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# *MECHANISM OF CHEMICAL TRANSFORMATIONS OF HEAVY METALS AS A RESULT OF OXIDATION–REDUCTION PROCESSES IN ECOSYSTEMS*

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**Abstract.**
This article investigates the environmental damage caused by the oxidation and reduction processes of certain heavy metals in soil and water ecosystems. It has been determined that the distribution of heavy metals in ecosystems, together with their high toxicity, persistence, and susceptibility to chemical transformations, leads to serious ecological problems. The environmental impact of heavy metals largely depends on their chemical transformations, which become particularly evident during oxidation–reduction processes.

The study mainly examines the mechanisms of chemical transformations occurring as a result of oxidation–reduction reactions of heavy metals in soil and aquatic ecosystems. The oxidation states, solubility, mobility, and bioavailability of heavy metals such as lead, cadmium, mercury, and arsenic under different oxidation–reduction conditions were analyzed. In addition, the effects of pH, oxidation potential, and the presence of oxidizing and reducing agents on these processes were evaluated.

The results demonstrate that oxidation–reduction processes directly affect the toxicity and bioaccumulation potential of heavy metals, thereby increasing the ecological risk to ecosystems. The obtained findings are of significant importance for assessing the impact of chemical transformations of heavy metals on ecosystems and for developing effective pollution mitigation strategies.

**Keywords:** Heavy metals, oxidation–reduction processes, chemical transformations, ecosystems, toxicity, bioavailability, pH, oxidation potential

## 1. Introduction

It is well known that the contamination of soil and groundwater with heavy metals as a result of natural and anthropogenic impacts is a serious environmental problem. In particular, heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), and arsenic (As) pose a significant threat to ecosystems. Due to their high persistence and toxicity, heavy metals play an important role in environmental pollution because they are resistant to degradation and are considered hazardous substances. As a result of anthropogenic activities, these elements enter soil and aquatic environments and become involved in the biogeochemical cycle. The transformation of heavy metals within ecosystems depends on their chemical forms and oxidation states.

Heavy metals enter the environment through various types of waste and remain there for long periods because they are not biodegradable. As a result, their concentrations in soil and groundwater increase, adversely affecting biota, humans, and the ecosystem as a whole. This creates risks to human health and threatens ecosystem stability. Many heavy metals are toxic and can accumulate in biological systems due to their adverse effects on proteins and enzymes. For example, copper is present in nutrients at low concentrations; however, at elevated concentrations, it has harmful effects on aquatic organisms [1].

Studies have shown that chronic exposure to copper in aquatic environments has destructive effects on many aquatic organisms. Furthermore, copper not only poses a threat to aquatic life but

also exerts strong reactive and toxic effects on the human body when present at high concentrations. As a consequence, it may lead to immune system disorders, fatigue, Alzheimer's disease, and other health problems.
The behavior and transformation of heavy metals within ecosystems depend on their chemical forms, oxidation states, and environmental conditions. For example, although copper (Cu) is an essential biogenic element for living organisms at low concentrations, it is known to exhibit toxic effects at elevated concentrations. In particular, the $Cu^{2+}$ ion is the most widespread and highly reactive form of copper in aquatic environments. Studies indicate that high concentrations of copper in water may adversely affect aquatic organisms and, upon prolonged exposure, may cause immune system suppression, neurological disorders, and other pathological conditions in humans [2–5].
Cadmium (Cd) is one of the highly toxic heavy metals and is considered an important component of atmospheric pollution. Although this element occurs naturally in small amounts, its atmospheric concentration has increased significantly due to anthropogenic activities. In particular, the metallurgical industry, the combustion of coal and petroleum products, waste incineration, and phosphate fertilizer production are the major sources of cadmium emissions. In the atmosphere, cadmium is mainly present in the form of fine dispersed aerosol particles. These particles can remain suspended in the air for long periods and be transported over large distances by wind currents. Consequently, cadmium contamination is observed not only near emission sources but also in remote regions. Atmospheric cadmium subsequently enters soil and aquatic ecosystems through dry deposition or precipitation, resulting in a multi-stage contamination process.
The presence of cadmium in the atmosphere has adverse effects on vegetation. Plants can absorb this element directly through their leaves, leading to a reduction in the intensity of photosynthesis. This negatively affects plant growth, productivity, and overall biological activity. Furthermore, after entering the soil, cadmium is also absorbed through the root system of plants and subsequently enters the food chain. From the perspective of human health, atmospheric cadmium poses a serious hazard. This metal enters the human body primarily through inhalation and accumulates mainly in the lungs and kidneys. Long-term exposure to cadmium may result in impaired kidney function, weakening of bone tissue, and respiratory diseases. In addition, numerous scientific studies have confirmed the carcinogenic properties of cadmium [6–8].

## 2. Experimental Section.

Studies have shown that atmospheric cadmium levels are higher in industrial zones and large urban areas. This results in increased adverse effects on environmental quality and human health. To address this problem, reducing emissions, implementing filtration systems, and strengthening environmental monitoring are considered essential.
Mercury exists in the atmosphere in several chemical forms, including elemental mercury ($Hg^0$), oxidized mercury ($Hg^{2+}$), and organic mercury compounds. Since elemental mercury is highly volatile, it can remain in the atmosphere for extended periods and be transported globally by atmospheric air currents. This characteristic makes mercury not merely a local pollutant but a global environmental concern. Atmospheric mercury enters soil and aquatic ecosystems through either dry deposition or precipitation. Once it enters aquatic environments, mercury undergoes complex biogeochemical transformations. As a result of microbial activity, inorganic mercury is converted into methylmercury, a highly toxic organic form. Methylmercury is readily absorbed by aquatic organisms and accumulates along the food chain, thereby enhancing the process of biomagnification. Consequently, mercury concentrations become particularly high in predatory fish. The presence of atmospheric mercury also adversely affects plants and soil systems. Plants can absorb mercury through their leaves, negatively affecting their physiological processes, particularly photosynthesis. At the same time, mercury accumulated in soils suppresses microbial activity and reduces soil fertility.
From the perspective of human health, mercury is considered one of the most hazardous heavy metals. Mercury enters the human body either through inhalation of contaminated air or through

the consumption of contaminated food originating from aquatic environments, causing severe damage to the central nervous system. In particular, methylmercury exhibits pronounced neurotoxic effects, leading to memory impairment, coordination disorders, and other neurological diseases. Exposure to mercury during pregnancy may also adversely affect fetal development [9]. Studies have demonstrated that mercury contamination is more pronounced in industrial regions and in areas adjacent to water bodies. This poses a serious threat to the sustainability of ecosystems. The reduction of mercury emissions, proper waste management, and the implementation of environmental protection programs at the international level play a crucial role in addressing this issue. Overall, the impacts of mercury on the atmosphere and aquatic environments are multifaceted and long-lasting. Research has shown that the environmental cycling of mercury contributes to its widespread distribution and accumulation in living organisms. Therefore, preventing mercury pollution and minimizing its adverse effects are regarded as fundamental objectives of modern environmental science [10,11].

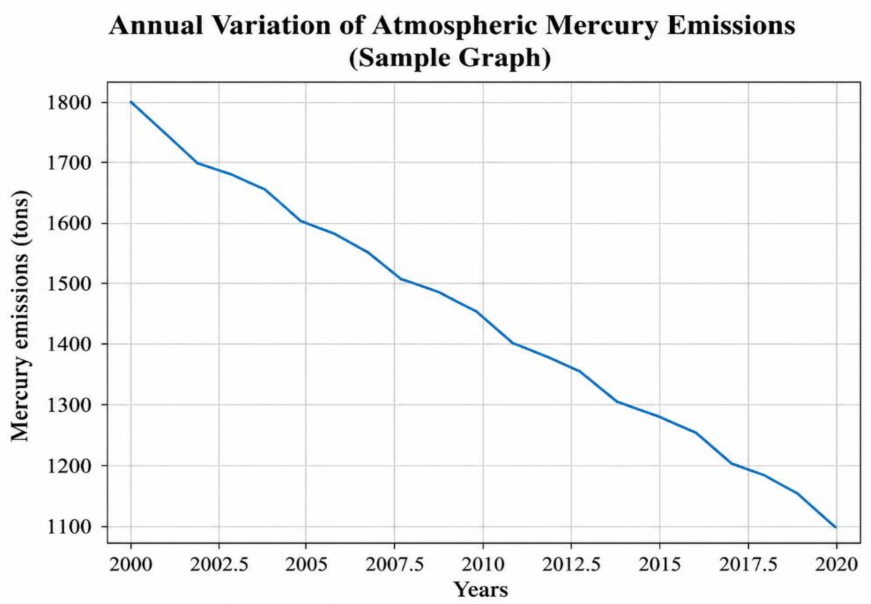


**Figure 1. Annual Variation of Atmospheric Mercury Emissions (Sample Graph).**

### 2.1 Oxidation–Reduction Processes in Ecosystems

Oxidation–reduction (redox) processes occurring in ecosystems are considered one of the primary mechanisms responsible for the chemical transformation of these elements. Changes in oxidation and reduction conditions directly affect the solubility and oxidation potential of heavy metals. These processes are closely associated with the oxygen regime of the environment, pH, the amount of organic matter, and the activity of microorganisms. Heavy metals such as iron, manganese, chromium, arsenic, and mercury are particularly sensitive to redox changes. The different oxidation states of these elements determine their bioavailability and toxicity within ecosystems. Furthermore, the oxidation and reduction transformations of heavy metals influence the processes of bioaccumulation and biomagnification.

During the ion-exchange reaction, heavy metal ions (e.g., $Pb^{2+}$, $Cd^{2+}$, and $Hg^{2+}$) are removed from the solution and replaced by other ions. This process is generally carried out using ion-exchange reagents or naturally occurring minerals.

**The general form of the reaction is:**

$$\mathbf{R{-}X + M^{2+} \rightarrow R{-}M + X^{+}} \quad (1)$$

For example:

For lead:

$$\mathbf{R{-}X + Pb^{2+} \rightarrow R{-}Pb + X^{+}} \quad (2)$$

For cadmium:

$$\mathbf{R{-}X + Cd^{2+} \rightarrow R{-}Cd + X^{+}} \quad (3)$$

For mercury:

$$\mathbf{R{-}X + Hg^{2+} \rightarrow R{-}Hg + X^{+}} \quad (4)$$

Various methods, including precipitation and ion exchange, are widely employed for the removal of heavy metal contamination. Therefore, investigating the mechanisms of the chemical transformations of heavy metals resulting from oxidation–reduction processes in ecosystems is of great scientific importance for the assessment of ecological risks [12-16].

**3. Result and Discussion**

The chemical transformations of heavy metals in ecosystems resulting from oxidation–reduction (redox) processes involve electron transfer between chemical species and depend on several environmental factors. The oxidation state, solubility, bioavailability, and toxicity of elements within compounds vary according to these factors.

In general, oxidation–reduction processes are characterized by two fundamental mechanisms: oxidation, which involves the loss of electrons, and reduction, which involves the gain of electrons. The conducted studies have shown that the principal factors influencing redox mechanisms in ecosystems include environmental pH, oxidation potential (Eh), microbial activity, and the presence of organic matter. Oxidation–reduction reactions occur under both aerobic and anaerobic environmental conditions. Among heavy metals, chromium has been one of the most extensively studied elements with respect to its transformation mechanisms, which are described below.

Chromium belongs to the transition metals and occurs naturally in the Earth's crust. With the development of industrialization, the distribution of chromium in the environment has increased considerably, making its biogeochemical cycling an important environmental concern. In particular, the high toxicity of hexavalent chromium (Cr(VI)) has made the investigation of its chemical transformations a subject of great scientific importance.

Chromium primarily occurs in two oxidation states: Cr(III) and Cr(VI).

Cr(III) forms poorly soluble compounds and is considerably less toxic. In contrast, Cr(VI) is highly soluble and possesses well-established carcinogenic properties.

Under aerobic (oxygen-rich) conditions, the transformation mechanism is as follows:

$Cr^{3+} \rightarrow Cr^{6+}$

(Chromium is oxidized from the +3 oxidation state to the +6 oxidation state.) (5)

Under anaerobic (oxygen-deficient) conditions and in environments rich in organic matter, the transformation proceeds as follows:

$Cr^{6+} \rightarrow Cr^{3+}$

(Chromium is reduced from the +6 oxidation state to the +3 oxidation state.)

As the oxidation potential (Eh) increases, the Cr(VI) species becomes more stable, resulting in greater mobility of chromium in soils [17-20].

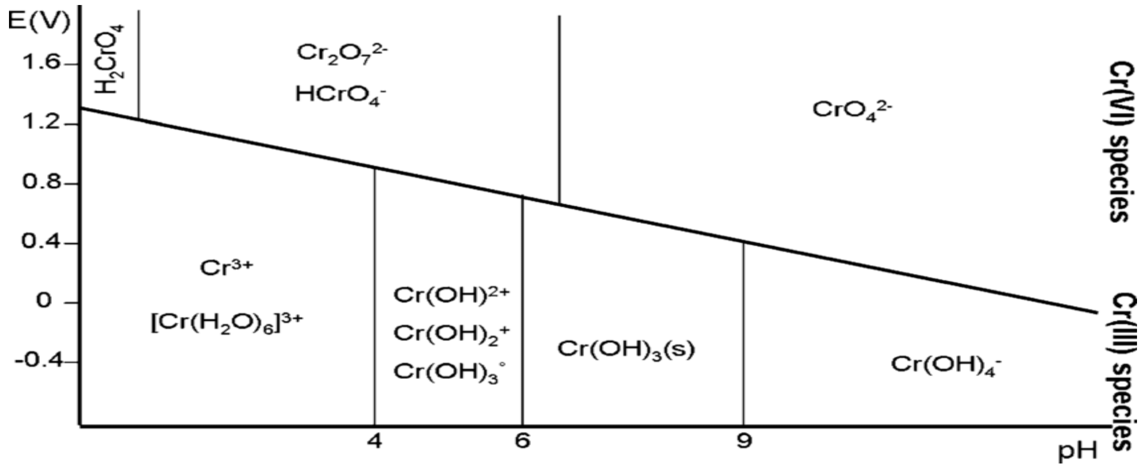


**Figure 1. Eh–pH Diagram of Chromium (Cr).**

Mercury is one of the heavy metals with the most complex transformation mechanisms. Its various chemical forms exhibit different levels of toxicity, mobility, and bioaccumulation potential. The behavior of mercury in ecosystems is primarily governed by oxidation–reduction reactions, microbial methylation, and complexation processes. In terms of its chemical transformation mechanism, mercury exists in three principal forms: $Hg^0$ (elemental mercury), $Hg^{2+}$ (oxidized mercury), and $CH_3Hg^+$ (methylmercury).

$Hg^0$ (elemental mercury) is highly volatile, can remain in the atmosphere for extended periods, and is relatively sparingly soluble.

$Hg^{2+}$ (divalent mercury) is highly soluble in aqueous environments and participates more readily in chemical reactions. Since this form can be assimilated by microorganisms, it serves as a substrate in their metabolic processes.

$CH_3Hg^+$ (methylmercury) possesses high lipophilicity, enabling it to accumulate efficiently in biological tissues [21].

During the oxidation process, elemental mercury is converted into oxidized mercury in the atmosphere:

$$Hg^0 \rightarrow Hg^{2+} \quad (6)$$

This transformation occurs in the presence of hydroxyl radicals (OH) and chlorine radicals (Cl). As a result of oxidation, mercury is converted into a water-soluble and chemically reactive form.

The reduction process occurs through photoreduction under the influence of sunlight, as well as in the presence of organic matter. Consequently, oxidized mercury is reduced back to elemental mercury:

$$Hg^{2+} \rightarrow Hg^0 \quad (7)$$

The elemental mercury produced is subsequently released back into the atmosphere.

The most environmentally hazardous stage of mercury transformation is methylation. Under anaerobic conditions, oxidized mercury is converted into methylmercury through the activity of sulfur- and iron-reducing bacteria:

$$Hg^{2+} \rightarrow CH_3Hg^+ \quad (8)$$

The formation of methylmercury is particularly associated with the development of disorders affecting the nervous system.

The most hazardous characteristic of mercury is its progressive accumulation in the food chain in the form of methylmercury ($CH_3Hg^+$), with its concentration increasing at each successive trophic level. This process is known as biomagnification [22,23].

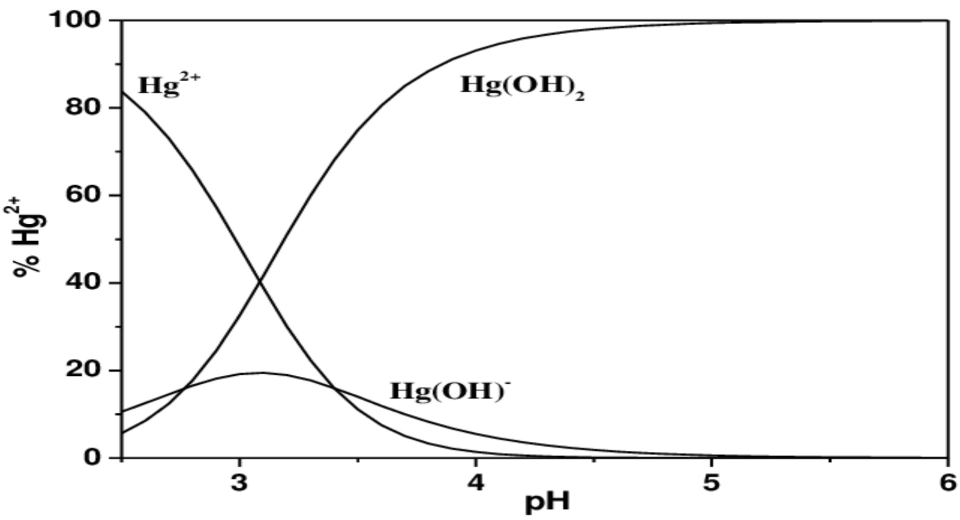


**Figure 2. Distribution of $Hg^{2+}$, $Hg(OH)^{+}$, and $Hg(OH)_2$ Species as a Function of pH.**

**Lead**

Lead is a heavy metal with no known biological function in nature but exhibits high toxicity. It enters soil and aquatic environments primarily through industrial activities, fuel residues, mining operations, and battery waste. The behavior of lead in ecosystems is strongly influenced by pH, oxidation potential (Eh), organic matter, and clay minerals. The presence of lead in soil disrupts the nitrogen cycle and reduces soil biochemical activity. It persists in soils for long periods, decreases biological activity, inhibits the growth of plants and aquatic organisms, and poses a threat to human health through its transfer along the food chain.

**Cadmium**

Cadmium is a highly toxic heavy metal with no biological function. It is released into the environment through mining, metal smelting, phosphate fertilizers, batteries, and industrial waste. In ecosystems, cadmium predominantly exists in the $Cd^{2+}$ form and exhibits high mobility that is strongly dependent on pH. It has significant adverse effects on soil microflora by reducing enzyme activity, suppressing nitrogen fixation, decreasing microbial diversity, and disrupting the biochemical cycling of soils. Consequently, soil fertility declines.

Cadmium is characterized by high chronic toxicity in ecosystems. Its bioavailability increases particularly in acidic soils and agricultural lands. It is transferred through the soil–plant–animal–human pathway, causing long-term health and environmental problems. Therefore, cadmium contamination requires continuous monitoring and risk-based management of soil and water systems [24-26].

The transformation mechanism of cadmium is as follows:

Acidic conditions (pH < 6):

$$Cd^{2+} + H_2O \rightleftharpoons Cd^{2+} \quad (9)$$

Under acidic conditions, cadmium exhibits maximum solubility.

Neutral to alkaline conditions (pH 6–9):

Hydrolysis begins:

$$Cd^{2+} + 2OH^- \rightleftharpoons Cd(OH)_2\downarrow \quad (10)$$

Carbonate precipitation occurs in soil:

$$Cd^{2+} + CO_3^{2-} \rightleftharpoons CdCO_3\downarrow \quad (11)$$

Complexation with organic matter takes place:

$$Cd^{2+} + R–COO^- \rightleftharpoons Cd(RCOO)_2 \quad (12)$$

Overall, the findings indicate that mercury exhibits a high potential for biomagnification following its conversion into methylmercury ($CH_3Hg^+$), thereby increasing its toxicity throughout the food chain. Lead demonstrates high persistence in soil environments, remaining for extended periods without significant degradation or transformation, resulting in localized contamination and bioaccumulation. Cadmium is a highly mobile heavy metal that readily migrates through soil layers and accumulates in plants and aquatic organisms, causing chronic toxic effects. The toxicity of chromium and arsenic varies depending on the prevailing redox conditions. In particular, the $Cr^{6+}$ and $As^{3+}$ species present significant ecotoxicological risks. Both chromium (Cr) and arsenic (As) undergo changes in chemical speciation under different redox conditions, leading to variations in their toxicity. The $Cr^{6+}$ and $As^{3+}$ forms are especially hazardous, posing substantial ecological risks and potentially causing long-term environmental degradation as well as adverse effects on human health [27,28].

**Table 1. Oxidation–Reduction Transformation Mechanisms of Heavy Metals in Ecosystems**

| **Heavy Metal** | **Forms in Soil** | **Forms in Aquatic Environment** | **Redox Reaction** | **Bioavailability** | **Representative Environmental Impact** |
|---|---|---|---|---|---|
| **Mercury (Hg)** | $Hg^0$, $Hg^{2+}$ | $Hg^{2+}$, $CH_3Hg^+$ | $Hg^0 \rightarrow Hg^{2+}$ (oxidation); $Hg^{2+} \rightarrow CH_3Hg^+$ (methylation) | High | Bioaccumulation in aquatic organisms; neurotoxic effects |
| **Lead (Pb)** | $Pb^{2+}$, $PbCO_3$ | $Pb^{2+}$, $Pb(OH)_2$ | $Pb^{2+} \leftrightarrow Pb^0$ (reduction/oxidation) | Moderate | Accumulation in soil; uptake by plants |
| **Cadmium (Cd)** | $Cd^{2+}$ | $Cd^{2+}$ | Stable $Cd^{2+}$ (low redox activity) | High | Readily migrates in soil and aquatic environments |
| **Chromium (Cr)** | $Cr^{3+}$, $Cr^{6+}$ | $Cr^{3+}$, $Cr^{6+}$ | $Cr^{3+} \rightarrow Cr^{6+}$ (oxidation); $Cr^{6+} \rightarrow Cr^{3+}$ (reduction) | Moderate | The toxic $Cr^{6+}$ species exhibits high mobility |
| **Arsenic (As)** | $As^{3+}$, $As^{5+}$ | $H_3AsO_3$, $HAsO_4^{2-}$ | $As^{3+} \leftrightarrow As^{5+}$ | Moderate | High toxicity in soil and aquatic environments |

**Table 2. Average Concentrations of Heavy Metals in Soil.**

| Heavy Metal | Average Concentration (mg/kg) | Minimum (mg/kg) | Maximum (mg/kg) |
|---|---|---|---|
| **Lead (Pb)** | 20–25 | 14 | 76 |
| **Cadmium (Cd)** | 0.12–0.16 | 0.03 | 0.83 |
| **Arsenic (As)** | 10–13 | 4 | 27 |
| **Mercury (Hg)** | 0.03–0.05 | 0.01 | 0.64 |
| **Chromium (Cr)** | 70–76 | 34 | 182 |

## 4. CONCLUSION

The findings of this study demonstrate that heavy metals, including mercury (Hg), lead (Pb), cadmium (Cd), chromium (Cr), and arsenic (As), pose significant chemical and biological risks to ecosystems. The environmental behavior of these elements is governed by complex geochemical and biogeochemical processes. Their transformation is primarily controlled by reduction, oxidation, hydrolysis, precipitation, complexation, and methylation reactions and is closely associated with environmental parameters such as pH, oxidation–reduction potential (Eh), organic matter content, and the presence of sulfides. One of the most important characteristics of heavy metals is their ability to persist and accumulate within ecosystem components. These elements exist in various chemical forms in soil and aquatic environments, participate in biogeochemical cycling, and gradually accumulate in soils, sediments, and biological systems.

In general, heavy metals exhibit long-term persistence and accumulation in terrestrial and aquatic ecosystems, leading to bioaccumulation and, in some cases, biomagnification in plants and animals. Moreover, the ecological hazards associated with heavy metals are further intensified by their toxic effects on living organisms. These elements interfere with intracellular biochemical reactions, impair enzyme activity, induce oxidative stress, and disrupt various physiological functions. Numerous scientific studies have demonstrated that metals such as mercury, lead, and cadmium possess pronounced neurotoxic properties and may also adversely affect the kidneys and bone tissues, resulting in long-term health disorders. Furthermore, many studies have reported the detrimental effects of these elements on the reproductive system and embryonic development.

From this perspective, comprehensive investigations into the distribution of heavy metals in ecosystems, their transformation mechanisms, and their pathways of transfer into biological systems are of considerable scientific importance. Consequently, identifying pollution sources, evaluating the distribution of heavy metals in soil and aquatic environments, and determining their levels of bioavailability are essential prerequisites for the accurate assessment of ecological risks.

In conclusion, continuous monitoring of ecosystems contaminated with heavy metals, regular assessment of geochemical and ecotoxicological indicators, and the application of modern analytical techniques are of paramount importance. Furthermore, the development and implementation of risk-based management strategies aimed at preventing environmental contamination are of significant scientific and practical value for environmental protection and the safeguarding of human health. Such approaches contribute to maintaining ecosystem sustainability and minimizing the adverse impacts of anthropogenic activities.

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