Evaluation of Heavy Metal Contamination in Irrigation Water from the Yamuna River: A Review

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ABSTRACT
Delhi relies on the Yamuna River, one of the nation's most contaminated. Yamuna River is the main irrigation and water source. Farmers farm the entire Yamuna Pusta. Water quality depends on physicochemical and biological qualities. pH, temperature, and minute amounts of necessary and superfluous metals in water can make it unsafe for humans. Home and industrial sources cause 85% of pollution. Private and industrial waste from coal washery, plastic, steel, food processing, metal work, and leather tanning pollutes the river. The principal sources of heavy metal contamination in water are these activities. Metals in polluted soil bioaccumulate in crops. Heavy metal ions like Cd (II), Hg (II), Pb (II), Ni (II), As (V and III), Cr (VI), and Cu (II) in water can cause liver damage, kidney impairment, stomach and skin tumors, mental ailments, and reproductive system damage. Therefore, heavy metal effluence in water must be measured and eliminated. This study examines Yamuna River water and agricultural samples. To study heavy metals' harmful consequences.

Keywords: Heavy Metals , Yamuna Water , Contamination , Acid Mine Drainage (AMD) , Bioaccumulation

1. INTRODUCTION

In contemporary times, industrial expansion has resulted in increased pressure on rivers, leading to water pollution and exacerbating environmental health concerns (Brhane *et al*. 2014). Rivers are crucial freshwater supplies that have supported the growth of our ancient civilizations and continue to play a vital role in various activities. Various sectors, including agriculture, industry, transportation, aquaculture, and public water supply, utilize river water. The River Yamuna is the main water source for home and agricultural needs in various regions of India, meeting over 90% of the total water demand (Salgarello *et al.* 2013). Regrettably, in recent times, the Indian Yamuna river, its primary tributaries, and catchment region have experienced significant pollution as a result of the release of untreated or poorly treated wastewater containing high amounts of harmful metals (Sen *et al*. 2011). People have also used rivers for waste cleansing and disposal (Asim and Rao 2021; Ayandiran *et al.* 2009). The Yamuna is the Ganga's primary affluent river. The Yamuna river's primary source starts at the Yamnotri glacier near Bandar Punch (38° 59' N, 78° 27' E) in the Mussoorie range of the lower Himalayas. It is located at an altitude of approximately 6320 meters above mean sea level in the Uttarkashi district of Uttarakhand, as stated by Ball and Izbicki (2004). The Yamuna river catchment encompasses regions in Uttarakhand, Uttar Pradesh (U.P.), Himachal Pradesh, Haryana, Rajasthan, Madhya Pradesh, and the entirety of Delhi. The river Yamuna flows for approximately 1370 km over the plain, starting from Saharanpur district in Uttar Pradesh and ending at the point where it meets the river Ganga in Allahabad (Bhutiani *et al.* 2018a). Over 70% of Delhi's water supply comes from the Yamuna River, which has an annual flow rate of approximately 10,000 cubic meters and supplies roughly 4,400 cubic meters of water. In addition, the river serves as a vital source of irrigation for extensive agricultural areas located along its path (CWC 2007). The Yamuna River is a significant tributary of the Ganga River. It begins in the Himalayas and traverses many geological landscapes.

Heavy metals are metallic elements with a density that is relatively higher than that of water. The group primarily consists of transition metals, some metalloids, lanthanides, and actinides. It is believed that there is a connection between heaviness and toxicity, and heavy metals, including metalloids like arsenic, can cause toxicity even at low levels of exposure (Corcoran *et al.* 2010). In recent years, environmental pollution caused by these metals has become a growing ecological and global public health concern. Moreover, there has been a significant surge in human exposure due to the exponential growth in their utilization across many industrial, agricultural, home, and technology sectors. Heavy metals in the environment can come from various sources, such as natural geological processes (geogenic), industrial activities, agricultural practices, pharmaceuticals, residential waste, and atmospheric pollution. Environmental contamination is particularly prevalent in specific locations where pollution originates from identifiable sources, such as mining, foundries, smelters, and other industrial processes that include metals (CPCB 2000). Industrial effluents and surface and agricultural runoff are significant contributors to water pollution, mostly due to the presence of heavy metals. This contamination poses significant dangers to human health. Heavy metals possess the characteristic of being environmentally persistent and capable of bioaccumulation. These heavy metals infiltrate the aquatic system through multiple pathways. Heavy metals have a negative impact on both the condition of the aquatic ecosystem and human health (Grunert *et al*. 2010). Heavy metal contamination has many effects on animal and human health, such as muscle weakness, decreased psychometric performance, and signs of peripheral neuropathy (Fergusson 1990). Occupationally exposed people have exhibited respiratory difficulties and impaired motor nerve conduction. We classify certain heavy metals as human carcinogens. Prolonged environmental exposure to certain heavy metals can result in detrimental consequences. Heavy metals are hazardous to the human body and can cause a decrease in energy levels, impair brain function, alter the functioning of organs such as the brain, lungs, liver, and kidney, and interfere with blood composition. Prolonged exposure to heavy metals can impede physical, neurological, and muscle performance. These disorders, such as multiple sclerosis, Parkinson's disease, muscular dystrophy, and Alzheimer's disease, contribute to the a fore mentioned conditions. Prolonged exposure to certain heavy metals and their compounds can potentially lead to cancer development (CWC 2007). The introduction of these heavy metals into the river may have a negative impact on the aquatic environment's ecological equilibrium. Additionally, the contamination can lead to a reduction in the diversity of aquatic animals (Asim and Rao 2021). Pollutants present in the food chain of organisms cause detrimental impacts, ultimately leading to the demise of aquaculture. These metallic elements act as neurotoxic substances for fish living in aquatic ecosystems.

2. SOURCES OF WATER IN DELHI

Delhi, the capital of the nation, is the primary source of pollution in the Yamuna River, with Agra and Mathura also contributing significantly (Malik *et al*. 2014). Different urban areas have built Sewage Treatment Facilities to preserve the river's water quality. Either directly or through a carrier drain, the sewage, whether treated, untreated, or partially treated, discharged into the river (CSE 2009). These sewage treatment plants (STPs) are unable to operate continuously due to factors beyond control, such as power failures, mechanical problems, or maintenance issues. The release of gathered sewage into the river at limited points without any form of treatment poses a significant risk to the water quality (CWC 2007). This region, spanning 1,483 square kilometers and divided into nine districts, accommodates an estimated population of 17.6 million.

The primary water sources in Delhi include the Yamuna river (surface water and Western Yamuna Canal WYC), the Ganga (Upper Ganga Canal), Bhakra-Beas reservoir, as well as groundwater obtained from tube wells and Ranney wells. The projected water supply from surface water sources in Delhi's National Capital Territory (NCT), including the Yamuna River, the Ganga River, and the Western Yamuna Canal (WYC), is approximately 1150.2 million cubic meters. The river Yamuna provides a significant volume of 724 m^3, which is a large portion of the overall water demand. The route starts in the Palla area, passes through the NCT, and ends at Jaitpur in the south. The river zone has a total area of around 9700 hectares, with 1600 hectares of irrigated land and 8100 hectares of dry land. The runoff from the dry land is a significant source of pollution in the river.

3. SOURCES OF CONTAMINATION IN WATER

High-density elements on the water's surface may be the result of either natural or human actions. These include natural processes such as the weathering of metal-containing rocks, volcanic eruptions, and forest fires. These actions lead to the introduction of metal into many parts of the environment. The significant accumulation of heavy metals in the water is primarily caused by both human activities and natural processes (Dubey *et al.* 2012; Jaiswal *et al.* 2019). The National Capital Territory (NCT) is where the Yamuna River experiences the highest levels of pollution during its passage. The Central Pollution Control Board (CPCB), Central Water Commission (CWC), Delhi Pollution Control Committee (DPCC), and State Pollution Control Board (SPCB) conduct regular monitoring of the Yamuna river at 19 different places. Furthermore, there is ongoing monitoring of twenty-eight significant drain outfalls that discharge into the Yamuna River. The river experiences a lack of freshwater flow for around nine months. The barrage built at Wazirabad in Delhi stores water (Bhutiani *et al.* 2018a). Water that runs continuously contains only sewage and garbage. The river frequently exhibits anaerobic conditions, as evidenced by the presence of rising muck, gas bubbles, and floating materials on the surface. The level of bacterial pollution along the entire length of the Yamuna River is quite high (Karalliedde and Brooke 2012). The primary causes of pollution in this region include:

- the increasing concentration of human population along river banks; and
- inadequate sanitation procedures. Unprocessed home sewage and unprocessed industrial waste liquids are the primary sources of pollution in this region.
- Diffuse pollution refers to the contamination of water bodies by various sources, such as agricultural runoff, the disposal of dead bodies, and the washing of livestock.
- Unnoticed and untreated pesticide residues contaminate the entire river with harmful substances.
- Religious activities and idol immersion contribute to this issue (Ghosh *et al*. 2007).

Scientific evidence indicates that the level of industrial pollution in the Yamuna River exceeds the allowable limit by roughly 13 times. The Yamuna river exhibits the highest concentration of biochemical oxygen demand (BOD) when it flows through Delhi, according to data collected by the Central Water Commission over a span of 10 years using 371 monitoring stations throughout the country. We conduct chemical oxygen demand (COD) tests to quantify the extent of industrial pollution in waterways. Delhi is associated with 26 industrial sites that contribute their waste to the river Yamuna (Mishra 2010).

3.1. Sources of Heavy Metal Contamination

Due to human-induced ecological stress on the aquatic environment, pollution levels have markedly risen. Several investigations have been undertaken to assess the presence of heavy metals in the Yamuna River. A study conducted by Mishra in 2010 aimed to determine the levels of heavy metals in fish species. The study found that the concentrations of calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), and phosphorus (P) were excessively high compared to other metals. These concentrations exceeded the maximum permissible levels set by the World Health Organization (WHO). Delhi is home to 26 industrial sectors that discharge waste into the Yamuna River. The river in the NCT of Delhi has been receiving a significant influx of both partially treated and untreated effluent, particularly between Wazirabad and Okhla.

Industrial discharge, the release of organic material into water, and home waste have all led to a decrease in oxygen levels and are significant contributors to eutrophication. Flamingos have been recorded in large numbers at the lake formed by the Okhla Barrage, where they gather to consume fish, insects, seeds, and marsh plant roots. They construct their nests within a mound of mud, resembling a concave shape. An immediate need has arisen to improve the water quality in order to protect the habitat of the rare and endangered flamingos at Okhla Barrage. In recent years, the global issue of heavy metal pollution in aquatic environments has escalated due to their non-biodegradable nature and the destructive impact they have on species. Due to their poisonous nature and capacity to accumulate in marine creatures, heavy metals are considered the primary source of pollution in aquatic environments (Karalliede and Brooke, 2012). The multiple industrial discharges that flow into the river are likely to be the primary cause of the presence of heavy metals in the Yamuna, resulting in significant harmful impacts on humans, fish, and plants. The immersion of idols in the river during the festival season has raised concerns due to the widespread use of inexpensive paints containing Pb and Cr.

3.1.1. Natural Resources

Excessive amounts of trace metals are present in the environment, resulting from geological phenomena such as volcanic eruptions, rock weathering, and the leaching of metals into rivers, lakes, and oceans by water action (Ayandiran *et al*. 2009) as shown in **Figure 1**. The specific geological, hydrogeological, and geochemical properties of the underlying aquifer influence the occurrence of heavy metals in water. Weathering is a significant contributor to pollution. The erosion of sedimentary rocks, such as limestone, dolomite, or shale, results in water contamination or pollution. Some examples of these elements include granite, syenite, basalt, gabbro, nepheline, and andesite. The presence of specific ores or minerals leads to an increase in element concentration. Examples of elements include magnetite, hematite, goethite, siderite, calcite, cuprite, malachite, azurite, chromite, kaolinite, montmorillonite, arsenic trioxide, orpiment, arsenopyrite, calamine, smithsonite, pyrolusite, and rhodochrosite. (Jaiswal *et al*. 2019; Bagul *et al.* 2015; Lokeshappa *et al*. 2012).

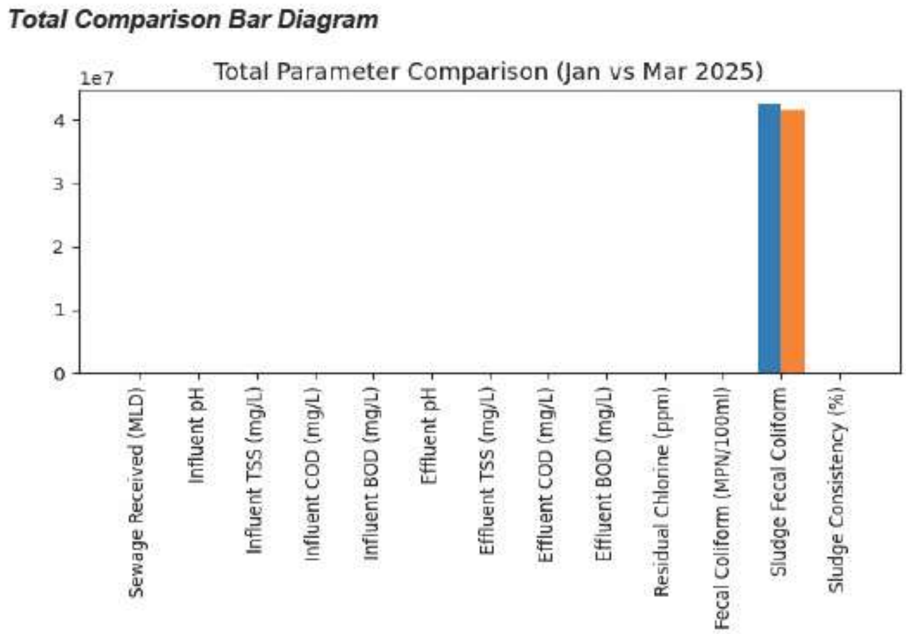

Figure 1

3.1.2. Anthropogenic Sources

Currently, human activities leading to pollution have introduced heavy metals into the ecosystem. Mining operations are the primary source of emissions. Typically, hard rock mines operate for 5 to 15 years until they exhaust all the minerals. However, the resulting metal contamination from hard rock mining can continue for several centuries. Due to their lack of biodegradability, it is necessary to create a technique that is efficient, cost-effective, and quickly deployable in various physical environments (Bhardwaj *et al.* 2017). In regions with poor drainage, acid water downstream or run-off transports these metals to the sea. The risk of contamination is higher when mining involves extracting metal-bearing ores rather than relying on natural erosion to expose ore bodies, which increases the risk of contamination. Additionally, human dressing procedures further increase the possibility of contamination by depositing mined ores on Rivers and streams carry the metals either as dissolved species in water or as part of suspended sediments. Deposits of mining waste in the river bed infiltrate the subterranean water, thereby polluting water from underground sources, particularly wells. The level of pollution will vary depending on the mining site's proximity to the river or any other water body. An analysis of Yamuna River water revealed the presence of metals including iron (Fe), copper (Cu), zinc (Zn), and chromium (Cr). The presence of heavy metals in the environment is a significant problem because they are widespread and long-lasting. The surrounding environment's attributes, geological activities, and the hydrological features of water sources influence water quality. The presence of heavy metals in water is a result of industrial activities, including distilleries, tanneries, pulp and paper industries, textile industries, food industries, iron and steel industries, nuclear industries, and others (Kumar 2012).

3.1.3. Domestic Sewage

Households and other residential buildings discharge waste water into the river in significant quantities. The river receives a significant amount of untreated residential sewage. This untreated home garbage contains toxins. The presence of solid trash or plastic litter can cause toxins to accumulate in the water. Furthermore, the water can become polluted due to bacterial contamination caused by these factors. Direct discharge of untreated domestic water into water bodies causes significant water pollution and ecological damage. These pollutants majorly depend upon what kind of industry has thrown those pollutants. When these noxious metals infiltrate the water, they reduce its quality. These businesses are solely responsible for around 25% of water pollution (Dubey *et al.* 2012). When water becomes contaminated, it becomes enhanced with nitrogen and phosphorus components. The presence of these nutrients significantly increases the development rate of algae, causing it to compete with other aquatic organisms for the dissolved oxygen in water. Chlorine in urine enriches the water sources receiving this sewage, and NaCl consumption resulting in high percentages of chloride (Ayandiran *et al.* 2009). Industrial procedures can also enhance its concentration.

3.1.4. Industrial Source

Heavy metals pose a significant threat to the aquatic environment due to their non-degradable nature and tendency to accumulate within living organisms. The primary pathway for heavy metals to enter aquatic environments is through industrial residue, and the concentration of these metals in water depends on the specific method of wastewater treatment. Metal particles introduced into the water system can cause undesirable effects. Several sources, including industrial effluent, leaks in water tanks, improper waste disposal near marine areas, radioactive waste, and atmospheric deposition, can cause Rivers and lakes often deposit industrial waste, including heavy metals, which have detrimental effects on both wildlife and humans. Toxins are responsible for suppressing the immune system, causing reproductive failure, and inducing acute poisoning.

3.1.5. Atmospheric Source

Microscopic particulate matter suspended in the atmosphere. The sea and other bodies of water subsequently deposit these particles, contributing to water pollution. Pollutants, such as CO2, typically contaminate the air due to the combustion of fossil fuels. This CO2 then reacts with water to form sulfuric acid. Sulfur dioxide, generated by volcanic eruptions and industrial activities, undergoes a chemical reaction to form the sulfuric acid. Coal combustion and petroleum products also generates sulfur dioxide. In a similar manner, nitrogen dioxide also combines with the water and forms the nitric acid. They infiltrate water sources with the assistance of rainwater (Husain 2014). The soil located near the river, which is irrigated with water containing a significant amount of heavy metals, exhibited a substantial level of metal pollution. The metal accumulated in the soil and then bioaccumulated in the crops cultivated on the contaminated agricultural field.

3.1.6. Mining source

Heavy metals naturally occur on Earth and can enter the water system through pathways and one of them is through mining sources. Peplow (1999) states that hard rock mines typically operate for 5 to 15 years until they exhaust. However, even after the mining operations cease, the metal contamination from the mining process may continue for several centuries. Besides mining activities, the use of cosmetic items and manufacturing processes like sodium hydroxide (NaOH) release mercury (Hg) into the environment. Heavy metals are emitted both in elemental and compound (organic and inorganic) forms (Chojnacka 2010). When it rains or through flowing water, it leaches heavy metals out from their geological formation. These processes get disturbed through human-induced economic activities, such as mining, disrupting. During these processes, the previously excavated area is exposed to water and air, resulting in acid mine drainage (AMD). Acidic conditions in AMD cause the release of heavy metals, including radionuclides, if they are present (Li *et al*. 2016).

3.1.7. Dumping of Waste and Landfills

The issue of dumping and sanitary waste erosion is a pressing one, deserving the attention of the scholar. Municipal solid wastes (MSW) includes house hold, health and industrial waste; however, sorting does not occur since all types are dumped in the same landfill (Bayat *et al.* 2015). The main place to dump solid waste is in the dump, and disadvantage of that is a serious environmental pollution and the spread of disease in a number of cases (Sari and Tuzen 2008). Open dumping sites: The transportation of leachate is a major source of heavy metals in surface and groundwater, soil and vegetation (Hadjmohammadi *et al.* 2010). When flora absorb heavy metals from polluted soil, the heavy metals could be incorporated into the human food chain after ingestion of these plants (Nandagopal *et al.* 2018). Various heavy metals such as Cd (II) & Cr (VI) are present in the food chain can cause several health problems in humans and animals .

3.1.8. Heavy metal intake through water

When heavy metals are present in both surface and subsurface water, the soil becomes contaminated. Disposing mined ores on the ground surface for manual processing leads to an increase in soil contamination. Because the metals are dumping on the surface, they become exposed to air and rain, resulting in significant acid mine drainage (AMD). Contaminated soil infiltrates plant tissue, accumulating there. When animals feed on those plants and drink polluted water, heavy metals enter their bodies. the pollutants, heavy metals enter their bodies. In addition, marine organisms that reproduce in polluted water also accumulate heavy metals in their bodily tissues, all creatures in a specific environment encounter these contaminants through their food chains, leading to contamination (Nduka *et al*. 2015) as represented in **Figure. 2**. Consuming these contaminated vegetables may result in the ingestion of heavy metals, which in turn can cause a variety of chronic illnesses. The toxic effects of various heavy metals typically vary based on the concentration and oxidation state of the specific heavy metal (CWC 2007). Furthermore, several heavy metals possess a high level of toxicity only due to their ability to dissolve in substances. The presence of lower levels of heavy metals within the food chain can lead to significant consequences, as there is no specific mechanism for removing these heavy metal contaminants from an organism's body. Metal ions are considered hazardous, dangerous, and damaging among the different types of organic and inorganic water contaminants due to their ability to degrade tissues in nature. Toxic metals are both bio-accumulative and persistent, making them carcinogenic, so, deep monitoring is necessary (Singh *et al.* 2010a). The high toxicity of metal ions in natural water supplies has drawn scientists to their study. Natural water supplies due to their high toxicity. Rivers, as a type of natural water resource, experience significant pollution from toxic metals as a result of the direct release of municipal and industrial waste into them. The utilization of river water for residential water supply is prevalent in various regions worldwide, thus prompting significant focus on the examination This analysis specifically focused on the problem of toxic heavy metals causing water contamination and their detrimental effects on human health.

We can categorize heavy metal contamination in water into two primary types: point sources and non-point sources. Effluent released from a point source, such as an overflow or drainage, can contaminate surface water sources like Rainwater runoff, also known as surface runoff, transports heavy metal contamination from non-point sources into surface water sources (Kaushik *et al.* 2012).The heavy metal contamination load (CL) in water can be calculated using equation:

$$CL=HC\times Q\times 86.4$$

Where CL is heavy metal contamination load (kg/day), HC is heavy metal contamination in contaminated water (mg/l), and Q is the flow rate (m^3/s).

The solid state of heavy metals contributes to their contamination in water, bringing risks to the water-short areas of developing economies like China and India (Xiao *et al*. 2018), due to the deteriorated balance between ecology and health. In parts of the world where water is untreated or treated to a minor extent, for agricultural irrigation, there is excessively high percentage of water consumption due to imbalance (Khalid *et al*. 2018). Wastewater irrigation has been practiced for centuries in some regions of developing countries to be used for agricultural production water demand and it is a major source of land and food contamination by heavy metals, and it could provide a significant source of heavy metal exposure for humans and may constitute a risk to human health and food safety (Lai 2017). Drinking water consumption has shown heavy metals to be one of the major contaminants, which has been found to have a harmful effect on human health. The morbidity rate in a sewer-irrigated village in India is higher than in a village that uses normal groundwater (Blanco and Roper 2007).

4. SOURCES OF CONTAMINATION OF SPECIFIC METALS

Arsenic: Arsenic enters water through the processes of weathering and leaching of rocks, the use of arsenical pesticides and fertilizers, and the discharge of industrial and animal wastes (Kabata and Pendias 1984). Research has demonstrated a correlation between the presence of arsenic in Delhi's Yamuna River and the operation of coal-fired thermal power plants. Prashar *et al.* (2012) reported that the highest recorded amount of arsenic (As) in the Yamuna River was 6 g/l in a separate investigation.

Cadmium: We observe elevated concentrations of cadmium during the non-monsoon season. The utilization of Cd-containing fertilizers, combustion emissions, and industrial activities like mining and metal production are responsible for the elevated levels in these districts (Kabata and Pendias 1984).

Chromium: Elevated levels of Cr may be associated with its release through rainfall and other industrial processes such as electroplating, textile manufacturing, metal polishing, and leather tanning (Bhardwaj *et al.* 2017).

Copper: Elevated copper levels can be linked to excessive use of fungicides, fertilizers, and pesticides in irrigation, as well as industrial operations such as leather and paint manufacturing (Ravindra and Kaushik 2003).

Nickel: Many industrial processes, such as electroplating, porcelain enameling, and metal finishing, may be to blame for the elevated concentration of nickel in water samples (Asim and Rao 2021).

Lead: Significant human activities like the use of pigments, electroplating, and battery production are responsible for elevated levels of Pb. Balali *et al.* (2021) have reported that these enterprises release effluents containing lead (Pb) into the aquatic environment.

Iron: During the non-monsoon season, the Fe levels at several locations approached the allowable threshold. The presence of high Fe levels in water samples suggests that the release of iron-related enterprises in multiple places, including Agra, along with other human and natural causes, affects the River Yamuna.

5. HUMAN HEAVY METAL TOXICITY

Food and water consumption primarily introduce heavy metals into the human body, which are known to have significant health consequences. Arsenic (As), cadmium (Cd), chromium (Cr), and lead (Pb) are considered priority metals due to their significant impact on public health. Studies on both human populations and in laboratory settings have designated these metals as either "known" or "probable" human carcinogens. Additional consequences linked to heavy metals include gastrointestinal and renal failure, neurological issues, dermatological lesions, vascular harm, immune system impairment, and congenital abnormalities (Ball and Izbicki 2004). The International Agency for Research on Cancer (IARC) has categorized nickel as a chemical that has the potential to cause cancer. Zinc, copper, and iron are vital elements necessary for various chemical and biological activities in the body. However, they become harmful when their concentration exceeds a particular level (Liu *et al*. 2012). Anthropogenic activities have led to a significant increase in the concentration of metals in nearly all Indian rivers over the past few decades (Sall *et al.* 2020). The presence of heavy metals in industrial effluents and surface and agricultural runoff significantly contributes to water pollution. This contamination poses significant dangers to human health (Kamble 2014; Duruibe *et al*. 2007). Hence, it is imperative to conduct thorough inquiries in order to evaluate the potential health hazards linked to human contact with water contaminated by metals while also devising long-lasting approaches to effectively manage river systems. The following heavy metals have toxic effects on humans. Paints and storage batteries frequently use lead (Pb) as a heavy metal, and high-quality crystal glass uses the oxide. Elevated levels can result in cognitive impairment in children and peripheral neuropathy in adults. Electroplating companies located along the banks of rivers utilize Copper (Cu). At low concentrations, the presence of Cu can result in symptoms such as headaches, nausea, vomiting, and diarrhea. However, when Cu levels increase, it can cause liver and kidney dysfunction. Electroplating companies, sewage discharge, and the submersion of painted idols release zinc (Zn) into rivers as effluents. Zinc poisoning results in symptoms such as vomiting, diarrhea, and icterus, as well as damage to the liver and kidneys. Industries such as stainless-steel manufacturing units and electroplating factories dump nickel (Ni) into rivers. Nickel (Ni) is a neurotoxic, genotoxic, and carcinogenic substance, which means it can damage the nervous system and genetic material and potentially lead to cancer development. Exposure to nickel can result in health issues such as nickel dermatitis. Several industrial procedures generate Cadmium (Cd), including the application of protective coatings (electroplating) on metals like iron, the manufacturing of Cd-Ni batteries, the production of control rods and shields for nuclear reactors, and the creation of television phosphors. Chronic exposure to Cd leads to its accumulation in the kidney and liver, causing significant harm. The electroplating industries located around the banks of the Yamuna River utilize the chromium (Cr) found in the river. Consuming excessive quantities of Cr also leads to significant adverse health consequences, such as damage to the gastrointestinal, hepatic, and renal systems.

6. METHODS OF DETECTION AND MONITORING

Monitoring heavy metal contamination in irrigation water requires precise analytical techniques, well-structured sampling strategies, and reference to established regulatory standards. Over the years, various sophisticated methods have been employed to detect and quantify heavy metals in the Yamuna River. Among these, Atomic Absorption Spectroscopy (AAS) is one of the most widely used techniques due to its affordability, simplicity, and capability to detect metals like lead (Pb), cadmium (Cd), zinc (Zn), and copper (Cu). For more sensitive and multi-elemental analysis, Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) are preferred, offering high accuracy and the ability to detect metals at ultra-trace levels. X-ray Fluorescence (XRF), while mainly applied to sediments, and UV-Visible spectrophotometry, used for selective metal ions like hexavalent chromium (Cr^{6+}), also contribute to preliminary assessments (Carter *et al.* 2020). Proper sample preparation-such as filtration, acidification, and refrigeration are essential to ensure data reliability.

In terms of sampling strategies, both spatial and temporal variations are taken into account in most studies. Water samples are typically collected from multiple points along the Yamuna River, especially near industrial discharge zones, urban centers, and agricultural regions. Temporal sampling often includes pre-monsoon, monsoon, and post-monsoon seasons, as the concentration of heavy metals can vary significantly depending on river flow and dilution effects. Depth and flow-based considerations, such as collecting samples from both surface and sub-surface levels or from stagnant versus flowing areas, also help capture a comprehensive picture of contamination. Furthermore, the use of geospatial tools such as GIS and remote sensing is growing, aiding in visualizing the spatial distribution of contaminants and identifying pollution hotspots.

To evaluate contamination levels, measured concentrations are compared against established national and international guidelines. The Bureau of Indian Standards (BIS – IS: 10500) prescribes maximum permissible limits for heavy metals in drinking water, such as 0.01 mg/l for Pb, 0.003 mg/l for Cd, and 0.01 mg/l for As (Sandeep *et al.* 2012). The Central Pollution Control Board (CPCB) provides standards for effluent discharge into water bodies and categorizes surface waters based on their intended use. For irrigation purposes (Class E), while guidelines are somewhat relaxed, long-term exposure still raises serious concerns. The World Health Organization (WHO) also offers globally recognized limits for drinking water, which serve as a valuable benchmark, particularly for understanding chronic toxicity. Many studies report metal concentrations in Yamuna River water that exceed these permissible limits, underscoring the urgent need for rigorous monitoring, improved waste treatment, and enforcement of environmental regulations.

7. HEALTH RISK INDEX

We determined the health risk index by dividing the estimated exposure of the test vegetables by the oral reference dose. The oral reference doses for Cu, Zn, and Cd were 4 × 10-2, 0.3, and 1 × 10-3 mg/day, respectively. For Pb, Ni, and Cr, the oral reference doses were 0.004, 0.02, and 1.5 mg/day, respectively. We calculate the estimated exposure by dividing the daily intake of heavy metals by their established safe threshold. Human health considers an index with a value greater than 1 to be hazardous (Bhutiani *et al.* 2018b). The World Health Organization (WHO) guidelines recommend a daily vegetable intake of 300 to 350 grams per person. We conducted a survey of 100 individuals with an average weight of 70 kg to determine the mean daily consumption of vegetables. According to the World Health Organization (Karalliede and Brooke 2012), the average body weight for adults is 70 kg.

8. REMEDIATION AND MITIGATION STRATEGIES

The growing concern over heavy metal contamination in the Yamuna River necessitates the implementation of effective remediation and mitigation strategies. These strategies aim not only to reduce the pollutant load but also to restore the ecological balance and ensure the safety of irrigation practices.

8.1 Phytoremediation and Bioremediation

Phytoremediation, the use of metal-accumulating plants to remove toxic elements from water or soil, has shown promise in treating contaminated sites along the Yamuna basin. Plants such as *Eichhornia crassipes* (water hyacinth), *Typha latifolia* (cattail), and *Phragmites australis* (reed) have been reported to effectively absorb heavy metals like lead (Pb), cadmium (Cd), and chromium (Cr) from wastewater (Singh *et a*l. 2010b). Bioremediation, which involves the use of microorganisms to detoxify contaminants, is another eco-friendly option. Certain bacterial strains, such as

Pseudomonas spp. and *Bacillus* spp., have demonstrated the ability to immobilize and transform heavy metals through bioaccumulation and enzymatic activity (Kumar *et al*. 2020).

8.2 Constructed Wetlands and Natural Attenuation

Constructed wetlands are engineered ecosystems designed to mimic natural wetlands, which can treat wastewater through sedimentation, filtration, and microbial degradation. These systems are cost-effective and particularly suitable for rural and peri-urban areas along the Yamuna. Natural attenuation processes, such as dilution, dispersion, and chemical precipitation, also play a role in mitigating contamination, especially during the monsoon season, though they are insufficient on their own to address chronic pollution.

8.3 Advanced Wastewater Treatment

Industrial effluents often lack adequate pre-treatment before discharge into the river. Technologies such as membrane filtration (reverse osmosis, nanofiltration), electrocoagulation, and adsorption using activated carbon or metal-organic frameworks (MOFs) have shown effectiveness in removing heavy metals at the source (Bolisetty *et al*. 2019). However, the high cost and maintenance requirements limit their widespread use in developing regions.

8.4 Policy and Institutional Interventions

Government-led initiatives such as the Yamuna Action Plan (YAP) have aimed at reducing pollution through the construction of sewage treatment plants (STPs) and public awareness campaigns. However, implementation has often been delayed or incomplete due to bureaucratic hurdles and lack of inter-agency coordination (CPCB 2000). Strengthening environmental monitoring, enforcing discharge standards, and incentivizing industries to adopt clean technologies are critical policy measures that need urgent attention.

9. RESEARCH GAPS AND FUTURE PERSPECTIVES

Despite numerous studies on Yamuna River pollution, several critical research gaps remain that hinder the formulation of comprehensive and sustainable solutions.

9.1 Limited Longitudinal and Integrated Studies

Most existing studies are short-term and localized, lacking comprehensive temporal data that could reveal long-term contamination trends and seasonal patterns. Longitudinal studies are needed to assess the cumulative impacts of heavy metal exposure on soil health, crop productivity, and human health.

9.2 Inadequate Risk Assessment Models

Current assessments often focus on total metal concentrations without considering bioavailability, speciation, or synergistic effects with other pollutants. Developing predictive models that incorporate these factors could improve risk assessment and decision-making (Ogwu *et al.* 2025).

9.3 Lack of Linkage with Human and Agricultural Health

There is insufficient research connecting heavy metal contamination in irrigation water with its impact on agricultural output and public health outcomes such as cancer prevalence, kidney damage, or neurotoxicity in exposed populations. Interdisciplinary studies involving environmental science, toxicology, agronomy, and public health are essential.

9.4 Monitoring Gaps and Technological Constraints

Regular and real-time monitoring of heavy metals is still limited due to the lack of infrastructure and technical expertise in many regions. Incorporating remote sensing, GIS-based tools, and IoT-enabled sensors could revolutionize monitoring and help in early warning and targeted interventions (Popescu *et al.* 2024).

9.5 Need for Community Involvement

Sustainable river management must involve local communities, especially farmers who rely on the river for irrigation. Community-based monitoring programs, education on safe farming practices, and participatory watershed management can foster ownership and accountability at the grassroots level.

10. CONCLUSION

The Yamuna River, an imperative tributary of the Ganga and an essential asset for thousands in northern India, is facing major ecological distress because of ongoing and rising pollutants. The investigation underscores the concerning prevalence of heavy metals, including lead (Pb), cadmium (Cd), arsenic (As), chromium (Cr), and mercury (Hg), in agricultural water sourced from different sections of the Yamuna. The origins of these contaminants are many, encompassing untreated industrial effluents, home sewage, crop residue, and infiltration from solid waste waste sites, all of which collectively contribute to the deterioration of the water's purity. The build-up of heavy metals in water for irrigation adversely impacts fertility of the soil and productivity in farming, while also causing biological accumulation in crop residues, which subsequently enters the human food system and presents significant healthcare risks, including neurotoxicity, renal impairment, and carcinogenic consequences. Research indicates a regional disparity in contamination phases, with the Delhi segment being the most adversely impacted due to extensive urbanization and industrial operations. Seasonal variations additionally affect metal concentrations, with maximum values being recorded during low flow periods.

Notwithstanding numerous monitoring programs and regulatory frameworks, enforcement is inconsistent and feeble. Analytical evidence demonstrates that heavy metal quantities in numerous regions frequently surpass permitted limits established by national and international organizations, including BIS, CPCB, and WHO. There is an urgent necessity for the implementation of extensive remediation techniques, comprising the utilization of sustainable technologies such as phytoremediation and the development of decentralized treatment facilities for wastewater. This review emphasizes critical research deficiencies, particularly the absence of longitudinal studies and cohesive methodologies that connect measurements of water quality with human health effects and agricultural outputs. A multi-stakeholder strategy that includes the scientific community, legislators, municipality officials, and the agricultural sector is crucial for sustainable abatement.

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The authors affirm that there is no conflict of interest.

DECLARATION
Ethics, Consent to Participate, and Consent to Publish declarations: not applicable.

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Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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Table 1: Permissible limits of heavy metals in water and sediment [12]

Metal	Water (WHO) (ppm)	Sediments (WHO) (ppm)
Arsenic (As)	10	20.00
Iron (Fe)	5.00	5.00
Zinc (Zn)	5.00	< 1
Manganese (Mn)	5.00	0.2
Copper (Cu)	3.00	0.05-0.15
Chromium (Cr)	0.1	0.03-0.3
Lead (Pb)	0.1	5.00
Cadmium (Cd)	0.001-0.005	0.1

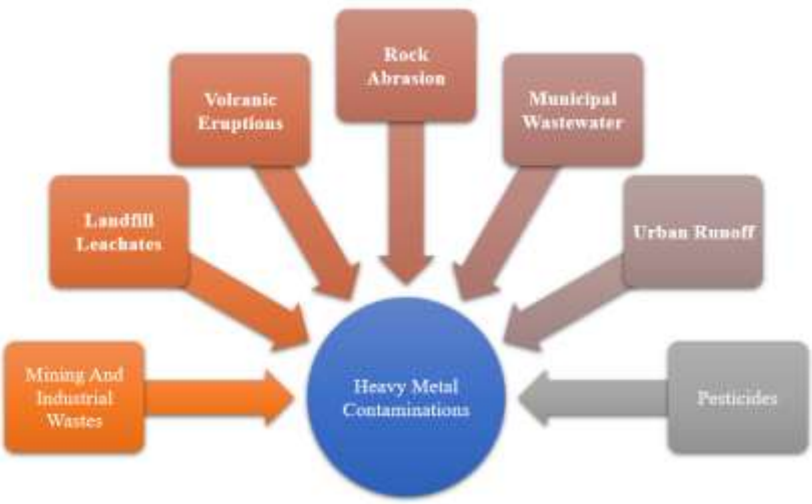

Fig.1 Major sources of some heavy metal ions in water

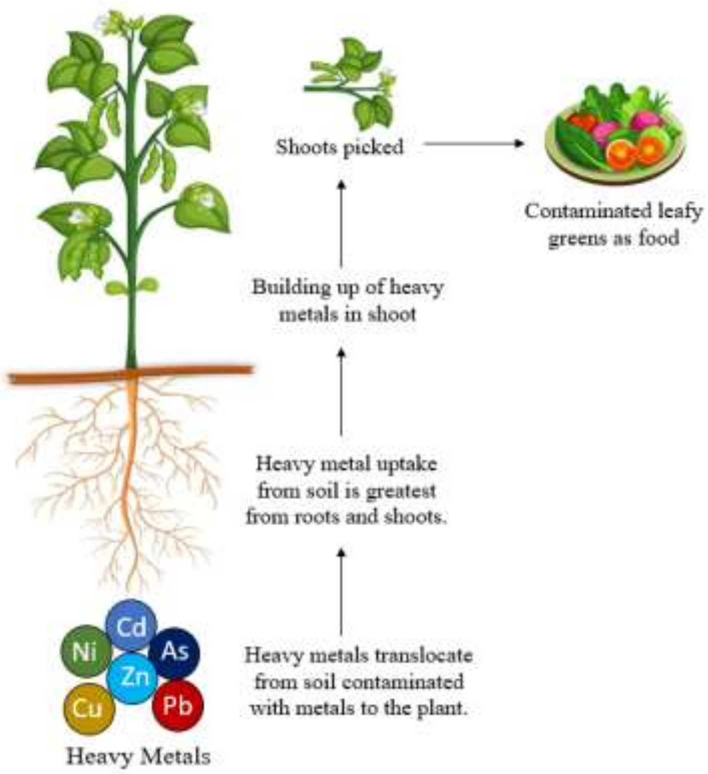

Fig.2 Heavy metal contamination from farm to plate (Soil to Vegetable)