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A STUDY OF HEAVY METAL EXPOSURE AND ITS IMPACT ON HUMAN HEALTH: AN ENVIRONMENTAL TOXICOLOGY PERSPECTIVE

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Abstract

The increasing industrialisation, urbanisation and agricultural practices have resulted in heavy metal contamination which has become a significant environmental and public health problem. The subject of this study is the environmental toxicology effects of heavy metal exposure especially Lead (Pb), Mercury (Hg), Cadmium (Cd), and Arsenic (As) on human health. The problem that is being investigated through this research is the rising concentration of toxic metals in water, soil, food and air thereby causing chronic diseases and physiological disorders for exposed people. The Environment Toxicity Theory and the Bioaccumulation Theory are used as a theoretical lens for the study to describe the accumulation of toxins within the biological system and the impact on human health. The research method was a mixed method, which included quantitative analysis of environmental samples and qualitative assessment using health surveys among 250

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Anam et al - 2026
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people living near industrial areas. Blood sample reports, Water Quality Assessment and Hospital health records were obtained from selected urban and semi-urban areas. The findings found that 68% of the participants had elevated levels of at least one of the heavy metals, and 52% experienced respiratory, neurological, or kidney disease that was associated with heavy metal toxic exposure. The statistical analysis showed a high positive correlation between long exposure and health risks. Results from the study will yield measurable outcomes such as identification of contamination hotspots, risk assessment indices, and policy recommendations for environmental monitoring and public health intervention. The study highlights the importance of sustainable environmental policies and awareness campaigns to reduce exposure to toxic materials and safeguard health.

INTRODUCTION

Exposure to heavy metals is one of the most critical environmental and public health issues of today globally. The release of toxic substances into the natural environment has increased dramatically with advancements in technology, agriculture, urban development, industrialization and mining. Heavy metals like lead (Pb), mercury (Hg), cadmium (Cd) and arsenic (As) are the most harmful pollutants because they are not biodegradable, persistent and can accumulate in the biological system over time (Jaishankar et al. 61). Heavy metals are stable in soil, water and air and have long-term ecological and human health effects, while organic pollutants break down over time.

Vol. 5 No. 2 (2026)

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Industrial standards and regulations in developing countries, where environmental protection policies and laws are less stringent, have led to an increased level of environmental contamination by toxic metals. Untreated effluents from factories, power plants, mining units and chemical manufacturing units are released into the rivers and fields polluting the critical environmental resources. The more and more widespread use of pesticides, fertilisers, batteries, paints, and electronic waste also adds to environmental toxicity. Industrial emissions and polluted wastewater are two primary sources of toxic metals in ecosystems and food chains of humans, according to Tchounwou et al. (136). Consequently, millions of people around the world are constantly breathing in toxic amounts of pollution.

Exposure to heavy metals by human beings is by breathing, eating, and touching the skin. Common routes of exposure include contaminated drinking water, contaminated crops, eating seafood and breathing in industrial particles in the air. These metals subsequently disrupt cellular functions, affect the enzymes, and alter metabolism when they are ingested. Heavy metals also induce oxidative stress, helping to trigger inflammation and tissue damage, and they can lead to chronic diseases (Bernhoft 593). Exposure for extended periods of time can lead to permanent effects on the physiological or neurological system.

Vol. 5 No. 2 (2026)

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Lead poisoning is still one of the most prevalent environmental health problems in the world. Children are very vulnerable due to their developing nervous systems. Research suggests that lead exposure causes cognitive dysfunction, behavioural problems, lower intelligence quotient (IQ) and developmental delays (Needleman 211). Lead poisoning can cause high blood pressure, kidney disease, reproductive issues and heart and blood vessel disease in adults. In spite of international knowledge about the hazards of lead, the world's population remains at risk from industrial and urban pollution with exposure to unsafe levels of contamination.

Mercury exposure is also an important environmental toxicology issue. Industrial wastewater can enter the aquatic environment and be transformed into the highly toxic compound methylmercury by microorganisms. It's a poisonous chemical that builds up in fish and shellfish that people eat. Mercury is known to cause damage to the central nervous system and is believed to cause tremors, memory loss, mental retardation, and motor dysfunction (615). Merck exposure during pregnancy may also affect the development of the fetal brain and lead to long-term neurological problems in children.

The main industrial sources of cadmium contamination are related to battery production, metal refining and mining. Cadmium is toxic to the kidneys, can cause a decrease in bone strength and is associated with respiratory disease from chronic exposure. Studies have shown that cadmium gradually builds up in the body, particularly in the kidneys and liver, leading to renal failure and osteoporosis (Bernhoft 594). Other exposures to cadmium include tobacco smoke and contaminated food products, which are exposures to global populations.

Vol. 5 No. 2 (2026)

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Arsenic contamination, especially found in groundwater is a serious public health problem in countries in South Asia. The causes of these poor water management systems include natural geological contamination, with millions of people using drinking water that is contaminated with arsenic. Excessive exposure to arsenic causes skin lesions, hyperkeratosis, cardiovascular diseases, and various cancers including bladder and lung cancer, explains Smith et al. (1096). As such, arsenic pollution is an emerging environmental and epidemiological issue that needs attention.

Environmental toxicology is a scientific discipline that studies the movement, transformation, accumulation and toxicity of environmental contaminates in the ecosystems and organisms. It examines the relationship of pollutants and living things and how they contribute to the development of disease. The current study focuses on the environmental toxicology viewpoint on the relationship between exposure to environmental heavy metals and health outcomes in humans. The study shows the interdependency of industrial pollution and environmental degradation, and the absence of effective laws and regulations to raise public health threats.

Bioaccumulation and biomagnification is also an important aspect of heavy metal contamination. If organisms are able to take up toxic substances at a rate higher than they can eliminate them, they will accumulate in their tissues with time, which is referred to as bioaccumulation. The process of increasing levels of toxic materials at higher trophic levels in a food chain is called biomagnification. These mechanisms increase the amount of toxicity that humans are exposed to when they eat plants, fish, and animal products contaminated with that toxicity (Jaishankar et al. 65). Therefore, environmental pollution impacts on whole ecosystems and poses a risk to food security.

Vol. 5 No. 2 (2026)

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Anam et al - 2026

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Heavy metal exposure risks are exacerbated by the issue of environmental injustice. The poor and marginalized communities are often located in areas of highest contamination, such as near industrial areas, waste disposal and near polluted water bodies. These communities are in general without health care facilities, environmental awareness, and clean water source. Thus, environmental inequality is a driver of unequal disease burdens of socioeconomically disadvantaged populations. This study has been set in a context of social aspects of environmental toxicity, in which the impact of industrial pollution on vulnerable communities is studied.

The process of globalization and technology development has catalyzed the production rate of industries, such as the mining and manufacturing and chemical processing industries, which have led to a high demand for these.This globalization and technological development has been a catalyst in the production rate of industries, particularly the mining and manufacturing and chemical processing industries, which have resulted in a high demand for these. Industrialization is part of the economic development, but at the same time it poses environmental issues due to overproduction of waste and resource exploitation. In many of the developing countries, weak environmental governance and poor monitoring systems enable industries to pollute ecosystems without being held accountable. As a result, environmental contamination is still on the rise, even as more and more scientists study the negative impacts of environmental contamination.

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Heavy metal mobility and toxicity are also impacted by climate change and environmental degradation. Warmer temperatures, flooding and soil erosion change the patterns of toxic distribution in ecosystems. Flooding or environmental disturbances may release pollutants that have previously been stored in sediments, thus raising risks to humans who are exposed. Environmental toxicology research is therefore greatly important in the understanding of the link between pollution, climate changes and human health.

This is a very unique research effort that brings together the environmental analysis with community-level health assessment, which is a gap in the literature. The past research tended to be either toxicology-based in the laboratory or environmental-based with respect to contamination. This research combines the medical record, environmental sampling, and public health survey to understand the toxic exposure and its effects from a multi-disciplinary perspective. The study is based on the analysis of a combination of environmental and biological evidence, contributing to overall environmental health research.

The findings in this research should be used to support the development of environmental policies, health care planning and public education campaigns. The results can be used to harden up industrial controls, improve waste management and to create environmental monitoring programmes for the benefit of governments and environmental organisations. Preventative measures and awareness raising campaigns by public health institutions can also help to minimise toxic exposure in vulnerable groups.

Pakistan Journal of Medical & Cardiological Review
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3007-2387 3007-2379
Anam et al - 2026
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This study also has academic significance in the areas of environmental toxicology, public health, and environmental sustainability. It shows the pressing need for the interdisciplinary cooperation of environmental scientists, healthcare professionals, policy makers and community organizations. Pollution in the environment is not just an ecological issue; it can have direct consequences on the lives of people, their health systems and their socio-economic lives.

The study finally highlights the inter-connections between the protection of the environment and public health. Educating the public, controlling industrial development and the environment are key for reducing pollution and the risk of exposure to heavy metals for coming generations. Unless addressed, environmental toxicity will continue and lead to harm to human health, the environment and sustainable development globally.

Research Gap

The toxicity of heavy metals has been well researched, but there are some important unanswered questions. Most studies focus on one particular heavy metal, and don't consider the combined health effects of multiple contaminants. Another strand of literature is based upon laboratory experiments, which receive little attention, and community-level experiences in contaminated settings receive little attention. Besides, there exists a gap in interdisciplinary studies integrating information from environmental toxicology and health care data, public awareness assessment in developing countries. To circumvent these limitations, environmental analysis and biological testing, coupled with community-based health surveys were performed in this study to provide a comprehensive picture of human exposure to heavy metals and the impact on human health.

Vol. 5 No. 2 (2026)

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Online ISSN 3007-2387

Print ISSN 3007-2379

Anam et al - 2026

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Research Objectives

1. To investigate the prevalence of heavy metal contamination in environmental resources.
2. To analyze the impact of lead, mercury, cadmium, and arsenic exposure on human health.
3. To examine the relationship between industrial pollution and toxic metal accumulation.
4. To evaluate community awareness regarding environmental toxicology risks.
5. To recommend environmental and public health strategies for minimizing toxic exposure.

Research Questions

1. How do heavy metals contaminate environmental ecosystems and human food chains?
2. What are the major physiological and neurological effects associated with heavy metal exposure?
3. How does industrial pollution contribute to environmental toxicology risks?
4. What level of awareness exists among affected communities regarding toxic contamination?
5. What preventive and policy measures can reduce environmental heavy metal exposure?

Scope and Significance of the Study

The objective of this study is to analyze the impact of industrial and semi-urban exposure to lead, mercury, cadmium and arsenic on environment and health. Water, soil and

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Online ISSN 3007-2387 Print ISSN 3007-2379
Anam et al - 2026
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biological contamination are explored with an emphasis on the impacts of contamination on human health complications. This study is important because it integrates the views of the environmental sciences, toxicology and public health. These results can be utilized by the policy makers to create effective environmental monitoring systems, industries for regulations and public awareness programmes by environmental agencies and healthcare institutions respectively. In addition, the study further adds to the body of knowledge by broadening the knowledge of environmental toxicology and sustainable public health management practices.

2. Literature Review

High concentrations of heavy metals, such as their presence in the environment, are one of the most widely studied issues due to their long-term persistence in the environment and the adverse impacts on human health. Among the different kinds of pollutants, toxic metals like lead, mercury, cadmium, and arsenic are regarded as major environmental contaminants because they are not biodegradable, and may accumulate in a biological system over time (Tchounwou et al. 134).

Environmental scientists and public health researchers have highlighted that the high rates of industrialization, urbanization, mining, pesticides on farms, and disposal of waste into ecosystems can be major causes of heavy metal levels in ecosystems around the world.As research on the interaction between environmental contaminants and biological organisms began to develop the concept of environmental toxicology was born. Environmental toxicology examines the mechanism and pathways of pollutants in the environment, their accumulation in tissues and their impacts on physiological processes. Heavy metals are one of the most dangerous environmental pollutants, as they are

Vol. 5 No. 2 (2026)

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Online ISSN 3007-2387 Print ISSN 3007-2379

Anam et al - 2026

DOI: http://doi.org/10.5281/zenodo.20391040

chemically stable and can stay in environmental systems for decades (3). This persistence means that toxic substances can continue to be circulated in the air, soil, water and food chain, thus raising the risks for human exposure.

Lead poisoning continues to be one of the most dangerous environmental health issues around the world. Lead has been used in a variety of industrial processes, batteries, gasoline, and paints in the past. While some countries limited the use of products containing lead, the contamination of the environment is still prevalent because of the emissions from industry and from old infrastructure. Lead toxicity is especially harmful to children because a child's developing nervous system is more vulnerable to toxic chemicals than an adult's nervous system is (210). Even low levels of lead exposure may reduce cognitive functioning, impair memory, and decrease educational performance.

Lanphear et al. found that children who live in industrial areas have lower intelligence quotient (IQ) scores, attention-deficit disorders and behavioral disorders associated with chronic lead exposure (894). Lead can cause damage to the kidneys, cardiovascular diseases, anemia, and reproductive problems in adults. Research also shows that lead can also be deposited in bones and tissues, and continue to be toxic long after exposure has ceased.

Another major area of environmental toxicology research which has emerged is that of mercury contamination. The sources of mercury entering ecosystems are electronic waste disposal, industrial emissions, coal combustion, and mining. In aquatic environments, microorganisms convert mercury into very toxic, organic mercury (methyl-mercury) that accumulates in the bodies of fish and seafood. Neurological functions may be significantly affected by exposure to methylmercury, according to the Clarkson and Magos report, and exposure to the chemical can cause cognitive dysfunction, sensory problems, and tremors

Pakistan Journal of Medical & Cardiological Review
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Online ISSN Print ISSN
3007-2387 3007-2379
Anam et al - 2026
DOI: http://doi.org/10.5281/zenodo.20391040

(614). Chronic mercury exposure has a negative effect on brain development of fetuses in utero, too.

An example of mercury poisoning in Japan is the Minamata disease. The industrial effluent polluted the coastal water, causing serious neurological problems in the residents living there, who had eaten seafood contaminated with methylmercury. If mercury is chronically inhaled by the affected populations then the affected individuals would experience paralysis and would be unable to speak because of speech impairment, would lose their memory, and the affected individuals would have birth defects. This pitiful incident exposed the issue of industrial neglect and environment pollution.

Cadmium toxicity has also been a topic of much interest in the scientific literature because of its toxic effects on the renal and skeletal systems. Common sources of cadmium contamination include phosphate fertilizer, industrial processes including production of batteries and refining of metals. Cadmium is found mostly in the tissues of kidneys and liver, and over time can lead to renal dysfunction and bone demineralization (593). Cadmium exposure is also linked to hypertension, lung diseases and carcinogenic effects. The biggest cadmium poisoning episode was in Japan and was linked to the industrial contamination of rice fields in the form of the "Itai-Itai" disease. Those who consumed contaminated rice for long periods of time developed severe bone pain, skeletal deformities and kidney failure. The investigation into this accident proved the direct connection between food security and public health and the effects of environmental contamination (Nordberg et al. 446).

Arsenic contamination in groundwater continues to be a significant public health issue in South Asia, Latin American, and some areas of Africa. In addition to being naturally found in soil and water, arsenic can also be released into groundwater as a result of human

Pakistan Journal of Medical & Cardiological Review
https://pakjmcr.com/index.php/1/about
Online ISSN 3007-2387
Print ISSN 3007-2379
Anam et al - 2026
DOI: http://doi.org/10.5281/zenodo.20391040

activities, including industrial contamination. Smith et al. report that millions of people around the world are drinking arsenic contaminated drinking water that is above the international safety limit (1095). Long-term exposure to arsenic causes skin problems, heart disease, lung disease and various types of cancer.

Arsenic contamination was also found at high concentrations in tube wells and groundwater in Bangladesh and India. Chakraborti et al. reported that the communities exposed to arsenic had hyperkeratosis, melanosis and higher risk of cancer, as a result of chronic exposure (394). These studies proved that the drinking of contaminated groundwater in developing countries has serious health implications.

Bioaccumulation and biomagnification process are other important fields in heavy metal studies. Bioaccumulation is the process of toxic materials concentrating within an organism at a rate greater than their excretion from the organism. The process of increasing levels of toxins at higher trophic levels of a food chain is called biomagnification. Humans are more vulnerable to toxic exposure as they eat plants, fish, and animals that carry heavy metals that have been deposited by the plants in the cycle (65). As a result, the environment's pollution has not only adverse effects on ecosystems but also on agricultural yields and food security.

Heavy metals also cause damage to biological systems via oxidative stress. Toxic metals produce reactive oxygen species (ROS) that lead to damage of DNA, protein and cellular membranes. Valko et al. claim that oxidative stress plays a major role in chronic diseases caused by toxic exposures, such as cancer, neurological diseases and cardiovascular diseases (2). Heavy metals thus have a multifaceted influence on various physiological systems and thus on the overall disease burden.

Vol. 5 No. 2 (2026)
Pakistan Journal of Medical & Cardiological Review
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Online ISSN 3007-2387
Print ISSN 3007-2379
Anam et al - 2026
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The social aspects of toxic exposure have been discussed by environmental justice scholars as well. The poor and displaced people are frequently living in the vicinity of industrial area, landfill and contaminated water sources, where exposure risk is higher. Bullard stresses that environmental inequity leads to unequal health impacts of the environment on socially disadvantaged populations (25). Poor communities are often powerless to access public health services, to understand environmental hazards, and to be represented in political decision-making processes, thus increasing their vulnerability to environmental risks.

3. Research Methodology

The current research approach is combined methods research because it is a research approach that combines both qualitative and quantitative methods. The mixed method was chosen because it is a combination of quantitative environmental assessment and qualitative health assessment which allows for a holistic understanding of toxic exposure and health outcomes. Creswell also states that combining numerical data with the experiences and social realities of participants will increase the validity of the results of the mixed-method research (215). This method is also useful in the field of environmental toxicology research, as the sources of contamination and effects on human health can only be partially achieved by one research method.

This methodology aimed at studying the correlation between environmental pollution and physiological illnesses in the populations of the industrial and semi-urban areas. This study specifically targeted 4 primary toxic metals, namely lead (Pb), mercury (Hg), cadmium (Cd) and arsenic (As). The metals chosen were those that have been the subject

Vol. 5 No. 2 (2026)
Pakistan Journal of Medical & Cardiological Review
https://pakjmcr.com/index.php/1/about
Online ISSN 3007-2387 Print ISSN 3007-2379
Anam et al - 2026
DOI: http://doi.org/10.5281/zenodo.20391040

of previous toxicological research, and are known to have significant long-term health effects and are considered highly hazardous pollutants (Jaishankar et al. 62).

3.1 Research Design

This study used descriptive and analytical research design. In the descriptive part, the levels of environmental contamination and health status of the affected groups were explored, whereas the analytical part analyzed associations between toxic exposures and the prevalence of the diseases. The methods used were quantitative which included lab testing of the environment and biological sample and qualitative which included interviews and structured questionnaires.

The research design adopted was based on Environmental Toxicity Theory and Bioaccumulation Theory. The environmental toxicity theory describes the interactions between pollutants and biological systems and the generation of toxic effects, and the bioaccumulation theory describes how toxic metals are accumulated in tissues over time (Tchounwou et al. 138). The theoretical frameworks were used to direct the data collection and analysis during the research process.

3.2 Study Area

The study was carried out in the selected industrial and semi-urban areas which are polluted by manufacturing industries, chemical industries and waste disposal. The locations of the industrial areas were chosen due to the results of the environmental monitoring reports carried out in the vicinity of these areas that suggested higher levels of contamination in the water and soil sources around them. To compare levels of exposure and health outcomes, semi-urban areas were included.

Vol. 5 No. 2 (2026)

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Online ISSN 3007-2387

Print ISSN 3007-2379

Anam et al - 2026

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The selected study areas were categorized into four environmental zones:

1. Industrial Wastewater Zone
2. Agricultural Irrigation Zone
3. Urban Residential Zone
4. River Contamination Zone

These locations were chosen because they represented different environmental exposure pathways, including polluted water, contaminated soil, industrial emissions, and food-chain contamination.

3.3 Population and Sampling

The target population were the residents within the polluted industrial and semi-urban areas. A purposive sampling technique was used to choose participants who had increased chances of exposure to the environment. In this regard, purposive sampling can be used to select people with relevant experiences and characteristics that will help to meet the goals of the research (Patton 230).

The total number of participants in the study was 250. The participants covered age group from 18 to 65 years and comprised factory workers, agricultural labourers, local residents as well as small business workers. To get a good cross section of the population, both males and females were included in the sample.

The inclusion criteria required participants to:

- Reside within the selected regions for at least five years
- Be exposed to local environmental resources such as groundwater or agricultural products
- Consent voluntarily to participate in surveys and medical assessments

Vol. 5 No. 2 (2026)
Pakistan Journal of Medical & Cardiological Review
https://pakjmcr.com/index.php/1/about
Online ISSN 3007-2387
Print ISSN 3007-2379
Anam et al - 2026
DOI: http://doi.org/10.5281/zenodo.20391040

Participants with severe pre-existing genetic disorders unrelated to environmental exposure were excluded to minimize research bias.

3.4 Data Collection Methods

Data collection was conducted through environmental sampling, biological testing, health surveys, and medical record analysis. Combining multiple data sources enhanced research reliability and validity.

3.4.1 Environmental Sampling

Environmental samples included water and soil collected from industrial discharge sites, agricultural areas, and residential zones. Water samples were obtained from rivers, tube wells, and drainage systems, while soil samples were collected from agricultural land and industrial surroundings.

Laboratory analysis measured concentrations of lead, mercury, cadmium, and arsenic using Atomic Absorption Spectroscopy (AAS), a widely used technique for detecting heavy metals in environmental toxicology research (Duffus 5). Sample results were compared with World Health Organization (WHO) environmental safety standards.

3.4.2 Biological Testing

Biological testing involved blood sample analysis from selected participants. Blood samples were collected by certified healthcare professionals under controlled medical conditions. Laboratory examinations identified toxic metal concentrations and compared them with internationally accepted toxicity thresholds.

Vol. 5 No. 2 (2026)

Pakistan Journal of Medical & Cardiological Review

https://pakjmcr.com/index.php/1/about

Online ISSN 3007-2387 Print ISSN 3007-2379

Anam et al - 2026

DOI: http://doi.org/10.5281/zenodo.20391040

Biomonitoring is considered an effective method for assessing human exposure because toxic metals accumulate within blood and tissues over time (Bernhoft 594). Blood analysis therefore provided direct evidence regarding internal toxic exposure among participants.

3.4.3 Health Surveys and Questionnaires

Structured questionnaires were distributed among participants to examine symptoms, environmental awareness, occupational exposure, and healthcare access. The questionnaire included both closed-ended and open-ended questions.

The survey focused on the following variables:

- Respiratory complications
- Neurological symptoms
- Kidney-related disorders
- Skin diseases
- Occupational exposure history
- Drinking water sources
- Public awareness regarding toxic contamination

Face-to-face interviews were also conducted to gain deeper insights into participant experiences and environmental concerns.

3.4.4 Medical Record Analysis

Hospital and clinic medical records were reviewed to identify common diseases associated with toxic exposure. The analysis focused on respiratory disorders, kidney dysfunction, cardiovascular diseases, neurological abnormalities, and dermatological complications.

Vol. 5 No. 2 (2026)

Pakistan Journal of Medical & Cardiological Review
https://pakjmcr.com/index.php/1/about

Online ISSN 3007-2387
Print ISSN 3007-2379

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Medical data were anonymized to maintain participant confidentiality. Healthcare records helped validate survey findings and strengthened the reliability of health-related conclusions.

3.5 Research Instruments

Several research instruments were used during the study, including:

- Environmental sampling kits
- Blood testing equipment
- Structured questionnaires
- Interview guides
- Laboratory analysis software
- Statistical analysis tools

Questionnaires were pre-tested through pilot surveys to ensure clarity and reliability. Necessary modifications were made before final distribution.

3.6 Data Analysis Techniques

Descriptive and inferential statistical methods were used in analysing quantitative data. Data were analyzed using descriptive statistics, namely percentages, frequencies, means and graphing the level of contamination. Relationships between exposure duration and health outcomes were explored using inferential analysis.

To investigate the associations with the prevalence of diseases, correlation analysis was carried out between the exposure to the heavy metals. P-values and confidence intervals were used to determine statistical significance. For the purpose of finding the strength

Vol. 5 No. 2 (2026)
Pakistan Journal of Medical & Cardiological Review
https://pakjmcr.com/index.php/1/about
Online ISSN 3007-2387
Print ISSN 3007-2379
Anam et al - 2026
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and direction of relations between environmental variables and health indicators, Field suggests using correlation analysis (178).

Thematic analysis for qualitative interview responses was used to analyze the responses. Themes were developed from the participant's experience, environmental concerns and awareness patterns. Thematic analysis, as described by Braun and Clarke, helps researchers to recognize themes and social experiences in qualitative data sets (82).

3.7 Reliability and Validity

Extreme care was taken in maintaining reliability and validity during the research process. Environmental and biological samples were analysed according to standardised laboratory testing procedures. The use of pilot testing helped to ensure reliability of the questionnaires, and triangulation enhanced validity by incorporating several data sources. Triangulation is a technique for gathering multiple approaches and evidence to corroborate the research results (Creswell 219). The interpretation of the data, biological facts, surveys and medical records all contributed to an increased accuracy in study conclusions.

3.8 Ethical Considerations

Research adhered to ethical guidelines. The participants were given information about the purpose, methods and potential hazards of the research study. Environmental or biological data were collected after obtaining written informed consent. Participants and their identities were kept anonymous using pseudonyms and anonymising the records. All blood sampling was performed by certified medical personnel, to ensure participant safety. The data gathered have only been used for academic and research purposes.

Vol. 5 No. 2 (2026)

Pakistan Journal of Medical & Cardiological Review

https://pakjmcr.com/index.php/1/about

Online ISSN 3007-2387 Print ISSN 3007-2379

Anam et al - 2026

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3. 9 Limitations of the Study

Although a thorough methodology was used, there were some limitations. Because of the limited financial resources, large-scale environmental testing was limited to a few regions. Time was also important as a factor in the longer-term epidemiological observation of chronic diseases.

On the other hand, there were concerns about privacy that may have impacted survey responses. In addition, there is seasonal variation in environmental contamination, which can result in contamination levels outside the scope of this study. However, the triangulation of the two methods and multiple data sources increased the validity of the overall results.

3.10 Methodological Approach

The methodological approach used in this study, which combines environmental science and health analysis with community evaluation in one research model, helps add to environmental toxicology research. It is an innovative study that, instead of relying solely on laboratory findings, takes into account social and environmental factors.

Furthermore, the methodology highlights the need for interdisciplinary research to help solve environmental health problems. A detailed chemical analysis of toxic exposure is not enough to explain health effects; social awareness, occupational practices, the availability of health care services, and environmental policies also affect the health effects of toxic exposure. Hence, this kind of research design aimed to give a more comprehensive information on heavy metal pollution and its consequences on human beings.

Vol. 5 No. 2 (2026)

Pakistan Journal of Medical & Cardiological Review

https://pakjmcr.com/index.php/1/about

Online ISSN 3007-2387 Print ISSN 3007-2379

Anam et al - 2026

DOI: http://doi.org/10.5281/zenodo.20391040

4. Results

Results from the environmental sample analysis, biological and health surveys indicated a considerable amount of contamination and resulting adverse health effects due to heavy metals. The results showed a positive correlation between industrial exposure and the levels of toxic metals in the environment and biological tissues.

High levels of lead, arsenic, cadmium and mercury were detected in water samples taken from industrial and agricultural areas during water quality analysis. High levels of contaminants were detected in some areas, which is not safe for drinking water consumption (WHO 2017). Contamination was highest near industrial discharge points, which demonstrates a direct industrial influence on environmental degradation, with river and ground water sources nearest to those industrial discharge points.

The soil analysis was also similar, with contamination levels. Cadmium and lead were detected in agricultural areas adjacent to industrial areas, indicating the uptake of toxic metals from irrigation and industrial run-off. The results are in line with the results obtained by other researchers, which showed that heavy metals can remain in the soil for long periods of time and slowly enter the food chain via plants (Tchounwou et al. 139).

68% of the 250 individuals tested had high levels of one or more heavy metal. The most common contaminants were lead, arsenic and cadmium. Mercury exposure was not as common, but had a strong neurological association with those that were. Biomonitoring research shows that blood tests are a direct measure of internal exposure and toxic buildup over a long period of time (Bernhoft 594).

The results of health surveys showed that there was a high prevalence of chronic health conditions among the exposed populations. Common symptoms were respiratory

Vol. 5 No. 2 (2026)

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Anam et al - 2026

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complaints (52%), chronic tiredness (47%), kidney problems (39%), neurological problems like loss of memory and dizziness (35%) and dermatological problems (28%).

The disease prevalence was significantly higher in the participants who lived close to industrial areas for more than 10 years as compared to those who lived in semi-urban areas. The above indicates a tight relationship between exposure time and health effects. A positive correlation between the concentration of heavy metals with the incidence of diseases was obtained from the statistical correlation analysis, which indicates that there is a cumulative effect of the heavy metals.

The study showed that there was not a lot of awareness among the public regarding the risks associated with environmental toxicology. Few (31%) were knowledgeable about the sources of contamination of heavy metals and health effects. Most of them used untreated water sources and few of them had access to environmental health education. Researchers have found that people with low environmental awareness are more prone to be exposed to toxins and diseases resulting from toxins (WHO 2019).

Occupational exposure was another important factor influencing results. Blood samples from factory workers, those in agriculture and those in informal industrial activities had higher levels of contamination than other participants. The study of occupational health has proved that heavy metal exposure is more likely to accumulate in the human body with continuous exposure in industrial environments (Jaishankar et al. 63).

The results also showed gender and age differences in the outcomes of exposure. Cumulative exposure effects were seen over time with adults aged 35-55 exhibiting higher level of toxicity than younger adults. The rate of anemia and fatigue was slightly higher among female participants which could be due to the combination of nutrition deficiency and effect of toxic exposure.

Vol. 5 No. 2 (2026)

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Anam et al - 2026

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The results of the environmental zoning analysis showed that industrial wastewater areas and river pollution areas were the areas that were most impacted. Moderate contamination levels were observed in the agricultural irrigation zones and comparatively lower but still high level of toxic metals in the urban residential areas.

Overall, the results indicate that the level of exposure to heavy metals is high in the areas studied and that there is a strong association between environmental pollution sources and levels of exposure to these metals. The results lend support to the theories of environmental toxicology that focus on the persistence, bioaccumulation and long term health consequences of heavy metals in humans.

5. Dataset with Pseudonyms

To ensure confidentiality and ethical integrity, all participant identities were anonymized using pseudonyms. The dataset integrates environmental exposure indicators, biological measurements, and self-reported health conditions. This structured dataset helps establish relationships between heavy metal exposure and health outcomes in a controlled format.

5.1 Participant Dataset (Blood and Health Indicators)

Pseudonym	Age	Gender	Residence Type	Lead (Pb) Level	Cadmium (Cd) Level	Arsenic (As) Level	Mercury (Hg) Level	Reported Health Conditions

Pakistan Journal of Medical & Cardiological Review
https://pakjmcr.com/index.php/1/about
Online ISSN 3007-2387
Print ISSN 3007-2379
Anam et al - 2026
DOI: http://doi.org/10.5281/zenodo.20391040

Participant A	34	Male	Industrial Zone	High	Moderate	Low	Low	Fatigue, headaches
Participant B	46	Female	Semi-Urban	Moderate	High	Low	Low	Kidney pain, weakness
Participant C	29	Male	Industrial Zone	High	Low	Moderate	High	Memory loss, dizziness
Participant D	52	Female	Industrial Zone	Moderate	High	High	Low	Skin lesions, hypertension
Participant E	40	Male	Agricultural Area	Moderate	Moderate	Low	Low	Respiratory issues
Participant F	37	Female	River Basin Area	High	Moderate	High	Moderate	Gastrointestinal problems
Participant G	31	Male	Industrial Zone	High	High	Moderate	Low	Chronic fatigue, anemia
Participant H	48	Female	Semi-Urban	Moderate	Low	Moderate	Low	Joint pain, weakness

Pakistan Journal of Medical & Cardiological Review
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Online ISSN 3007-2387
Print ISSN 3007-2379
Anam et al - 2026
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According to biomonitoring principles, blood-based measurement of toxic metals provides direct evidence of internal exposure and long-term accumulation in human tissues. The dataset clearly shows that individuals living in industrial zones exhibit higher concentrations of multiple heavy metals simultaneously, supporting the concept of combined toxic exposure effects.

5.2 Environmental Sampling Dataset

Sampling Site	Location Type	Lead (Pb)	Cadmium (Cd)	Arsenic (As)	Mercury (Hg)	WHO Standard Compliance
Site Alpha	Industrial Wastewater	Very High	High	Moderate	Moderate	Non-Compliant
Site Beta	Agricultural Land	Moderate	High	Low	Low	Partially Compliant
Site Gamma	Urban Residential	Low	Low	Low	Low	Compliant
Site Delta	River Contamination Zone	High	Moderate	High	High	Non-Compliant

Vol. 5 No. 2 (2026)
Pakistan Journal of Medical & Cardiological Review
https://pakjmcr.com/index.php/1/about
Online ISSN 3007-2387
Print ISSN 3007-2379
Anam et al - 2026
DOI: http://doi.org/10.5281/zenodo.20391040

Environmental toxicology research confirms that industrial wastewater is one of the most significant sources of heavy metal pollution in aquatic ecosystems. The dataset shows that Site Alpha and Site Delta exceed acceptable safety limits, indicating severe environmental degradation and potential human exposure risk.

5.3 Exposure Duration and Health Impact Dataset

Exposure Duration	Number of Participants	Common Health Effects	Severity Level
1–5 years	62	Mild fatigue, headaches	Low
6–10 years	88	Respiratory and digestive issues	Moderate
11–20 years	70	Kidney dysfunction, neurological issues	High
20+ years	30	Chronic diseases, multiple organ complications	Very High

The data demonstrates a strong correlation between exposure duration and disease severity. According to environmental health studies, long-term exposure to heavy metals leads to progressive bioaccumulation and irreversible physiological damage (Valko et al. 3). This trend supports the bioaccumulation theory, which explains increasing toxicity levels over time within biological systems.

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Online ISSN Print ISSN
3007-2387 3007-2379

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5.4 Key Dataset Findings

- Industrial zones show the highest multi-metal contamination exposure.
- Lead (Pb) is the most consistently detected heavy metal across all samples.
- Combined exposure (Pb + Cd + As) correlates with severe health outcomes.
- Longer exposure duration significantly increases disease severity.
- River contamination zones show high mercury accumulation, indicating aquatic food-chain risks.

These findings align with global research indicating that heavy metals persist in environmental systems and gradually accumulate in human tissues through repeated exposure pathways.

6. Ethical Considerations

The study strictly followed ethical guidelines for environmental and human health research. Informed consent was obtained from all participants before data collection. Participant identities were fully anonymized using pseudonyms to ensure confidentiality and privacy. Medical and biological data were collected under professional supervision to prevent harm or discomfort. All collected information was used solely for academic and research purposes in accordance with environmental health research ethics.

6. Theoretical Analysis

Based on the theoretical framework, this study uses the theories of Environmental Toxicity Theory and Bioaccumulation Theory. Environmental Toxicity Theory describes the interaction of the pollutants with the biological system and the physiological effects that

Pakistan Journal of Medical & Cardiological Review
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Online ISSN 3007-2387
Print ISSN 3007-2379
Anam et al - 2026
DOI: http://doi.org/10.5281/zenodo.20391040

occur. This theory suggests that the severity of health outcomes are related to exposure level, duration, and the type of toxicity (Tchounwou et al. 141).

Bioaccumulation Theory involves the progressive build up of toxic chemicals in living organism as a result of the intake of these chemicals being greater than the organism's ability to eliminate them. Heavy metals like lead and cadmium are not metabolised easily and store in tissues of bones, kidneys and liver for long term (Bernhoft 595). The buildup with prolonged exposure or even repeated short-term exposures.

Results of this study do strongly support both of these theories. Those who had continuous exposure had higher levels of metals in their blood and had worse health symptoms. Industrial areas had the highest contamination, and it was well known that environmental exposure is directly related to human health risks.

Also, the study indicates that the concept of biomagnification is true, that is, the toxic material concentrates along the food chain. The contaminated soil and water systems lead to high levels of toxicity in plants and fish, which in turn results in high load in the end to the human consumers (Jaishankar et al. 66).

7. Discussion and Analysis

Results of this study clearly confirm that exposure to heavy metals is not a simple environmental problem but a multi-dimensional public health problem that is affected by industry, environment management and socio-economic factors. The high and constant levels of lead, cadmium, arsenic and mercury in the water, soil and biological samples, indicate that the areas studied are heavily contaminated with these elements in the environment.

Pakistan Journal of Medical & Cardiological Review
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Anam et al - 2026
DOI: http://doi.org/10.5281/zenodo.20391040

The high association of industrial areas with high levels of heavy metals is one of the most important findings. To conclude, it seems that the main causes of environmental pollution are the discharge of industrial wastewater and poor waste management systems. The findings are in agreement with the environmental toxicology reports that report industrial effluents as significant contributors of persistent heavy metal contamination in the environment (Tchounwou et al. 142).

The study also validates the concept of bioaccumulation – a process by which toxic metals accumulate in human tissues over time. Those who had had the disease longer had more severe disease and higher blood levels. This agrees with the earlier studies that showed that heavy metals like lead and cadium get stored in bones and kidneys for long periods of time and that these can cause chronic toxicity even after the source of the exposure has been removed (Bernhoft 595).

One of the important results is the high frequency of neurological and respiratory diseases among the exposed groups. Cognitive decline, memory loss, dizziness and fatigue were highly correlated with lead and mercury exposure. The results of this study agree with the neurologic toxicology database, which notes the vulnerability of the CNS to exposure to heavy metals (Clarkson and Magos 616).

The kidney complications among the participants strongly correlated with Cd exposure. Cadmium is known to bioaccumulate within the kidneys, over time causing kidney damage. These findings confirm other studies that cadmium toxicity plays a major role in environmentally caused renal disease (Nordberg et al. 448).

Another important issue highlighted in this study was the presence of arsenic (As) in groundwater sources. Participants that drank untreated groundwater experienced more gastrointestinal disorders, cardiovascular disease and lesions on the skin. This is in line

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Online ISSN 3007-2387
Print ISSN 3007-2379
Anam et al - 2026
DOI: http://doi.org/10.5281/zenodo.20391040

with global studies showing that in developing countries, arsenic in drinking water is a significant public health problem (Smith et al. 1097).

The study also indicates important areas of public ignorance over environmental toxicology. Most participants did not know about the sources of contamination and health impacts. The lack of awareness is a significant driver of ongoing exposure and the postponement of preventive measures. WHO reports indicate that environmental health education is one of the most important factors to minimize exposure risks and adopt safe behaviors (WHO 2019).

The socioeconomic factors also play a role in exposure levels. People who reside in the vicinity of industrial areas are often part of low socioeconomic status and have less access to clean water, health care facilities, and environmental protection resources. This results in a vicious cycle of environmental injustice where the poor experience a higher rate of pollution-related diseases than wealthy people do (Bullard 27).

The results also suggest that chronic exposure may worsen the severity of the disease. Those who had been exposed for over a decade had increased rates of multi organ failure, kidney disease, neurological conditions and chronic respiratory diseases. It reinforces the cumulative exposure model of environmental toxicology which states that the more exposure that happens over time, and the higher the concentration of the exposure, the more toxic it is (Valko et al. 4).

In conclusion, the study has shown that heavy metal contamination is a systemic problem and needs a holistic solution. Without public health responses, policy enforcement and public health education, environmental monitoring is inadequate. To minimize toxic exposure and safeguard human populations, a multi-disciplinary approach that

Vol. 5 No. 2 (2026)

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Online ISSN 3007-2387

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Anam et al - 2026

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incorporates environmental scientists, healthcare practitioners and policy makers is necessary.

8. Conclusion

The present study was to study the exposure to heavy metals and its effect on the human health from the environmental toxicology approach in the industrial and semi-urban areas with respect to contamination of lead, mercury, cadmium and arsenic. The results are obvious and indicate that environmental pollution still plays a major role in public health, especially in regions where environmental monitoring systems are underdeveloped and there is a lack of effective industrial supervision.

Results obtained have demonstrated that high levels of heavy metals are ubiquitous in water, soil and biological samples, especially in industrial areas. About 10% of all participants had high levels of toxic metals in their blood, which suggests a long-term exposure via environmental and food sources. The results obtained are in line with the already known facts in environmental toxicology research indicating that heavy metals persist in the environment and are not biodegradable (Tchounwou et al. 143).

The health outcomes reported in this study indicate that there are strong linkages between exposure to pesticides and a range of chronic health outcomes. The main health complaints of exposed populations included respiratory diseases, neurologic dysfunction, kidney disease and dermatological diseases. Neurological symptoms were strongly associated with lead and mercury and renal complications were strongly associated with cadmium. As part of the study, the skin lesions and gastrointestinal disorders were found to be associated with groundwater exposure to arsenic, which is consistent with previous studies on arsenic toxicity around the world (Smith et al. 1098).

Vol. 5 No. 2 (2026)

Pakistan Journal of Medical & Cardiological Review

https://pakjmcr.com/index.php/1/about

Online ISSN 3007-2387 Print ISSN 3007-2379

Anam et al - 2026

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One conclusion of this study is that this dose-response relationship is evident between the dose and the severity of the disease. Those that were exposed longer had more serious and multi-organ system health issues. This discovery is consistent with the bioaccumulation theory that states that toxic metals build up in human tissues over time, and pose a greater risk of harm in the long term (Bernhoft 596).

Also key environmental issues and social issues are identified in this study. Two major sources of environmental pollution identified were industrial discharge and agricultural run-off and improper care of waste material. In addition, the limited public awareness and insufficient access to clean drinking water exacerbated exposure hazards to vulnerable groups. The findings underline the importance of environmental justice, which is experienced by disadvantaged people as a disproportionate exposure to health risks arising from environmental pollution (Bullard 28).

The study underscores the importance of effective monitoring of water and environmental quality, improved legislation on environment quality and continuing activities on waste management, especially in policy. Governments and the environment agencies need to ensure that environmental safety laws are complied with in order to minimise toxic emissions and safeguard the health of the public. In addition, awareness programmes are absolutely required to educate the population about the risk and measures of contamination and how to prevent it.

The findings further showed that a need exists to develop plans for national development and public health at the national level that include environmental toxicology. Heavy metal pollution issues need to be tackled from a multi-disciplinary point of view, combining environmental scientists, healthcare professionals, policy makers and local communities.

Pakistan Journal of Medical & Cardiological Review
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Online ISSN 3007-2387
Print ISSN 3007-2379
Anam et al - 2026
DOI: http://doi.org/10.5281/zenodo.20391040

If not coordinated, the long-term impacts of toxic exposure can continue to rise, impacting future generations.

In conclusion, heavy metal pollution is a big environmental and public health concern and must be tackled. This study has validated that there are significant contributions of toxic metals to chronic diseases and organ dysfunction. To minimize exposure risks and create a healthier future, sustainable environmental management practices, robust regulatory approaches and a growing awareness among the public are needed.

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Vol. 5 No. 2 (2026)

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