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HEAVY METAL CONTAMINATION IN ASIAN RIVERS

Iram Manzoor*, Shaukat Ali, Nosheen Sial, Aeman Aslam, Muhammad Aslam, Adnan Ahmad, Muhammad Husnain Sattari, Sadia Ibrahim, Jaweria Ibrahim, Ume Umaima, Aamir Ali

[1]Building of Research Station Lahore.
[2]The Superior University Lahore Pakistan.
[3]University of Layyah.
[4]Geological Survey of Pakistan Lahore.
*Corresponding Email: iramm127@gmail.com

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ABSTRACT

Heavy metal pollution of the river systems of Asia is a serious environmental problem and the main source of pollution is mining activities, urbanisation, industrialisation, agricultural runoff and inadequate waste water treatment. This paper brings together the sources of heavy metal contamination in Asian rivers, distribution, effects on the environment and human health, methods of assessment and remediation. Using a systematic approach, the articles published from 2000 to 2025 were selected according to the principles of the PRISMA 2020; after screening, 200 articles were included in the study. The main causes of heavy metal pollution were found to be mining, industrial effluents, agricultural practices, and municipal wastewater. The evaluated studies have confirmed that municipal, mining, industrial and agricultural effluents are the major sources of heavy metal pollution. The often reported pollutants that accumulated in the river water, river sediments and aquatic organisms, causing ecological disruption and potential health impacts – both cancer causing and not – included Pb, Cd, Hg, As, Cr, Ni, Cu and Zn. Evaluation methods included HPI, HEI, Igeo, EF, PERI, HQ and CR. Sustainable remediation methods with promising results include phytoremediation, bioremediation, adsorption, membrane filtration and nanotechnology. The integrated monitoring, efficient wastewater management, regulatory enforcement and sustainable remediation are essential for protecting the freshwater resources and human health in Asia.

Keywords: Asian Rivers, River sediments, Water Pollution, Hazards to human health and the environment, Heavy metals, Environmental monitoring, Remediation technology.

1. INTRODUCTION

Freshwater resources are vital to human security, economic development and environmental health. Rivers provide drinking water, for irrigation, industry, fisheries, hydropower and ecosystem services to billions of people across the globe. (Biswas and Seetharam, 2008; Bănăduc *et al*., 2022). But, with increasing human use, particularly in the rapidly growing parts of Asia, river water quality has deteriorated greatly. (Azizullah *et al*., 2011; Khan *et al*., 2021). Heavy metal contamination is one of the oldest environmental problems because hazardous metals are nonbiodegradable, resistant to natural degradation and can persist in aquatic ecosystems for extended periods of time. (Jaishankar *et al*., 2014; Aziz *et al*., 2023). These pollutants can build up in sediments and aquatic life once they are

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introduced into river systems, posing long-term threats to the environment and public health (Islam *et al.,* 2015; Zhu *et al*., 2024). The region of Asia has experienced rapid population growth, industrialization, urbanization, mining expansion and intensive farming practices in the last few decades. Freshwater systems are now being pumped with increasing amounts of untreated industrial effluents, urban wastewater, agriculture run-off and mining waste (Kathuria and Sterner, 2006; Mansor *et al*., 2024). Islam *et al.,* 2015; Khan *et al.,* 2021) has reported that the major Asian rivers contain potentially hazardous elements in high concentrations such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), nickel (Ni), copper (Cu) and zinc (Zn) which affect aquatic biodiversity and human health. Heavy metals are sinks but also a secondary source in river sediments. Fine sediment particles are good at absorbing dissolved metals due to their high surface area, concentration of clay mineral and the presence of organic materials. Increased bioavailability and ecological toxicity can occur when sediment-bound metals are released from the sediment into the water column due to changes in hydrology, pH, redox potential, and temperature (Zhu *et al.,* 2024; Chakraborty *et al*., 2022). The ongoing sediment-water exchange allows for extended exposure time to the above-water ecosystems and makes pollutant control more difficult. Heavy metals also pose significant risk to human population, as concluded contaminated drinking water, aquatic organism eating and agricultural products irrigated with contaminated water. Long-term exposure has been associated with neurological disorders, kidney dysfunction, liver damage, developmental abnormalities, cardiovascular diseases, impaired immune system, and various forms of cancer (Jaishankar *et al*., 2014; Bansal, 2020). Thus, the effective monitoring programmes and comprehensive ecological and health-risk assessments are essential for protecting freshwater ecosystems and public health. Heavy metal contamination has increased in importance in the context of environmental concerns and this review aims to critically evaluate the scientific information regarding contamination sources, spatial distribution, ecological effects, risks to humans, pollution assessment techniques and sustainable practices.

2. OBJECTIVES OF THE STUDY

This systematic review's main goal is to objectively assess the prevalence, causes, distribution, ecological dangers, effects on human health, and remediation techniques related to heavy metal contamination in Asian river systems. This review is a summary of published scientific data, which is used to improve understanding of pollution levels and to encourage sustainable river management.

Specific Objectives

- To determine the pollutants of interest in Asian river systems in terms of heavy metals.
- To assess natural and anthropogenic sources which contribute to the contamination of the heavy metals.
- To assess temporal and spatial distribution of heavy metals in sediments, river water and aquatic organisms.
- To understand the effects of ecology on aquatic biodiversity and ecosystem function.
- To assess any health threats that humans might face when exposed to polluted water and water-based food.
- To explore pollution assessment indices which is often used to assess pollution.
- To give an overview of the current heavy metal removal remediation technology.

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- To identify gaps in research and areas where future research should be conducted to promote the sustainable management of rivers.

3. MATERIALS AND METHODS

3.1 Review Design

In agreement with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses criteria, this investigation was carried out as a systematic review. The PRISMA framework was used to ensure methodological transparency, repeatability and detailed reporting throughout the process of literature search. The review focused on the sources, distribution, ecological impacts and human health risks, assessment methods for heavy metal pollution, and remediation strategies for heavy metal contaminated Asian river systems. To improve the scientific uniformity, repeatability and transparency, the review methodology was developed following the PRISMA 2020 statement. The review process involved the selection of studies, screening, evaluation for eligibility, data extraction, and qualitative synthesis.

3.2 Literature Search Strategy

Internationally recognized scientific databases were used to conduct a thorough literature search.

Databases Searched

- Scopus PubMed
- Google Scholar
- Search Keywords
- Web of Science
- Science Direct
- Springer Link

Boolean operators (AND, OR) were used for the search strategy; the combination of keywords was included.

- Heavy metal contamination
- Asian rivers
- River sediments
- Water pollution
- Ecological risk assessment
- Human health risk
- Bioaccumulation
- Remediation technologies
- Lead (Pb)
- Cadmium (Cd)
- Mercury (Hg)
- Chromium (Cr)
- Arsenic (As)

3.3 Inclusion Standards

- Examined Asian river systems for heavy metal pollution.

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- Any reported heavy metal content levels in river water, sediments or aquatic life.
- Assessed the dangers to human health and/or the environment.
- Research released between 2000 and 2025.
- Studies carried out in Asian nations.
- Studies using well established analytical techniques (AAS, ICP-MS, ICP-OES and XRF).
- Were printed in scientific journals that undergo peer review.

3.4 Criteria for Exclusion

- Focussed exclusively on coastal or marine environments.
- Did not offer quantitative data on heavy metals.
- Were reviews, editorials, conference abstracts and duplicate articles lacking in primary data?
- The issue of heavy metal pollution in river ecosystems was not directly dealt with.

3.5 Data Extraction

From every eligible study, the following data was taken.

- Study location
- River name
- Pollution assessment indices
- Heavy metals investigated
- Heavy metal concentration Sampling period
- Analytical method
- Reference guideline used (WHO, USEPA, etc.)
- Risk assessment method
- Sources of contamination

3.6 Quality Assessment

Assessment of methodological quality of selected studies was made using the reliability of the data provided, analytical techniques, sampling design, and quality control measures. Studies that were not well described in terms of methodology or quantitative data were not included in the final synthesis.

3.7 Data Synthesis

The data extracted was organized into categories of sources of contamination, distribution of heavy metals, ecological effects, dangers to human health, techniques for pollution assessment, and remediation technologies. A qualitative synthesis was performed to compare the results from the various Asian river systems and identify similar contamination patterns, knowledge gaps and future research needs. The discussion and findings of this review were based on this synthesis. Summary of the databases and literature research methodology used in this review is shown in Table 1.

Table 1. Literature Search Strategy

Database	Search Terms	Years
Scopus	Heavy metal contamination AND Asian rivers	2000–2025
Web of Science	River sediments AND heavy metals	2000–2025

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Science Direct	Water pollution AND Asia	2000–2025
Springer Link	Heavy metals AND river systems	2000–2025
PubMed	Human health risk AND heavy metals	2000–2025
Google Scholar	Ecological risk AND river pollution	2000–2025

The results were compiled based on the sources of contamination, regional dispersion, environmental matrices, and ecological dangers, effects on human health, pollution indices, and remediation strategies.

4. RESULTS

PRISMA Flow Data

Stage	Number of Records
Records identified from databases	1,248
Duplicate records removed	312
Records screened by title and abstract	936
Full-text articles assessed for eligibility	421
Full-text articles excluded	221
Studies included in qualitative synthesis	200

4.1 Sources of Heavy Metal Contamination in Asian River Systems

This section discusses the sources of heavy metal contamination in Asian River Systems. The reviewed literature strongly indicates a dual source of heavy metal pollution in River systems of Asian continent, both natural and anthropogenic origin. Anthropogenic activities, however, are the primary sources of pollutants because of the dramatic increase in pollution discharges to fresh water systems as a result of industrialisation, urbanisation, mining and intensification of agriculture. Heavy metals that are discharged to rivers accumulate in the river bottom and in the water column and can stay there for decades because they are not biodegradable. Sediments are secondary sources of pollution when environmental conditions change, and the metals are liberated back into the water. Most of the Asian rivers have been found to be polluted primarily from industry. Mining, metal processing, electroplating, textile production, chemical industries, cement production, and electronic waste recycling all generate wastewater with dangerous metals like lead (Pb), cadmium (Cd), nickel (Ni), copper (Cu), zinc (Zn), and arsenic (As). Mercury (Hg) and chromium (Cr). In many developing countries, poor wastewater treatment facilities allow untreated industrial waste to directly flow into rivers, leading to higher water pollution and damage to water ecosystems.

Agriculture is one of the major sources of heavy metal pollution. Intensive use of fertilizers, pesticides, irrigation from contaminated water, and soil erosion are all sources of transportation of trace metals such as Cd, Cr, and Pb to neighbouring rivers through surface runoff. One of the agricultural areas most severely impacted by intense rice farming and overuse of fertilizer is the

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Indo-Gang etic Plain. Mining activities also contribute greatly to sediment pollution. Waste materials, which are high in metals, are discharged to the environment in large quantities in the extraction and processing of minerals. Long-term contamination is caused by these pollutants being washed downstream and settling in river sediments. Fine sediment (less than 63 μm) is also highly adsorptive, which means that heavy metals can only become available in the environment after a long period of time. Other natural processes, like air deposition, volcanic deposits, geologic weathering, and erosion of metal-rich rocks can also have an impact on background concentrations of heavy metals. However, their contribution to human activity, in very dense and well-developed human populations of Asia, is much more often than not smaller than their contribution. The major natural and anthropogenic sources of pollution from heavy metals in the rivers of Asia have been summarized in (Table 2).

Table 2. Major Sources of Heavy Metal Contamination in Asian Rivers

Source	**Major Heavy Metals**	**Environmental Impact**
Industrial wastewater	Pb, Cd, Cr, Hg, Cu, Zn, Ni	Water pollution, sediment contamination
Mining activities	Pb, Cd, As Fe, Hg,	Long-term sediment accumulation
Agriculture	Cd, Pb, Cr	Runoff contamination, soil degradation
Municipal wastewater	Cu, Zn, Pb	Decline in water quality
Geological weathering	Mn,Fe, Al,	Natural background contamination
Atmospheric deposition	Hg, Pb	Surface water contamination

4.2 Distribution Patterns of Heavy Metals

The literature analysed shows that the amount of heavy metals found in the river systems of Asia varies depending on the industrial development of the area, land use, hydrological features and management of the environment. Rivers flowing through less developed catchments areas tend to be less contaminated than rivers near industrial estates, mining areas and urban areas with high population density. The main sources of heavy metal build up are river sediments. Thru adsorption onto clay minerals, iron and manganese oxides, and organic matter, fine-grained sediments hold onto metals. Environmental factors such as pH, temperature, and oxidation-reduction potential and hydrologic variations over time affect the mobility of sediment-bound metals. These metals can be brought back into the water column in flooding and sediment activity, increasing the risk of exposure to aquatic organisms. In several studies reviewed in this publication, highly industrialized watersheds were seen to have higher concentrations of these contaminants than international standards for water quality have established: Pb, Cd, Cr, Hg, Ni, Cu and As. The likelihood of long-term ecological harm and human exposure thru the food chain is increased by continuous pollution discharge, which causes progressive build up within aquatic ecosystems. Heavy metal distribution characteristics in river systems are influenced by the sources, physiochemical properties, interactions with sediments, and hydrological conditions (Table 3).

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Table 3. Distribution Characteristics of Heavy Metals in River Systems

Environmental Matrix	Characteristics
Water	Reflects recent contamination events
Sediment	Long-term storage of heavy metals
Aquatic organisms	Bioaccumulation and bio magnification
Agricultural crops	Secondary contamination through irrigation

4.3 Heavy Metals Frequently Reported in Asian Rivers

In all of the analysed research eight heavy metals were consistently determined to be the most important environmental pollutants. Many heavy metals were detected in the river systems of Asian countries such as Pb, Cd, Cr, Hg, As, Cu, Zn, Ni and Mn (Table 4).

Table 4. Frequently Reported Heavy Metals

Heavy Metal	Primary Sources	Major Health Effects
Lead (Pb)	Industrial discharge, traffic	Neurological disorders
Cadmium (Cd)	Fertilizers, industries	Kidney damage
Mercury (Hg)	Mining, industrial waste	Nervous system toxicity
Arsenic (As)	Mining, groundwater	Skin cancer, carcinogenicity
Chromium (Cr)	Electroplating, textile industries	Respiratory diseases, cancer
Nickel (Ni)	Metal industries	Allergic reactions, toxicity
Copper (Cu)	Industrial wastewater	Liver toxicity (high doses)
Zinc (Zn)	Industrial and urban runoff	Toxic at elevated concentrations

Part 4: Ecological Impacts, Human Health Risks, Pollution Assessment, and Remediation

4.4 Ecological Impacts of Heavy Metal Contamination

Heavy metal poisoning is having a significant adverse effect on the ecological integrity of all river ecosystems in Asia. Heavy metal contamination is a chronic problem since they are non-biodegradable and can be accumulated for a long period of time in aquatic organisms and on the health of the environment. After discharged into river, these pollutants accumulate in aquatic biota and sediments and alter the ecosystem processes, and reduce biological diversity. Fish, aquatic plants, benthic macro invertebrates, zooplankton, phytoplankton, and other aquatic creatures are especially susceptible to heavy metal exposure. Toxic metals interfere with physiological and biochemical functions through cell damage, enzyme inhibition, oxidative stress and impairing

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reproductive function. Chronic exposure is frequently associated with poor reproductive performance, behavioural change, decreased immunity, developmental abnormalities, and decreased growth. All these biological processes lead to decreased ecosystem resilience and species richness in the end. Additionally, heavy metals bio accumulates in aquatic creatures and biomagnified as they move via the food web's trophic levels. Thus, predatory fish and higher trophic organisms contain much higher amounts than the lower trophic ones. Such pollution upsets the biological equilibrium of river ecosystems and endangers biodiversity. Heavy metals can affect aquatic animals through a number of pathways including: bioaccumulation, oxidative stress, decreased development and reproduction, and ecosystem disruption (Table 5).

Table 5. Ecological Effects of Major Heavy Metals

Heavy Metal	**Major Ecological Effects**
Lead (Pb)	Reduced fish growth, neurological toxicity
Cadmium (Cd)	Kidney damage in fish, reduced reproduction
Mercury (Hg)	Bio magnification, nervous system toxicity
Chromium (Cr)	Cellular damage, oxidative stress
Arsenic (As)	Reduced biodiversity, ecosystem degradation
Nickel (Ni)	Physiological stress in aquatic organisms
Copper (Cu)	Gill damage and impaired respiration
Zinc (Zn)	Growth inhibition at elevated concentrations

4.5 Human Health Risks

Because exposure to heavy metals can occur thru a variety of environmental pathways, heavy metal contamination presents serious public health risks. Humans may ingest heavy metals directly from contaminated rivers by fish, direct ingestion of contaminated water, or by indirect contact with contaminated sediments, particularly those who reside near the river. Exposure over a period of time can exacerbate cancer and non-cancer health risks. Lead (Pb) primarily causes neurological damage and is associated with kidney failure, hypertension and impaired cognitive function in children. Renal failure and skeletal diseases are caused by cadmium (Cd) accumulation, which primarily occurs in the kidneys and bones. Mercury (Hg) is very neurotoxic and affects the embryonic development and central nervous system. Excessive exposure to arsenic (As) may lead to skin lesions, heart disease, and certain cancers, while exposure to chromium (Cr) may increase the chances of respiratory diseases and cancer. Iron (Fe), zinc (Zn) and copper (Cu) are essential trace elements but excesses are also toxic. Heavy metals, such as Pb, Cd, Hg, As, Cr and Ni have a number of harmful health effects including neurological, kidney, respiratory, cardiovascular and developmental effects. These effects vary in severity depending on the type of metal, the intensity of the exposure, the length of time and the route of the exposure (Tchounwou *et al*., 2012; Jaishankar *et al.,* 2014; Briffa *et al*., 2020) Table 6.

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Table 6. Human Health Effects of Heavy Metals

Heavy Metal	Principal Health Effects
Lead (Pb)	Neurological disorders, developmental toxicity
Cadmium (Cd)	Kidney dysfunction, bone damage
Mercury (Hg)	Neurotoxicity, developmental disorders
Arsenic (As)	Skin lesions, carcinogenicity
Chromium (Cr)	Respiratory diseases, cancer
Nickel (Ni)	Allergic reactions, respiratory irritation
Copper (Cu)	Liver toxicity at excessive concentrations
Zinc (Zn)	Gastrointestinal disorders at high levels

4.6 Pollution Assessment Indices

Several pollution indices have been widely used to estimate the pollution level and the potential risk of heavy metal pollution to environmental and human health in river systems. These indexes provide a uniform way of comparing the level of pollution in different environmental matrices and geographical areas.
These are the most frequent indexes that are reported.

- Heavy Metal Pollution Index (HPI)
- Heavy Metal Evaluation Index (HEI)
- Degree of Contamination (Cd)
- Enrichment Factor (EF)
- Geo-accumulation Index (Igeo)
- Potential Ecological Risk Index (PERI)
- Hazard Quotient (HQ)
- Hazard Index (HI)
- Carcinogenic Risk (CR)

Table 7 summarises some commonly used pollution assessment indices for measuring heavy metal contamination.

Table 7. Common Pollution Assessment Indices

Index	Purpose
HPI	Overall heavy metal pollution assessment
HEI	Heavy metal contamination evaluation
Cd	Degree of contamination
EF	Anthropogenic enrichment determination
Igeo	Sediment contamination classification
PERI	Ecological risk assessment

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The review indicates that the use of these indices as a combined approach provides a comprehensive picture of contamination status and associated environmental hazards, when compared to the use of individual indicators alone.

4.7 Remediation Technologies

Toward lessen heavy metal pollution in river systems, a variety of remediation techniques have been created. A variety of "conventional" chemical precipitation, adsorption, membrane filtration, electrochemical treatment and ion exchange methods are also widely used that have proven to be effective in the lab. The methods tend to create secondary waste and can be very expensive to run. In recent years, the use of environmentally friendly technologies like phytoremediation, bioremediation and nanotechnology remediation has grown in popularity due to their low cost and minimal environmental impact. Bioremediation involves bacteria and microorganisms that bind and/or transform these harmful metals to less hazardous forms; phytoremediation involves using plants that can sequester these contaminants from soil and/or sediment. The advantage of nanotechnology based adsorbents is its high adsorption ability and large surface area and therefore it is more efficient to remove metals. Laboratory scale results are promising and it will require an extended performance test to demonstrate its viability in the field, along with economic analyses and incorporation into working environmental management programs. Therefore, long-term water quality benefits must rely on sustainable water quality remediation (community involvement, regulatory enforcement, industrial water quality treatment, and scientific innovations). Table 8 is a summary of some of the more common remediation methodologies for heavy metals.

Table 8. Heavy Metal Remediation Technologies

Technology	Advantages	Limitations
Adsorption	High removal efficiency	Adsorbent regeneration required
Chemical precipitation	Simple and effective	Produces chemical sludge
Membrane filtration	High purification efficiency	High operational cost
Electrochemical treatment	Rapid removal	Energy intensive
Phytoremediation	Eco-friendly and economical	Slow process
Bioremediation	Sustainable and environmentally friendly	Performance depends on environmental conditions
Nanotechnology	High adsorption capacity	Cost and field-scale application remain challenging

5. DISCUSSION

Heavy metal contamination in Asian river systems has become a serious problem because of the increasing industry, urbanisation, intensification of agriculture and lack of wastewater management. Based on results obtained from this systematic analysis, it can be concluded that human activity is the primary source of the accumulation of heavy metals in the water, sediments and aquatic organisms of the rivers of Asia. Although the background concentrations of toxic metals such as Pb, Cd, Hg, As, Cr, Ni, and Cu are also influenced by natural sources, such as geological weathering and

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soil erosion, the elevated concentrations are mainly associated with industrial discharges, mining activities, agricultural runoff and municipal wastewater discharges.

5.1 Sources and Distribution Patterns of Heavy Metals

The research analysed indicates that industrial activity is one of the primary reasons industrial pollution in the river systems of Asia. Industries such as mining, metal processing, electroplating, textiles, chemicals and E-waste recycling emit large quantities of toxic metals into aquatic environments. In some developing Asian countries, toxic effluents have been directly discharged to rivers due to the rapid pace of industrialization in the countries without any WWTPs. The overuse of pesticides, fertilizers, and tainted irrigation water are other agricultural practices that greatly contribute to heavy metal poisoning. These soils contain Cd, Pb and Cr that can get into the soil in the fields; erosion and runoff of the fields into streams can result in sediment contamination with the metals. The freshwater resources are also under stress due to intensive agriculture practices in large river basin like Indo-Gang etic plain, which releases pollutants like heavy metals, nutrients etc. Intensive agriculture practices are also a stress factor in big river basin like Indo-Gang etic plain by releasing pollutants like heavy metals and nutrients etc. River sediments can also be a reservoir of heavy metals that can be retained for long periods of time. Fine silt particles are particles with a large surface area and are able to bind metals. Environmental factors such as temperature, pH, redox potential or organic material, however, may result in release of metals from sediments and trigger ecological issues as a consequence of increased bioavailable fractions.

5.2 Ecological Impacts of Heavy Metal Contamination

Heavy metals are poisonous, bio-accumulative and are considered to be a serious threat to aquatic ecosystems. Heavy metals are not biodegradable and may stay in an aquatic habitat for a long time, whereas the organic pollutants will decompose. They can build up in animals and plants and in sediments, and can impact on ecological processes, biodiversity and ecosystem stability. Physiological stress, growth retardation, reduced reproduction and mortality have been attributed to high levels of Pb, Cd, Hg, Cr and As in aquatic animals. Fish and other aquatic organisms may also be exposed directly to contaminated sediments and water and become contaminated with metals, which could result in bio magnification via food chains. Administration so, human populations that depend on river resources as well as aquatic biodiversity are seriously threatened by heavy metal contamination. The amount of contaminants is often seen to differ from region to region, and appears higher in areas near to industrial sites, urban centres, mining areas, and agriculture. These trends highlight the need to constantly monitor and identify the sources of pollution in the river for efficient management.

5.3 Hazards to Human Health from Heavy Metals

Heavy metal contamination in river systems is a significant risk to human health due to exposure through drinking contaminated water, consuming fish and shellfish contaminated by heavy metals in the water, and using contaminated water for farming. Long-term exposure to hazardous metals has been associated with neurological diseases, kidney and liver damage, developmental abnormalities, cardiovascular diseases and a higher risk of cancer. Lead pollution is very harmful as it can impact the neurological development of children in particular. Exposure to arsenic is known to cause cancer,

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mercury to damage the nervous system, and cadmium to cause kidney failure and bone damage. Elements such as Zn, Fe and Cu are essential to living processes, but may be toxic and harmful at high concentrations. Thus, the use of concentration measurements as the only criterion for the evaluation of heavy metal pollution is not acceptable. Ecological risk indices and human health risk models, such as Hazard Quotient (HQ), Hazard Index (HI), and carcinogenic risk assessment can be used to get a more comprehensive assessment of the effects on the environment and on public health.

5.4 Pollution Assessment and Monitoring Approaches

To comprehend heavy metal distribution patterns and create suitable management plans, effective monitoring techniques are crucial. Pollution assessment tools like the Heavy Metal Pollution Index (HPI), the Heavy Metal Evaluation Index (HEI), the Geo-accumulation Index (Igeo), the Enrichment Factor (EF) and the Potential Ecological Risk Index (PERI) have been used extensively to measure the level of contamination and ecological hazard. This analysis highlights, however, several limitations in the existing monitoring systems across Asia, including disparities in sampling methods, limited long-term monitoring data and poor regional coordination. Geographic information systems (GIS), remote sensing, automated monitoring devices and predictive modelling are just some advanced technologies that can be integrated to improve pollution detection and assessment as well as environmental decisions. Multivariate statistical analysis in conjunction with ArcGIS spatial mapping can help identify contamination trends even further potential pollution sources, and associated human health risks (Bux *et al.,* 2024).

5.5 Remediation Strategies and Sustainable Management

The remediation techniques that were developed for the removal of heavy metals from contaminated aquatic environment are adsorption, precipitation, membrane filtration, phytoremediation, bioremediation and nanotechnology based treatment techniques. Low cost materials have been found successful in adsorption treatment; this is a technology that is promising to the developing countries where it is essential to provide a low cost treatment system. Likewise, biological methods include phytoremediation and microbial remediation which provide environmentally friendly alternatives. However, even with technological improvements, remediation procedures on a large scale scale are difficult to put into practice as the costs, efficiency, complexity of operation and sustainability issues are not trivial. For efficient heavy metal pollution control, an integrated approach is necessary such as pollution prevention, pollution control by building and upgrading wastewater treatment plants, effective environmental law enforcement, and sustainable resource use. In sum, the findings of our systematic investigation suggest that heavy metal contamination in Asian river networks is a multifaceted environmental issue that requires a multi-faceted approach of science, technology and policy in order to address it in the long-term. To safeguard freshwater ecosystems and mitigate risks to human health, monitoring programs need to be enhanced, industrial wastewater management needs to be improved, sustainable agriculture practices should be promoted, and the collaboration of regions should be strengthened.

6. FUTURE PERSPECTIVES

Integrated, long-term monitoring approach for heavy metal contamination in Asian river ecosystem should be developed in future research. The use of modern technology, like the real time sensors,

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geographic information systems (GIS), remote sensing and predictive modelling, which can facilitate the accurate detection of pollution and early-warning systems, should be used. In order to assess the changes in heavy metal contamination with time and space, large scale regional data sets need to be developed. Further research needs to assess the long-term efficacy of sustainable remediation technologies, including phytoremediation, bioremediation, adsorption technologies and nanotechnology based treatments, from an environmental safety and economic perspective. Researchers, lawmakers, businesses, and residents must work together to make sure the freshwater resources are managed in a sustainable way and to enhance pollution control practices.

7. CONCLUSION

Pollution control practices, heavy metals in industry, discharge of urban wastewater and agricultural runoff are the primary sources of heavy metal pollution in river systems in Asian countries. The presence of toxic metals, such as Pb, Cd, Hg, As, Cr, Ni, and Cu, in river water, sediments and aquatic organisms is not uncommon, and their presence can cause degradation to aquatic ecosystems and increase the threat to human health as this systematic study demonstrates. These qualities (persistance, toxicity, bio accumulation) must be monitored and managed effectively as well as being remediated in the long-term for the heavy metals. Advanced analytical techniques, health risk models and pollution assessment indices are important tools to quantify the levels and effects of contamination. However, more effective environmental regulations, integrated river management techniques and improvements in wastewater treatment plants are needed to reduce the amount of heavy metal pollution. Conservation activities need to become more scientific, develop new technologies, and involve policies and public participation to preserve freshwater ecosystems and ensure a future supply of clean water.

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