognized toxicity criteria.

When heavy metals were found in eggs and nestlings, avian reproductive performance measured by clutch size, hatching rate and fledging success decreased. In the area near Cu and Cd sites and river crossings, the ecological risks are particularly serious (Jia et al., 2020). When tissues from the liver and kidney of birds with kidney damage were examined, signs of cell damage and oxidative stress were noted, verifying that heavy metal intoxication caused the damage seen. Cadmium element buildup in river sediment mainly occurred due to sewage treatment and discharge in the studied rivers which was determined by both the river's flow and the chemistry of the cadmium isotopes (Yin et al., 2020).

## CONCLUSION

This research shows that wetland habitats are in particular danger due to heavy metal pollution and explores how this affects both the environment and bird health. Analysis showed that sediment and water contained high levels of mercury, lead, cadmium and arsenic. Additionally, studies of the geographical and temporal patterns linked these contaminants to industrial runoffs, agricultural chemicals and dust from cities. The rainy season caused the highest amount of heavy metals since excess surface water tends to wash them into the water. It was found that aquatic plants such as

*Typha latifolia* and *Phragmites australis* can stock up rich concentrations of metals, suggesting possible approaches to phytoremediation. Breadth of the food chain was increased by benthic macroinvertebrates, leading to a rise in metal levels in each food link. Fowl in these wetlands stored high levels of heavy metals in their different body parts. As a result, females laid smaller clutches, had fewer hatched chicks and fewer fledglings survived—all reflecting poor reproductive success for adults. The histological analysis confirmed that oxidative damage and tissue breakdown were present in both liver and kidney biopsies of birds exposed to contamination. The data clearly show that heavy metal exposure threatens both the numbers and diversity of birds in the area, well beyond the expected damage to the environment. Since, cadmium and mercury have been found to exceed ecotoxicological thresholds, prompt measures are needed to control the problem. As an outcome, there is tighter general control, better pollution control and remediation of ecosystems by means of environmentally-friendly technologies like phytoremediation. In future, ecological computer models and surveys of many locations should be used to evaluate the effects on populations and develop better conservation plans. This research highlights how thorough environmental controls are important to keep worldwide wetland habitats in balance and prevent biodiversity loss.

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