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REVIEW ARTICLE

A review on integrated assessment of heavy metal contamination in urban soils and groundwater

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Abstract

Heavy metal pollution in soils and groundwater has significantly increased due to rapid urbanization and industrialization in recent years, posing serious threats to ecosystem sustainability, food security and human health. Heavy metals are dangerous pollutants because they are persistent, non-biodegradable and capable of bioaccumulation, unlike organic pollutants. Anthropogenic activities such as the dumping of solid waste, car emissions, wastewater irrigation and industrial effluents are the primary contributors. Lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg) and chromium (Cr) are among the metals with the most diverse mobility and toxicity profiles in the environment. Although groundwater is contaminated via various sources such as leaching, landfill infiltration and hydrogeological transport, urban soils serve as the primary reservoirs, facilitating pollution through runoff and deposition. To understand this various assessment methods are adopted. Assessment methods range from simple geochemical analysis and traditional sampling to more complex methods like machine learning, remote sensing (RS), geographic information systems (GIS) and predictive modelling. Socioeconomic vulnerabilities and multi-pathway exposures are proving to be important factors in risk assessment models for human and ecological health. Remedial initiatives include both conventional approaches and eco-friendly strategies such as phytoremediation, bioremediation and artificial wetlands. This study identifies key gaps and future directions, including the use of digital technology, pollutant speciation, long-term monitoring and collaborative governance. A combined, preventative and context-specific strategy is needed for the maintenance of public health, urban ecosystems and sustainable urban resilience. This paper focuses on the state-of-the-art in the field and highlights the sources, pathways, environmental behaviour and remediation methods of heavy metals in urban soils and groundwater.

Keywords: groundwater pollution; heavy metal contamination; remediation strategies; urban environment

Introduction

Urbanization is one of the key features of the twenty-first century, disrupting ecosystems, landscapes and socioeconomic structures globally. As cities expand to accommodate growing populations, economic activity and infrastructure development, there is an increasing demand for land, water and energy resources. One of the most important environmental problems associated with this level of expansion is the accumulation of contaminants in soils and water systems. Heavy metals are different from other contaminants because of their toxicity and resistance and potential to enter the food chain. As a result, they pose long-term risks to human health and ecological sustainability (1).

Lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), nickel (Ni), copper (Cu) and zinc (Zn) are among the heavy metals that are important contaminants in urban environments around the world in this century. They are released into the environment by a variety of man-made sources, including the disposal of solid waste, automobile emissions, industrial discharges, wastewater irrigation and urban stormwater runoff (2, 3). Unlike organic toxins such as pesticides and insecticides, which can decompose over time, heavy metals are not biodegradable and accumulate in soils and groundwater systems, leaving an irreversible toxic impact. Because of the complex interactions between their mobility and bioavailability and soil chemistry, hydrology and land-use patterns, assessment and remediation are especially challenging (4).

The primary source of heavy metal surface discharge and atmospheric deposition is known to be urban soils. Over time, these soils become enriched with metals at concentrations that may far exceed natural background levels due to continued exposure to such pollutants (4). Exposure to polluted soils can have a direct impact on vulnerable populations, especially children, because urban soils are usually found close to residential areas, playgrounds, schools and peri-urban agricultural fields. Skin contact, soil particle ingestion, dust inhalation and plant absorption are among the ways through which exposure to polluted areas occurs (5).

However, groundwater is increasingly at risk from heavy metal leaching from contaminated soils, landfill leachates and industrial seepage. In many developing nations, groundwater serves as the primary source of drinking water and contamination with hazardous substances like As, fluoride and Cr has become a public health issue. Unlike surface water contamination, which is often visible and relatively simple to monitor, heavy metal pollution in groundwater is invisible, persistent and difficult to restore once aquifers are contaminated (6).

The complex nature of heavy metal pollution in urban environments requires an integrated evaluation method, since soil and groundwater systems are interdependent. The complex relationships between soils and groundwater have often been ignored in conventional research, which has often examined these separate areas independently. A multidisciplinary soil-groundwater approach is essential for identifying contamination pathways, evaluating hazards and developing thorough and durable remediation solutions.

Their combined dynamics in urban areas are highlighted in this article. It looks at the main metals of concern, geochemical interactions, case studies from various areas and the origins and routes of pollution. It also looks at the variety of potential assessment techniques, such as soil and water samples, hydrogeological and geochemical investigations and cutting-edge technologies like geographic information systems (GIS) remote sensing (RS) and predictive modelling. The study focuses on the scientific and policy aspects of urban heavy metal pollution by analysing risk assessment techniques and management approaches. The investigation identifies research gaps and suggests future directions while emphasizing the value of interdisciplinary approaches and innovative technology in addressing this urgent environmental challenge.

In summary, the study highlights that heavy metal contamination is not just a problem of soil chemistry or hydrogeology but rather is an international problem at the nexus of environmental science, public health and urban development. During a period of fast urban expansion, integrated assessments are the only way for urban areas to enact policies that minimize pollution, conserve ecosystems and protect human health.

Characteristics of urban soil

Urban soil science is a relatively new subject that emerged in the mid -1970s and focuses on soil in urban areas that are heavily influenced by human activities such as pollution, material mixing and soil import and export. Disturbances including compaction, size and the disappearance of natural substrates are characteristics of urban soil. It can be found in many locations as a result of urbanization, such as parks, roadsides, sports fields, riverbanks, landfills and mining areas.

Urbanization changes natural ecosystems into areas where humans live, affecting the quality of the soil even through it has benefits like improved health care. The development of urbanization, which is fuelled or accelerated by factors including garbage disposal, car pollution and building activity, poses a major threat to ecosystems and human health. Important soil functions including productivity, pollution management and the hydrological cycle are impacted by structural changes that occur when natural soil is replaced by urban soil (7).

Given that the physical, chemical and biological properties of urban soil differ significantly from those of natural soil, an understanding of urban soil dynamics is crucial for the health of urban ecosystems as well as for human well-being. Soil sealing and a decline in soil functionality are two effects of urbanization on landscapes. Therefore, research on urban soil is essential for reducing risks to its functions, maintaining the health of urban ecosystems and ensuring the welfare of human populations and surrounding environments.

Sources and pathways of heavy metal contamination anthropogenic sources

There are various urban sources from which heavy metals are

Table 1. A common urban source of heavy metals

Urban source	Typical associated heavy metals	Ranges	References
Vehicular traffic tailpipe & non-tailpipe (exhaust, tyre & brake wear, road abrasion)	Pb, Zn, Cu, Cd,	Pb: ~20 - 1,400; Zn: ~40 - 3,200; Cu: 5 - 1,000; Cd: ~0.1 - 8	(8)
Industrial emissions (metal processing, foundries, smelting, coal/chemical plants)	Pb, Cd, As, Hg, Cu, Zn	Lead levels are greater than 1,000; Cd ranges from 0.2 to 10; As ranges from 1 to 100	(8)
Mining/smelting/ legacy industrial sites (point sources)	Pb, Zn, Cu	Highly elevated near sources: Lead, Zn and Cu concentrations often reach hundreds to several thousand milligrams per kilogram in hotspot areas	(8)
Waste incineration & municipal solid waste/landfill leachate/e-waste recycling	Pb, Cd	Cadmium concentrations can reach several milligrams per kilogram, while Pb levels may increase to hundreds or even thousands in localized hotspots	(8)
Construction, demolition, building materials (paints, galvanized components)	Pb, Cr	Lead and Cr from aged paints and construction waste; Pb concentrations increase in urban soils adjacent to older structures (tens to hundreds mg/kg)	(9)
Wastewater irrigation/sewage sludge application/ urban agriculture	Cd, Cr, Cu, Zn	Cadmium levels can frequently exceed background levels, typically ranging from about 0.2 to 3 mg/kg in urban park and agricultural soils, while Cu and Zn concentrations can reach tens to hundreds of mg/kg	(9)
Atmospheric deposition/ long-range transport & road dust resuspension	Pb, Cd	Pb: 18-1,420 mg/kg, Cd: 0.4-4.5 mg/kg.	(9)
Corrosion of infrastructure/ Pb pipes/ plumbing	Pb (primary)	Concentrations of Pb in soils and dust near old plumbing and buildings can reach significant levels, ranging from several tens to hundreds of milligrams per kilogram in localized areas	(9)

present in the nature, they are shown in Table 1.

Industrial activities

Metal smelting, electroplating, leather tanning, textile dyeing, battery production and chemical synthesis are known to be industrial processes that discharge large quantities of heavy metals into the environment. Industries like textile industry as well as the dying industry directly contribute to groundwater and land contamination if their effluents are not cleaned or are improperly managed. Hexavalent chromium (Cr^{6+}), a highly toxic and carcinogenic type of Cr, is known to be released into soils and aquifers by tanneries. Additionally, it has been demonstrated that ferrochrome production, particularly in regions close to smelting activities, contributes to the pollution of groundwater systems with total Cr and Cr (VI). The sources of heavy metals are shown in the Fig. 1. Various ways in which contaminants move through environmental systems and ultimately come into contact with humans, plants, animals, or ecosystems are shown in Fig. 2.

Vehicular emissions

Congestion caused by traffic is one of the primary sources of Pb (historically from petrol and gasoline), Cd and Zn pollution in urban areas. These metal-containing particles land on surrounding soils and road dust after being released by burning fuel, lubricating oil leaks, tire abrasion and brake wear. Over time, vehicle metal emissions build up in roadside soils and precipitation facilitates the contaminants' entry into shallow groundwater. There are various authors who have explained about the factors influencing the pathway as shown in Table 2 .

Solid waste and landfills

Uncontrolled disposal of municipal solid waste, industrial wastes and electronic waste causes metals to accumulate in urban soils. Leachates from landfills that are loaded in Pb, Ni, As and Cd enter into aquifers through the soil profile. The problem is worse in developing countries when sanitary waste laws are not rigorously enforced.

Wastewater and sewage irrigation

In urban and rural areas, untreated sewage and industrial effluents are often utilized directly for irrigation, saves water and recycles nutrients. However, this practice also contaminates agricultural soils with dangerous metals such as Pb, Hg and Cd, which can then accumulate in food crops or seep into groundwater.

Construction and demolition activities

Large-scale building in association with rapid urbanization releases metals from cement, paints, roofing materials and plumbing systems. Metals may be released into the soil and airborne dust during the demolition of old structures that is said to have had Cr treatments or Pb-based paints. In the end, these metals can settle and contaminate groundwater (12). The intensity of development and demolition operations is linked to greater levels of Pb, Cr and Zn in the soil found in urban areas near demolition sites (13).

Natural sources

Although anthropogenic inputs dominate urban settings, natural geogenic sources also contribute to heavy metal levels. These include:

Parent material and rock weathering: Elevated levels of Cr, Ni and As are said to naturally occur in soils derived from parent rocks that are rich in metals. Weathering processes release these components into the soil-water system and these metals are released into the soil-

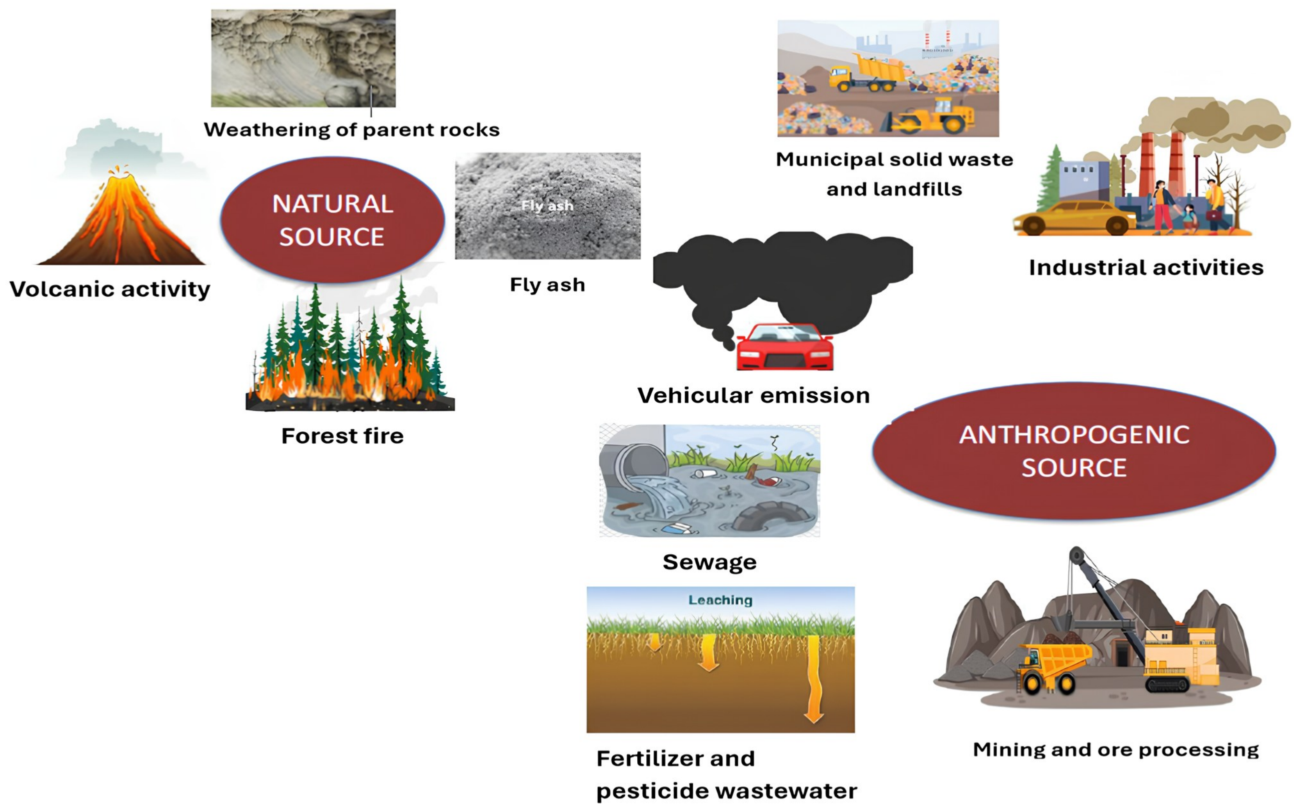

Fig. 1. Sources of heavy metals.

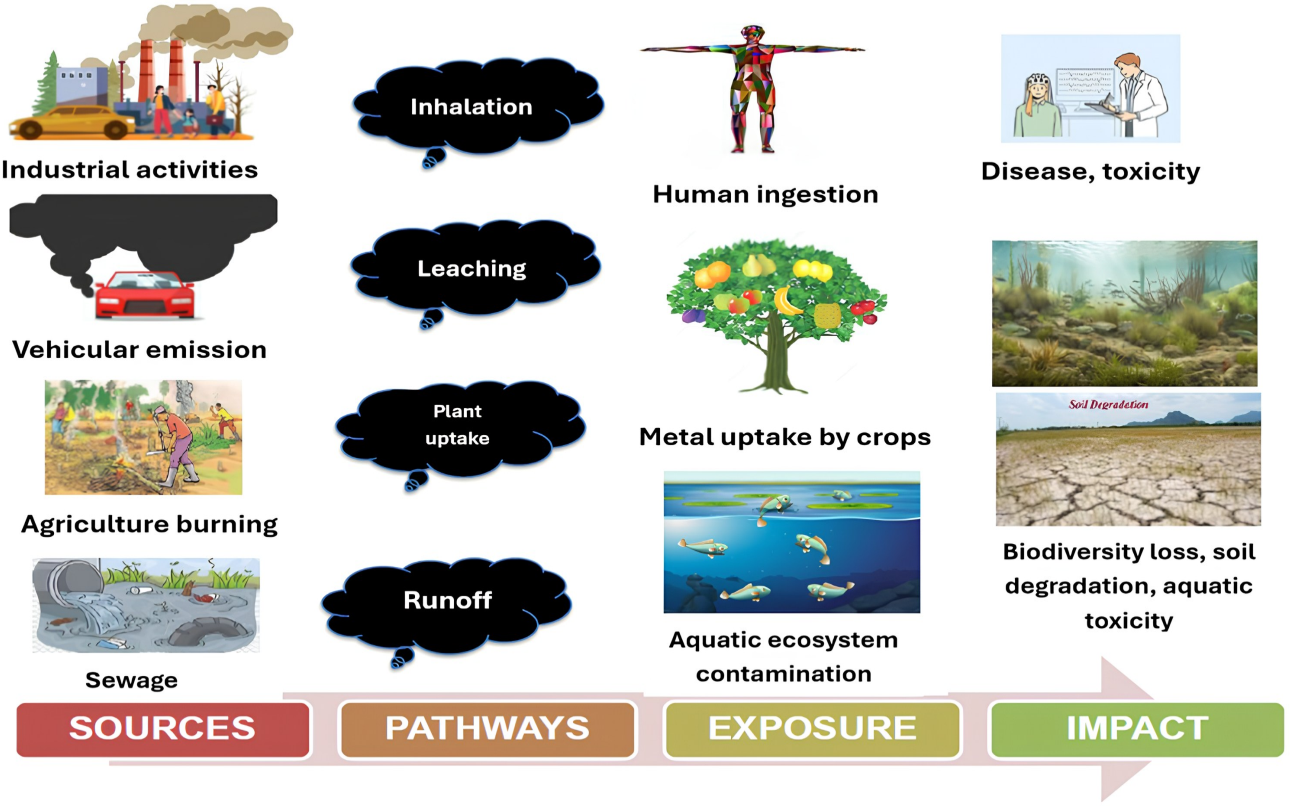

Fig. 2. Exposure pathway impacts.

Table 2. Factors influencing pathways

Factor	Influence on pathways (Transport / Bioavailability)	References
Soil pH	Lower pH increases solubility/mobility; higher pH promotes retention via adsorption/ precipitation	(10)
Clay content/texture / CEC (cation exchange capacity)	High clay & high CEC → more adsorption, slower transport	(10)
Organic matter	Binds metals; it can be a source/sink depending on decomposition & environmental change	(10)
Hydrogeological parameters (porosity, depth)	Affect vertical & lateral transport; shallow water table increases risk to groundwater	(11)
Land use (urban, agriculture)	Determines source strength; modifies hydrological pathways; changes exposure	(11)

water system through weathering and mineral breakdown, where they are said to build up in shallow aquifers.

Volcanic activity: Volcanic eruptions release trace metals like As and Hg into soils and aquifers. Furthermore, metals are added to groundwater by the process of long-term geothermal system degassing (14).

Atmospheric deposition: This process is especially relevant in arid regions with loose topsoil, when carried by the wind, dust from mineralized regions can enrich soils located distant from the source. It has been demonstrated that trace elements like As, Mn and Fe are carried by Saharan dust over thousands of kilometres, impacting ecosystems downstream (15).

Pathways of heavy metal contamination

The movement of heavy metals from sources to soils and groundwater follows complex pathways shaped by environmental processes.

Atmospheric deposition

Particulate pollution from industries and vehicular emissions enters the atmosphere and eventually lands on urban surfaces. Dust deposition is a major contributor to soil pollution, especially in areas near industrial areas and highways. Pb, Cd, Zn and Cr are among the metals found in particulate matter (PM_2, PM_{30}) from vehicles and factories. These particles become a chronic source of pollution when they ultimately make their way onto urban soils and surfaces. The regions most impacted are industrial and roadside areas.

Surface runoff and infiltration

Metals are transported into nearby soils and storm drains by rainfall and runoff from impermeable urban surfaces such as pavements, roofs and roadways. Polluted runoff infiltration serves as a key pathway for metal entry into shallow aquifers. Heavy metals are carried into neighbouring soils, storm drains and retention ponds by rainfall and precipitation from impermeable urban surfaces such as pavements, roads and roofs. These metals can then find their way into shallow aquifers (16).

Landfill leachate migration

Landfills produce metal-enriched leachates. These leachates penetrate groundwater through unsaturated zones, especially in regions where the soil has little residual attenuation capacity or built-in liners. High concentrations of Pb, Cd, Ni and As can be found in landfill leachates. In poorly planned or unlined sites, leachates leak into unsaturated regions, eventually contaminating groundwater. This path is especially hazardous in the developing areas with antiquated waste management infrastructure (17).

Factors influencing pathways

Several environmental and anthropogenic factors determine the extent and rate of heavy metal contamination:

Soil properties: The mobility and retention of heavy metals are significantly influenced by soil properties such as pH, organic matter, CEC and clay concentration. Clay and organic matter-rich soils are better at absorbing metals, which reduces the metals bioavailability. However, in low pH (acidic) soils, metals may become more soluble and mobile, increasing the risk of contamination (18).

Hydrogeology: Contaminants are controlled by the physical characteristics of aquifers, including their depth to the water table, permeability and porosity. Because heavy metals may travel quickly via shallow water tables groundwater pollution is more likely (19).

Climate: Climate conditions, especially rainfall and seasonal changes, have a major effect on the leaching and release of heavy metals. Rainfall can exacerbate pollution levels because it facilitates the transportation of metals from soil into surface and groundwater systems (20).

Land use: Emissions, waste management and runoff from impermeable surfaces represent key pathways that industry and urbanization contribute to heavy metal contamination. Elevated metal concentrations in soils and water bodies are frequently seen in areas with high levels of industry or transportation (21).

Management practices: To lessen heavy metal pollution, emission controls, efficient waste treatment and disposal infrastructure are required. However, poor management techniques can make pollution worse, which underlines the necessity of strict environmental laws and sustainable practices (22).

Heavy metals of concern in urban environments

Although a variety of heavy metals may be found in urban settings, a few elements are particularly notable for their toxicity, persistence and frequency. These consist of As, Ni, Cu, Zn, Pb, Cd, Hg and Cr. These metals are central to integrated soil–groundwater assessments due to their distinct origins, environmental behaviour and toxicological significance.

Lead (Pb)

Lead (Pb) is among the most extensively studied heavy metals due to its persistence and diverse health impacts. Even years after leaded gasoline was phased out in many countries, the usage of tetraethyl Pb in gasoline resulted in considerable air emissions and ongoing soil pollution along roadsides. Lead-based paints, glazed ceramics, Pb-acid batteries, plumbing supplies and electronic garbage are additional sources of Pb pollution in addition to automobiles. Lead's strong affinity for bonding with clay minerals, humic compounds and organic matter in soil restricts its downward mobility but often leads to higher concentrations in topsoil.

Epidemiological studies indicate that prolonged exposure, which frequently happens through the consumption of contaminated food or drink, inhalation of particles and ingestion of contaminated dust or soil, poses a major risk to children. Even at blood Pb levels once considered tolerable, neurodevelopmental impairments have been reported. For example, a systematic review and meta-analysis, revealed that children with blood Pb levels (BL) under 10 µg/dL performed better on IQ assessments compared to those with elevated Pb levels; even minor exposures were associated with significant outcomes. In a recent cohort study, each 1 µg/dL rise in early-life BL levels below 3.5 µg/dL correlated with poorer academic performance from elementary through high school, emphasizing that there might be no genuinely “safe” level of exposure (23).

In addition to its effects on neurodevelopment, Pb is associated with cardiovascular illnesses, kidney problems, reproductive system disorders and increased mortality rates. An analysis of global disease burden found that exposure to Pb has a substantial role in a number of disorders that affect both adults and children (24). Lead concentrations in soils ranged from around 78 to 832 ppm in research looking at roadside soils and plants in Damascus and plant Pb levels frequently above permissible limits. Furthermore, studies conducted in Kolkata and other regions have found high amounts of Pb in food crops, which poses a direct risk to human health (25). At the chemical behaviour level, studies on leaching and transformation indicate that soil properties influence Pb’s mobility. For instance, anoxic cycling in acidic soils alters Pb among exchangeable, adsorbed, Fe / Mn oxide-bound, fulvic / humic complex and sulphide-bound forms, depending on the content of organic matter and phosphorus. Bioavailability is significantly influenced by speciation variations (26).

Cadmium (Cd)

Cadmium (Cd), a hazardous heavy metal, is a common by-product of smelting of Pb and Zn, the production of batteries and the application of phosphate fertilizers. Leachates from landfills, sewage sludge, industrial discharges and wastewater irrigation are other urban sources. Wastewater irrigated soils often have far higher amounts of total and bioavailable Cd, according to recent soil and crop research. Grain Cd values (0.30-0.33 mg kg^{-1}) exceeded Food and Agriculture Organization standards, according to research on a wheat-sorghum cropping system in Pakistan exposed to industrial and municipal wastewater. Net Cd imports were determined to be between 66 and 86 g ha^{-1} each season (27).

Another urgent problem is Cd contamination of groundwater. Even though water concentrations were occasionally under recommended limits, a study conducted in Tianjin, China, revealed Cd buildup in sediments and soils in lands irrigated with wastewater and the related shallow groundwater, displaying strong pollution indicators (28). Chronic exposure to Cd can cause skeletal difficulties, bone loss and kidney problems, particularly damage to the proximal tubules. An important historical example is the Itai-Itai illness in Japan, where long-term use of rice and water contaminated with Cd led to osteomalacia, renal failure, excruciating pain and brittle bones (29). Increased crop absorption of Cd is frequently observed in urban agriculture. For instance, in the top 15 cm of soil in Multan and Faisalabad, Pakistan, soils irrigated with wastewater showed Cd (extractable using AB-DTPA) ranging from around 0.19 to 1.69 mg kg^{-1}. According to pollution indices (PIs) larger than 1 at different places, several crops, such as maize and leafy vegetables, accumulated Cd levels beyond safety limits, indicating long-term accumulation (30).

The concentrations of DTPA-extractable Cd (about 0.62–0.85 mg kg^{-1}) that impact the safety and quality of vegetables were found in 2024 in studies conducted on wastewater-irrigated farms in Iran that produced peppers, green beans, cabbage and lettuce. Epidemiological and toxicological studies have shown that chronic exposure to environmental Cd, even at low levels, can result in renal tubular dysfunction, decreased bone mineral density (increasing the risk of osteoporosis), an increased risk of cardiovascular and all-cause mortality and possibly some cancer risks (31). Furthermore,

more than ten years after ambient Cd exposure was reduced, a long-term study in Japan discovered persistent impacts on bone health (osteoporosis), especially among women (32).

Mercury (Hg)

Mercury (Hg) is one of the most common heavy metals which seen to have polluted the soils of urban areas of major cities has many sources of pollution. These sources include coal combustion, industrial emissions, dental and medical waste, small-scale gold mining, broken thermometers and landfill dumping. Mercury exists in three forms: elemental (Hg^0), inorganic (Hg^{2+}) and organic (methylmercury, MeHg). Living things can acquire the most dangerous form of Hg, MeHg. The two main methods that Hg reaches urban soils through atmospheric deposition are by wet deposition from rain and dry deposition from dust. Urban sediments and water sources are also contaminated by sewage, runoff, landfill leachates and industrial discharges.

Mercury is unique among heavy metals because it can travel great distances in the atmosphere, is prone to microbial modification and is volatile, particularly when in its basic form. Certain microbial communities can convert inorganic mercury that finds its way into soils or sediments into methyl mercury under the right conditions. A study discovered that dissolved organic matter (DOM) had a substantial impact on the kinds of Hg-methylating microorganisms and the amounts of MeHg generated in paddy soils that had been poisoned with Hg. Methylmercury concentrations were much higher in DOM-rich soils, mostly as a result of changes in the microbial community. Mercury levels are frequently higher in urban soils and living things, according to research. There was evidence of biomagnification, demonstrating elevated Hg levels in plants, insects and even birds (33).

The effectiveness of nature-based solutions for addressing Hg contamination was assessed and the findings demonstrated that, despite the presence of visible point sources of pollution, a significant amount of urban Hg issues are diffuse and distributed, originating from sources including runoff, impermeable surfaces and road dust.

Arsenic (As)

Arsenic (As) is one metalloid that originates from both natural (geogenic) and man-made (anthropogenic) sources. It is found naturally in sediments, mineral deposits and groundwater aquifers throughout South Asia (particularly Bangladesh, India and Nepal), Southeast Asia and also in certain regions of Latin America. Human activities have increased As levels in the environment include mining operations, coal burning and industrial discharges. Waste from specific manufacturing processes, arsenical herbicides and wood preservatives like chromated copper arsenate are also serve as a leading source of pollution in certain areas of urban cities.

Arsenic forms bonds with iron (Fe) oxyhydroxides and oxides under normal oxygen-rich soil conditions. However, in reducing or anoxic environments, such as flooded rice fields, damp soils or organic-rich aquifer sediments, arsenate (As^{5+}) may turn into arsenite (As^{3+}). Arsenite is more mobile, more toxic and more easily absorbed by plants and humans than arsenate.

Groundwater contamination is particularly dangerous since As has no taste or smell, so individuals might not know they are exposed to it until tests are conducted. Recent research indicates that a vast number of people are at risk showed that almost 80 million people in India, 60 million in Pakistan, 70 million in Bangladesh and 3 million in Nepal above the World Health Organization's recommended threshold of 10 µg/L for groundwater As (34).

An increased risk of cardiovascular illness, neurological diseases, skin conditions including hyperpigmentation and keratosis and many cancers, including skin, bladder, lung, liver and kidney cancer, is closely linked to long-term exposure to inorganic As.

Chromium (Cr)

Chromium (Cr), a heavy metal, is used intensively in many industrial processes, such as electroplating, leather tanning, pigment manufacturing and refractories. Higher amounts of Cr are frequently reported in soils close to leather tanning and electroplating plants in metropolitan areas. Because it can move into aquifers and contaminate sources of drinking water, the presence of Cr^{6+} in groundwater under oxidizing circumstances presents serious environmental issues. Inhalation of Cr^{6+} can increase the risk of skin illnesses, respiratory problems and cancer. There is proof that occupational exposure to Cr^{6+} compounds causes skin ulcers, respiratory system irritation and malignancies of the nose, sinuses and lungs (35).

Comprehensive analyses must differentiate between total Cr and its various forms due to the significant variations in the environmental and health issues between Cr^{3+} and Cr^{6+}. Recent research indicates that speciation analysis is essential for determining the bioavailability and toxicity of Cr in contaminated urban soils.

Nickel (Ni)

Heavy metal Ni is widely used for numerous industrial operations, including battery production, electroplating, the production of stainless steel and the burning of fossil fuels. In urban cities, soils near electroplating and stainless-steel manufacturing plants tend to have greater Ni contents.

Numerous health issues, including an elevated risk for cancer, respiratory conditions, cardiovascular illnesses and skin allergies, can result from prolonged exposure to high Ni concentrations. The international agency for research on cancer (IARC) has classified several Ni compounds as group one carcinogenic due to adequate evidence of their carcinogenicity. Therefore, rigorous monitoring and management of Ni levels is necessary to reduce possible health hazards in metropolitan settings.

Urban soils as reservoirs of heavy metals

Role of urban soils as contaminant sinks

Urban soils act as sinks and secondary sources of heavy metals through inputs from air deposition, traffic emissions and industrial discharge. Heavy metals such as Pb, Cd, Cr, Ni, Cu, Zn and As can accumulate in the soils over time from various industries, frequently to levels much higher than the natural background. They particularly contaminate parks, rural farming areas, industrial sites and highway boundaries. Because metals may return to the environment through erosion, leaching and particle re-suspension, this accumulation endangers not just the health of the soil but also the safety of the air, water and food (36).

Spatial distribution and hotspot formation

Heavy metal levels in urban soils show clear patterns that vary based on land use, traffic intensity and industrial activities. Here are some common observations:

Roadside soils: Soils near active roadways typically have greater amounts of Pb, Cd, Cu and Zn. The primary elements influencing these levels are vehicle emissions, tire and brake wear and fuel residues Metal concentrations generally decline with increasing distance from the roadway. A study found that the levels of these metals were much higher in Thai agricultural soils close to roads than in those 10-50 m distant. Similarly, it was shown that the levels of Pb in roadside soils in European towns would drop to less than 50 mg/kg after 50 m and reach 200 mg/kg within 5 m of heavy traffic.

Industrial areas: The degree of soil contamination in industrial zones is largely influenced by the type of industry present. While tanneries and the electroplating industry add Cr and Ni, Pb, Zn smelters increase the levels of lead and Cd in the soil. A previous study reported that the concentrations of Cd, Pb, Cr and Zn in topsoil decreased sharply with distance from a smelting industry, with the highest concentrations were found immediately adjacent to the source of pollution, according to data from China's Henan Province.

Residential and recreational areas: Due to urban air pollution, pesticides containing As and the historical use of Pb paint, Pb and As can build up in areas where people reside and spend their free time. Lead and As concentrations in the topsoil frequently surpassed 20 and 150 mg/kg, respectively, according to studies done in a number of metropolitan parks in China and India. This raises possible health risks for those who visit these places (37).

Soil-metal interactions

The mobility and bioavailability of heavy metals in soils depend on several physicochemical factors. Previous study investigated to evaluate the influence of soil properties on the availability and accumulation of heavy metals in crops. The results showed that the mobility and bioavailability of heavy metals including Cd, Pb and Zn were significantly influenced by soil pH, organic matter concentration and cation exchange capacity. It was demonstrated that acidic soils increase certain metals solubility and mobility, which increases plant uptake. On the other hand, soils with higher levels of organic matter and cation exchange capability exhibited lower levels of metal mobility, hence reducing the likelihood of heavy metal accumulation in crops.

Groundwater contamination and hydrogeological linkages

Sources of groundwater contamination

The contamination of urban groundwater by heavy metals originates from both point and non-point sources:

Landfills and dumpsites: Leachates from poorly designed or maintained landfills commonly pollute aquifers by introducing Cd, Pb, Ni and Zn.

Industrial effluents: In South Asia, the leather tanning industry is seen to be emerging as a significant contributor to groundwater contamination. A previous study, showed that hexavalent chromium (Cr^{6+}) is released into groundwater by tanneries in Kasur, Pakistan, negatively impacting the water quality in the surrounding area. Similarly, another research showed that Cr from waste from leather shavings may contaminate groundwater aquifers that supply drinking water by leaking into the soil (38).

Sewage and septic systems: Inadequate sanitation infrastructure, including septic tanks and soak pits, poses a major danger to groundwater quality. A study conducted previously, discovered that groundwater pollution can allow heavy metals and other sewage-related toxins to enter nearby ecosystems (39). The National Green Tribunal (NGT) of India has also voiced concerns over potential groundwater pollution in Bengaluru, where more than 30000 families dispose of their sewage in soak pits.

Urban agriculture: Heavy metals may move through the soil and eventually pollute groundwater when wastewater is used to irrigate crops. Using wastewater for irrigation increases groundwater's salinity, sodicity, ammonium and nitrate levels and that soil salinity affects the leaching of heavy metals (40).

Geogenic sources: Geological formations can naturally pollute groundwater in particular places. For instance, geogenic Ni, which is present in groundwater from the Himalayan Indus-Ganges-Brahmaputra river basin aquifers, is estimated to be responsible for around 60 % of the contaminated groundwater in the northern Indian plains.

Public health implications

Serious health hazards can arise from extended exposure to heavy metals found in groundwater, such as Pb, Cd and As. As these metals are imperceptible by sight, taste or smell, contamination often remains undetected until clinical symptoms emerge. Numerous types of cancer, skin disorders, heart issues and developmental abnormalities in children have all been related to drinking water contaminated with As are imperceptible. Since this pollution remains undetected, it is essential to conduct routine water testing and put in place efficient public health protection measures.

Assessment and monitoring approaches

A multimodal strategy that combines cutting edge modelling and RS technologies with conventional analytical approaches is required for the effective evaluation and monitoring of heavy metal pollution in urban environments. An outline of current practices and recent developments in the area may be found below:

Soil sampling and geochemical analysis

To assess heavy metal pollution, soil sample is necessary. Standard techniques commonly involve grid-based or stratified random sampling across a range of land uses, such as residential, roadside, agricultural and industrial areas. Atomic absorption spectroscopy (AAS), inductively coupled plasma mass spectrometry (ICP–MS) and X-ray fluorescence (XRF) are techniques used in labs to measure metal concentrations. Sequential extraction procedures give information on the mobility and bioavailability of metals by separating them into different fractions (reducible, oxidizable, carbonate-bound, exchangeable and residual). Recent research indicates that these techniques are useful for identifying and quantifying heavy metals in polluted soils (41).

Groundwater monitoring

Samples are collected from wells, boreholes and piezometers across depth gradients in order to evaluate the quality of groundwater. Laboratory analysis is used to assess metal concentrations, while in-situ characteristics such as pH, electrical conductivity and redox potential are tracked. Predictions of speciation, solubility and redox changes are made using hydrogeochemical modelling approaches like PHREEQC. Documenting seasonal and interannual changes requires long-term monitoring. Recent research highlights the necessity of combining hydrogeochemical models with empirical data to increase the accuracy of assessments of groundwater quality (42).

Integrated soil-groundwater monitoring frameworks

Integrated monitoring frameworks combine soil and groundwater sampling within a unified spatial design to capture contamination dynamics. Linkages between contaminants can be identified by placing monitoring wells and soil sample locations together. Both pollutant fate modelling and mass balance computations are supported by this integration. Research has shown that these integrated methods offer a more thorough comprehension of the distribution and movement of contaminants (43).

Biomonitoring and bioindicators

Biomonitoring techniques use microbial populations, plants and earthworms as markers of pollution levels in addition to physicochemical analyses. For example, the metal concentrations in earthworm tissues reveal the soil's accessible metal fractions. Tests for phytotoxicity provide a rapid method of evaluating the quality of soil. Because of their susceptibility to a variety of chemical, biological and physical contaminants, recent studies have emphasized the importance of soil and sediment species as bioindicators for assessing environmental contamination.

Remote sensing and geospatial tools

The application of machine learning to forecast contamination trends through the analysis of massive data sets, satellite imaging and land-use characteristics is gaining popularity. Recent developments have shown great promise in predicting the dangers of groundwater contamination by heavy metals.

Geospatial and modelling tools for integrated assessment

The assessment and control of heavy metal pollution in cities have significantly improved with recent advancements in geospatial technology. Monitoring and modelling pollution trends has become more comprehensive and predictive owing to the integration of GIS, RS and digital twin (DT) technologies.

Geospatial mapping and remote sensing

Geographic information systems enable the spatial estimation of data on soil and groundwater quality, giving rise to comprehensive maps that demonstrate the distribution of heavy metals in urban areas. Techniques such as ordinary Kriging, co-Kriging and inverse distance weighting (IDW) are frequently used to identify hazardous hotspots and guide cleaning operations. When leveraging satellite data like Sentinel-2, RS provides essential data on variations in temperature and vegetation stress related to polluted areas. For example, a study, showed the value of RS for comprehensive environmental monitoring by using Sentinel-2 imagery to assess heavy metal contamination in Tehrani districts that get wastewater irrigation (44).

Machine learning (ML) applications

The use of ML techniques to predict and analyse the concentrations of heavy metals in urban soil is growing. Variables such as land use, traffic volume and soil properties, methods like random forests (RF) and support vector machines (SVM) are used to classify contaminated sites. For instance, research conducted previously, used ML algorithms to explore the effects of heavy metal movement caused by acid rain in a mining region of southern China, highlighted us the effectiveness of ML in evaluating environmental risks.

Challenges and future directions

Urban pollution measurement remains difficult despite improvements. Challenges include uneven spatial distribution of data, high costs of advanced sensors and a lack of standardized monitoring protocols. Future studies should concentrate on creating affordable, scalable technologies and standardized practices to improve data comparability in different urban contexts.

Risk assessment frameworks

Rationale for risk assessment

Risk assessment serves as the critical link between environmental contamination and its implications for ecological and human health. The problem with heavy metals is not just their existence but also their toxicity, exposure routes and bioavailability. Risk frameworks provide systematic methods for assessing risks and guiding preventative actions.

Human health risk assessment (HHRA)

HHRA typically follows a four-step process

Hazard identification: Due to increasing industrial and commercial progress, the quantity and diversity of pollutants emitted into the environment have expanded dramatically. Even while people are becoming more conscious of pollution and its harmful effects on health, there are not enough resources to fully cure all contaminants. The contaminants that pose the greatest health hazards must be prioritized since toxicological research indicates that different contaminants produce varying degrees of harm. Since the mid-20th century, several nations and international organizations have created priority pollutant lists to direct environmental management since the middle of the 20th century (e.g., by the EU, USA, Japan, Germany and the Netherlands). The inadequacies of traditional static pollutant catalogues have been exposed throughout time, as they often primarily target domestic issues rather than transboundary ones and are unable to adapt to changing environmental circumstances (45). The creation of a dynamic risk list updating mechanism in the regional environment, risk identification of non-occupational long-term exposure with low dose and a new screening method of priority pollutants taking into account pollutants migration and transformation characteristics are the main focuses of contemporary hazard identification research.

Exposure assessment: Humans are exposed to a wide range of pollutants through different pathways, broadly classified as external exposure and internal exposure (46). Whereas internal exposure refers to the absorbed portion that enters systemic circulation, external exposure describes the interaction of pollutants with bodily surfaces such the skin, respiratory epithelium or gastrointestinal lining. The percentage of an external dose that is truly absorbed by the body is known as the pollutant's bioavailability.

Exposure assessment systematically evaluates the risks associated with pollutant interactions and pathways. It typically consists of five key components.

- The investigation and characterization of the exposure environment include identifying the characteristics of present and prospective future receptor populations, evaluating environmental factors such as soil, water, vegetation and climate and identifying sources of pollution.
- Exposure route analysis studies how contaminants move through the air, water or soil and the places or activities that expose people to them.
- Predictive environmental fate models or monitoring data are usually used to estimate exposure concentration.

- Intake calculation converts exposure to dosage, which is represented as the quantity of pollutant per unit of time and body weight.
- Regional epidemiology, occupational exposure studies and the creation of models that depict chemical transport and change in air, water, soil and multimedia environments have become the focus of much recent research in this area.

Dose-response assessment

I. No threshold effect (carcinogenic effect): Based on humanitarian and precautionary principles, most carcinogenic chemicals are assessed using low dose extrapolation models to estimate human risk probability (47). Various types of evidence are used in dose-response assessment, with human epidemiological data serving as the primary basis. In the absence of appropriate human clinical studies, data on animal species that close to humans should be used and in the long-term animal studies, the most sensitive and biologically acceptable data should be given to the greatest extent of attention.

II. Threshold effect (non-carcinogenic effects): The reference dose (RfD) is an important basic factor, which means that when the dose is below this level, the risk of harmful effects will not be expected. At present, the following methods are used to evaluate the dose-response effect of threshold dose: firstly, determine the key toxic effects (the initial deleterious effects at this dose) and the highest dose that does not occur harmful effects (no observed adverse effect level, NOAEL) through reading literatures. The NOAEL is then divided by an uncertainty factor (ranging from 10 to 1000) to derive a safety threshold, accounting for interspecies variability and data uncertainty. The uncertainty factor expresses a variety of internal uncertainties related to the existing data.

Risk characterization: Risk characterization encompasses both qualitative and quantitative assessments of risk (44). The qualitative aspect employs semi-quantitative terms such as "negligible", "slight", "medium" or "serious" to articulate the level of risk. In contrast, quantitative risk characterization expresses the degree of risk numerically, allowing for a more intuitive and effective representation of risk levels, which aids in the screening and prioritization of pollution factors, thereby providing a scientific foundation for decision-makers. The methodologies for risk characterization, both domestically and internationally, are developed within the framework of the risk assessment system established by the United States Environmental Protection Agency. Quantitative risk characterization is further categorized into carcinogenic and non-carcinogenic risk assessments. The outcomes of environmental risk characterization will serve as a scientific foundation for the development of environmental standards or management strategies at national, local and organizational levels. Additionally, the first stage in environmental governance is the development and implementation of environmental standards, which are essential to efficient environmental management use indicators including the hazard quotient (HQ), hazard index (HI) and lifetime cancer risk (LCR) to estimate total risk.

Key metrics:

- HQ > 1 indicates potential non-carcinogenic risk.
- HI = sum of HQs for multiple metals.

LCR between 10^{-6} and 10^{-4} is generally considered acceptable.

Ecological risk assessment (ERA)

Ecological risk assessment assesses ecological effects with an emphasis on aquatic biota, plants and soil organisms.

Index of deaccumulation

I_{geo}, is classified into seven levels and its corresponding contamination degrees of heavy metal are shown in Table 3. To assess the enrichment degree of heavy metals in the soils, the geo-accumulation index (1) was used. It can be calculated by the following formula:

$$I_{geo} = \log_2(kC_i/B_i) \quad \text{(Eqn. 1)}$$

Where C_i, is the actually measured concentration of the heavy metal in the samples. k is corrected coefficient, which take account of variation of background value caused by anthropogenic influences or lithologic variations in the soil (in general k = 1.5) B_i, is the reference value of heavy metal concentration in soil.

Potential ecological risk index (PERI)

The PERI was used to assess the possible ecological harm posed by heavy metals in soil. Hanson created the PERI in order to evaluate the properties of heavy metal pollutants using sedimentary theory.

Table 3. Classification of sediment contamination levels based on the geo-accumulation index (48, 49)

Class number	$I_{(geo)}$ value range	Degree / description
Class 0	$I_{(geo)} \le 0$	Uncontaminated / Practically unpolluted
Class 1	$0 < I_{(geo)} \le 1$	Uncontaminated to moderately contaminated
Class 2	$1 < I_{(geo)} \le 2$	Moderately contaminated
Class 3	$2 < I_{(geo)} \le 3$	Moderately to heavily contaminated
Class 4	$3 < I_{(geo)} \le 4$	Heavily contaminated
Class 5	$4 < I_{(geo)} \le 5$	Heavily to extremely contaminated
Class 6	$I_{(geo)} > 5$	Extremely contaminated

$$RI = \mathrm{sum}E^i_r, E^i_r = T^i_r - C^i_r = C^i_D - C^i_B \quad \text{(Eqn. 2)}$$

Where, RI is the sum of the potential risk of individual heavy metal, E^i_r is the potential risk of individual heavy metal, T^i_r, is the toxic-response factor for a given heavy metal, value of T for Cd, Ni, Zn, Cu and Cr are 30, 5, 1, 5 and 2, respectively. C^i_r is the contamination factor, C^i_D is the present concentration of heavy metals in soil and C^i_B is the reference value of heavy metal concentration in soil.

Soil quality guidelines

Examine recorded concentrations in relation to regulatory thresholds for the preservation of ecosystems. In urban parks, green spaces and peri-urban agricultural areas where ecological services are directly threatened, ERA is essential.

Integrated risk evaluation

Human health risk assessment (HHRA) and ERA are combined in an integrated risk strategy, which acknowledges the connection between ecological and human well-being. Metals in soil can affect soil microorganisms, which subsequently influence crop safety and nutrient cycling. These changes may ultimately pose risks to human health through food consumptions. Comprehensive insights are provided by methods such as multi-pathway exposure models and cumulative risk assessment (CRA). Recent studies highlight how crucial it is to combine HHRA with ERA in order to address the problems caused by contaminated urban soil. A notable study, investigated the extent of heavy metal pollution in Pakistani urban soils in sixteen cities, highlighting the urgent need for all-encompassing strategies to reduce environmental and public health risks.

Socio-economic and policy dimensions of risk

Not only may scientific assessments impact risk, but sociopolitical factors can as well. The people who live near the area of poverty, in small towns near landfills and communities that rely on groundwater are said to be at risk. Strong community participation and effective risk communication require trust and sustained engagement.

Remediation and management strategies

Improper waste management, vehicle emissions and fast urbanization are said to be the leading cause of heavy metal poisoning of soil and groundwater. Both ecological equilibrium and human health are seriously threatened by these pollutants. Reducing these hazards and improving environmental quality need efficient management and repair techniques.

Conventional remediation techniques

Soil washing

The process called "soil washing" uses chemical or water solutions to remove larger soil particles from finer, contaminated particles. Despite its high energy consumption and possibility for secondary waste, this technology effectively removes a sizable proportion of contaminants. The goal of recent advancements is to increase the effectiveness of cleaning products while reducing their adverse environmental consequences (50).

Stabilization and solidification

This method lessens heavy metals mobility and availability for plant absorption by immobilizing them in the soil. These chemical agents are used in this process that includes, for example, fly ash, cement and lime. Despite their affordability and cost, these methods do not totally eliminate pollutants and may alter the characteristics of the soil in some scenarios, which may have an effect on plant development.

Pump-and-treat systems

This method is frequently employed to purify groundwater. It is necessary to remove contaminated water, treat it by adsorption or precipitation and then release or re-inject it. Although successful, this method is energy-intensive and may not be suitable for addressing pervasive pollution issues (51).

Emerging and sustainable remediation approaches

Phytoremediation

The technique of employing plants to absorb, stabilize, or break down heavy metals in polluted soils is known as phytoremediation. *Helianthus annuus* and *Brassica juncea* are two plants that has demonstrated potential in the accumulation of metals such as Pb and Cd. Recent research has emphasized the use of soil amendments, such biochar, to improve plant growth and metal absorption.

Bioremediation is a process where microorganisms are used in this procedure to transform heavy metals into less dangerous forms. Sulfate-reducing bacteria and fungi, such as *Aspergilus* and *Trametes* species, can precipitate metals as sulphides or complex them, limiting their bioavailability in the soil. Advances in genetic engineering in recent years aim to increase microbial efficiency and adaptability under a range of environmental conditions.

Electrokinetic remediation

An electric field is used in electrokinetic remediation to move metal ions in the direction of electrodes for collection. The creation of sophisticated electrode materials and the adjustment of operating settings to increase effectiveness and lower energy consumption are examples of recent advancements (52).

Research gaps and future directions

Limitations in current understanding

There are still numerous unanswered questions about heavy metal pollution after decades of research, especially when it comes to the combined evaluation of soils and groundwater in metropolitan areas. These two environmental compartments are treated independently in a large portion of the research now in publication. Soil investigations mostly focus on surface exposure problems, pollution levels and geographic dispersion, whereas groundwater studies concentrate hydrogeological processes and aquifer quality. It is unclear how important connections between these systems work, such as how metals move across unsaturated zones from soils into aquifers. This difference in approach limits the development of complete management solutions and makes it more challenging to capture the whole cycle of contamination.

Single-metal evaluations are often used, which is another drawback. Despite their growing usage in electronics and industrial processes, metals like antimony, thallium and rare earth elements are still underreported, whereas Pb, Cd, As and Cr have been the subject of in-depth research. Furthermore, contamination in urban environments seldom happens in isolation; complex combinations of metals, organic pollutants and newly identified contaminants such organic pollutants and microplastics frequently affect soils and aquifers. Accurate risk assessment depends on knowing if such co-contamination has antagonistic or synergistic effects, but there is presently a dearth of study on this subject.

Methodological and monitoring gaps

There are still issues with monitoring programs temporal and spatial resolution. Seasonal fluctuations in contamination dynamics are not captured by the brief sample campaigns used in many studies. Despite the absence of long-term data, rainfall events, floods and drought cycles can have a significant impact on leaching and mobilization processes. Similar to this, the majority of soil and groundwater monitoring is limited to a small number of sites within cities, leaving out vast regions and leaving uncertainty into contamination maps.

Despite these developments, analytical methods still commonly prioritize total metal concentrations over speciation or bioavailability. Although they show promise, emerging technologies like Internet of Things (IoT) based sensors and RS are still not widely used in heavy metal monitoring.

Challenges in risk assessment

Multi-pathway and cumulative exposures are frequently understated in the risk assessment systems in use today. For example, urban dwellers may breathe resuspended dust, drink tainted groundwater, come into contact with soils through their skin and consume contaminated food crops all at the same time. However, the majority of evaluations only look at one route at a time. Additionally, while risk indices like the HQ and HI offer numerical standards, they fail to account for the cultural and socioeconomic aspects of exposure. Higher vulnerabilities that beyond numerical criteria are faced by underprivileged groups that depend on untreated groundwater, children playing in toxic playgrounds and informal labourers recycling electronic garbage. One important area of study is still how to include social determinants of health into risk models.

Remediation research needs

While there are many remediation options available, the majority have only been evaluated in pilot-scale or controlled laboratory settings. Their scalability and effectiveness in complex metropolitan environments are yet unclear. For example, phytoremediation is commonly known as a low-cost solution, but actual implementation is challenging because of long timescales, varying temperatures and land-use conflicts in highly populated places. One of the difficulties in bioremediation is sustaining microbial activity when soil pH and moisture content fluctuate.

Another pressing issue is the remediation of mixed contaminants. Most remediation technologies are designed to target either heavy metals or organic pollutants, but not both. However, groundwater and urban soils frequently contain toxins from other sources, requiring multiple strategies. Research on mixed approaches, such as phytoremediation with charcoal inputs or electrokinetic remediation with chemical stabilization, is still limited and in its early stages.

Data integration and modelling challenges

The incorporation of data from several sources into cohesive models is one enduring gap. Land use, soil chemistry, groundwater hydrogeology and socioeconomic indicator data are often gathered and stored in separate databases. The creation of thorough models of contamination dynamics is hampered by the lack of interoperability. Even though AI and machine learning have a lot of considerable potential, their application is constrained by a lack of data, inadequate quality assurance and opaque algorithm development.

Another unexplored field is predictive modelling of potential contamination situations under climate change. Urban heat island effects, rising groundwater tables and variations in rainfall intensity can all have an impact on metal mobility, even though few models account for climate. This absence leaves cities unprepared for new pollution issues associated with climate extremes.

Future directions

Future research must prioritize integrating frameworks that link soils and groundwater as an interdependent system. Using multidisciplinary approaches such as geochemistry, hydrogeology, public health and urban planning is essential. Long-term monitoring networks with real-time sensors must be installed in urban hotspots to capture temporal data. Digital platforms which GIS, RS and predictive modelling should integrate these data from these networks in order to provide dynamic risk mapping and scenario planning.

Urban development plans must incorporate pollution assessment at the policy level. Regulations that require soil and groundwater quality evaluations before new building projects. Enhancing public involvement requires integrating communities in monitoring and decision-making in addition to running awareness efforts. Participatory governance like this may increase compliance, lower distrust and guarantee that remediation plans take into account local needs.

International collaboration is another frontier. Air transportation, industrial emissions and international trade significantly contribute to the problem of heavy metal pollution. Urban pollution may be addressed; shared information and policy responses are coordinated through international frameworks like the Intergovernmental Panel on Climate Change (IPCC).

Conclusion

Heavy metal contamination of urban soil and groundwater remains a major environmental and public health issue. Unlike degradable pollutants, heavy metals are persistent, bio accumulative and may have long-term impacts on the environment and human health. This research emphasizes that soils and groundwater must be assessed as interconnected systems to fully capture contamination pathways and threats. Urban pollution is predominantly caused by anthropogenic activities, which contribute far more than natural sources. These include industrial effluents, automobile emissions, improper waste disposal and wastewater irrigation. This pollution is characterized by high concentrations of hazardous heavy metals which includes Pb, Cd, As, Hg and Cr. Continuous leaching of these metals leads to their accumulation in urban soils, creating hazardous reservoirs that endanger groundwater supplies. Altogether, these activities produce pollution cycles that threaten food availability, drinking water quality and ecosystem health in general.

Traditional hydrogeological modelling is being replaced by geospatial methods, predictive modelling and exciting new technologies like DT, ML and IoT-based sensors for the identification and understanding of this pollution. These technologies provide real-time monitoring and reliable hotspot detection are made possible but data integration remain significant barriers. Current risk assessment models often underestimate the total harm from repeated multi-pathway exposures and frequently overlook associated socio-economic disparities. Remedial strategies must include integrated, context-specific solutions that balance traditional techniques (such pump-and-treat) with sustainable, eco-friendly processes like bioremediation and phytoremediation. In order to establish an integrated, flexible and fair approach that will maintain public health over time and enhance urban resilience, the technological solutions must ultimately be paired with strong policy, preventative management and active involvement in the community.

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Authors' contributions

TKT conducted the literature review, structured the manuscript and prepared the initial draft. RKP and TVR developed the framework and revised the manuscript. PS, KP, SK, PPC and KG contributed to the revision and refinement of the manuscript. All authors read and approved the final manuscript.

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References

1. Tang S, Wang C, Song J, Ihenetu SC, Li G. Advances in studies on heavy metals in urban soil: a bibliometric analysis. Sustainability. 2024;16(2):860. https://doi.org/10.3390/su16020860
2. Wuana RA, Okieimen FE. Heavy metals in contaminated soils: a review of sources, chemistry, risks and best available strategies for remediation. Int Scholarly Res Notices. 2011;2011:402647. https://doi.org/10.5402/2011/402647
3. Angon PB, Islam MS, Das A, Anjum N, Poudel A, Suchi SA. Sources, effects and present perspectives of heavy metals contamination: soil, plants and human food chain. Heliyon. 2024;10(7):e28357. https://doi.org/10.1016/j.heliyon.2024
4. Raffa CM, Chiampo F, Shanthakumar S. Remediation of metal/metalloid-polluted soils: a short review. Appl Sci. 2021;11(9):4134. https://doi.org/10.3390/app11094134
5. Monib AW, Niazi P, Azizi A, Sediqi S, Baseer AQ. Heavy metal contamination in urban soils: health impacts on humans and plants: a review. Eur J Theor Appl Sci. 2024;2(1):546-65.
6. Sánchez-Soberón F, Ratola N. Seasonal occurrence, concentrations and occupational exposure to VMSs in different environments of a WWTP. Environ Pollut. 2022;315:120423. https://doi.org/10.1016/j.envpol.2022.120423
7. Haarstrick A, Sharma L. Urban river pollution control. Managing urban rivers. Elsevier; 2024. p. 131-59.
8. Cutts BB, Vilá O, Bray LA, Harris A, Hornsby G, Goins H, et al. Shifting terrains: understanding residential contaminants after flood disasters. Sci Total Environ. 2024;907:167577. https://doi.org/10.1016/j.scitotenv.2024.167577
9. Patra B, Das MT, Pradhan SN, Dash SR, Bhuyan PP, Pradhan B. Ferrochrome pollution and its consequences on groundwater ecosystems and public health. Limnol Rev. 2025;25(2):23-9. https://doi.org/10.2478/limre-2025-0003
10. Michikawa T, Yamazaki S, Ueda K, Yoshino A, Sugata S, Saito S, et al. Effects of exposure to chemical components of fine particulate matter on mortality in Tokyo: a case-crossover study. Sci Total Environ. 2021;755:142489. https://doi.org/10.1016/j.scitotenv.2020.142489
11. Saravanan P, Saravanan V, Rajeshkannan R, Arnica G, Rajasimman M, Baskar G, et al. Comprehensive review on toxic heavy metals in the aquatic system: sources, identification, treatment strategies and health risk assessment. Environ Res. 2024;258:119440. https://doi.org/10.1016/j.envres.2024.119440
12. Coxon S. Review of contaminants of potential human health concern in wastewater; 2023.
13. Prokeš L, Hegrová J, Průšová B, Baroň M, Hablovičová B, Sochor J, et al. Impact of traffic intensity and vehicular emissions on heavy metal content in vineyard soils, grapes and wine: a comparative study of two vineyards in South Moravia (Czech Republic). Environ Geochem Health. 2025;47(6):216-36. https://doi.org/10.1007/s10653-024-01762-8
14. Aleku DL, Lazareva O, Pichler T. Mercury in groundwater–source, transport and remediation. Appl Geochem. 2024;170:106060. https://doi.org/10.1016/j.apgeochem.2024.106060
15. Harr B, Pu B, Jin Q. The emission, transport and impacts of the extreme Saharan dust storm of 2015. Atmos Chem Phys. 2024;24(15):8625-51. https://doi.org/10.5194/acp-24-8625-2024
16. Charters FJ, Cochrane TA, O'Sullivan AD. Predicting event-based sediment and heavy metal loads in untreated urban runoff from impermeable surfaces. Water. 2020;12(4):969. https://doi.org/10.3390/w12040969
17. Ehsan N, Dawood A, Waheed F, Nasir R, Rebouh NY, Rizvi SI, et al. Human and ecological health risks from heavy metal contamination in groundwater aquifers. Sci Rep. 2025;15(1):22826. https://doi.org/10.1038/s41598-025-19844-7
18. Xu D, Shen Z, Dou C, Dou Z, Li Y, Gao Y, et al. Effects of soil properties on heavy metal bioavailability and accumulation in crop grains under different farmland use patterns. Sci Rep. 2022;12(1):9211. https://doi.org/10.1038/s41598-022-12936-5
19. Deng J, Yu J, Wang X, Yu D, Ma H, Wu Y, et al. Spatial distribution and migration characteristics of heavy metals at an abandoned industrial site in the Southwest of China. J Hazard Mater. 2024;480:136447. https://doi.org/10.1016/j.jhazmat.2024.136447
20. Kamali M, Alamdari N, Esfandarani MS, Esfandarani MS. Effects of rainfall characteristics on runoff quality parameters within an industrial sector in Tennessee, USA. J Contam Hydrol. 2023;256:104179. https://doi.org/10.1016/j.jconhyd.2023.104179
21. Rezapour S, Siavash Moghaddam S, Nouri A, Khosravi Aqdam K. Urbanization influences the distribution, enrichment and ecological health risk of heavy metals in croplands. Scientific Reports. 2022;12(1):3868. https://doi.org/10.1038/s41598-022-07835-3
22. Rajendran S, Priya T, Khoo KS, Hoang TK, Ng HS, Munawaroh HSH, et al. A critical review on various remediation approaches for heavy metal contaminants removal from contaminated soils. Chemosphere. 2022;287:132369. https://doi.org/10.1016/j.chemosphere.2021.132369
23. Heidari S, Mostafaei S, Razazian N, Rajati M, Saeedi A, Rajati F. The effect of lead exposure on IQ test scores in children under 12 years: a systematic review and meta-analysis of case-control studies. Systematic Rev. 2022;11(1):106. https://doi.org/10.1186/s13643-022-02020-3
24. Wehby GL. Early-life low lead levels and academic achievement in childhood and adolescence. JAMA Network Open. 2025;8(5):e2512796. https://doi.org/10.1001/jamanetworkopen.2025.12796
25. Xu T, Lin K, Cao M, Miao X, Guo H, Rui D, et al. Patterns of global burden of 13 diseases attributable to lead exposure, 1990–2019. BMC Public Health. 2023;23(1):1121. https://doi.org/10.1186/s12889-023-14951-9
26. Asowata TI, Olatunji AS. Tracking lead in environmental media in the City of Onitsha, Southeast Nigeria. J Health Poll. 2019;9(24):191202. https://doi.org/10.5696/2156-9614-9.24.191202
27. Kumar S, Islam R, Akash PB, Khan MHR, Proshad R, Karmoker J, et al. Lead (Pb) contamination in agricultural products and human health risk assessment in Bangladesh. Water Air Soil Poll. 2022;233(7):257. https://doi.org/10.1007/s11270-022-05686-9
28. Lu H, Yang Y, Huang K, Huang G, Hu S, Pan D, et al. Transformation kinetics of exogenous lead in an acidic soil during anoxic-oxic alteration: important roles of phosphorus and organic matter. Environ Poll. 2023;335:122271. https://doi.org/10.1016/j.envpol.2023.122271
29. Umar A, Nadeem M, Hussain S. Cadmium and zinc inflows through wastewater irrigation govern soil metal balances in wheat-sorghum cropping system. Environ Monitor Assess. 2025;197(9):988. https://doi.org/10.1007/s10661-025-10988-0
30. Wu GH, Cao SS. Mercury and cadmium contamination of irrigation water, sediment, soil and shallow groundwater in a wastewater-irrigated field in Tianjin, China. Bull Environ Contam Toxic. 2010;84(3):336-41. https://doi.org/10.1007/s00128-010-0026-1
31. Brevik EC, Khaledian Y, El-Ramady H. Assessing the complex links between soils and human health: an area of pressing need. Frontiers Media SA; 2021. p. 731085. https://doi.org/10.3389/fsufs.2021.731085
32. Hamoud YA, Shaghaleh H, Zia-ur-Rehman M, Rizwan M, Umair M,

Usman M, et al. Cadmium and lead accumulation in important food crops due to wastewater irrigation: pollution index and health risks assessment. Heliyon. 2024;10(3):e13698. https://doi.org/10.1016/j.heliyon.2024.e13698

33. Rasin P, Ashwathi A, Basheer SM, Haribabu J, Santibanez JF, Garrote CA, et al. Exposure to cadmium and its impacts on human health: a short review. J Hazard Mat Adv. 2025;100608. https://doi.org/10.1016/j.hazadv.2025.100608

34. La-Up A, Mahasakpan P, Saengow U. The current status of osteoporosis after 15 years of reduced cadmium exposure among residents living in cadmium-contaminated areas in northwestern Thailand. Environ Sci Poll Res. 2021;28(16):20121-7. https://doi.org/10.1007/s11356-021-13162-4

35. Pu Q, Meng B, Huang JH, Zhang K, Liu J, Liu Y, et al. Dissolved organic matter fosters core mercury-methylating microbiomes for methylmercury production in paddy soils. Biogeosciences. 2025;22(6):1543-56. https://doi.org/10.5194/bg-22-1543-2025

36. Zhang F, Xu Z, Xu X, Liang L, Chen Z, Dong X, et al. Terrestrial mercury and methylmercury bioaccumulation and trophic transfer in subtropical urban forest food webs. Chemosphere. 2022;299:134424. https://doi.org/10.1016/j.chemosphere.2022.134424

37. Robles ME, Oh Y, Haque MT, Jeon M, Kim LH. Soil mercury pollution in nature-based solutions across various land uses: a review of trends, treatment outcomes and future directions. Appl Sci. 2025;15(12):6502. https://doi.org/10.3390/app15126502

38. Aryan Y, Pon T, Panneerselvam B, Dikshit AK. A comprehensive review of human health risks of arsenic and fluoride contamination of groundwater in the South Asia region. J Water Health. 2024;22(2):235-67. https://doi.org/10.2166/wh.2024.123

39. Sadee BA, Zebari SM, Galali Y, Saleem MF. A review on arsenic contamination in drinking water: sources, health impacts and remediation approaches. RSC Adv. 2025;15(4):2684-703. https://doi.org/10.1039/D5RA01023B

40. Shin DY, Lee SM, Jang Y, Lee J, Lee CM, Cho EM, et al. Adverse human health effects of chromium by exposure route: a comprehensive review based on toxicogenomic approach. Int J Mol Sci. 2023;24(4):3410. https://doi.org/10.3390/ijms24043410

41. Krailertrattanachai N, Ketrot D, Wisawapipat W. The distribution of trace metals in roadside agricultural soils, Thailand. Int J Environ Res Public Health. 2019;16(5):714. https://doi.org/10.3390/ijerph16050714

42. Yang L, Ge S, Liu J, Iqbal Y, Jiang Y, Sun R, et al. Spatial distribution and risk assessment of heavy metal(oid)s contamination in topsoil around a lead and zinc smelter in Henan Province, Central China. Toxics. 2023;11(5):427. https://doi.org/10.3390/toxics11050427

43. Ali HQ, Yasir MU, Farooq A, Khan M, Salman M, Waqar M. Tanneries impact on groundwater quality: a case study of Kasur city in Pakistan. Environ Monit Assess. 2022;194(11):823. https://doi.org/10.1007/s10661-022-10308-7

44. Shaibur MR. Heavy metals in chrome-tanned shaving of the tannery industry are a potential hazard to the environment of Bangladesh. Case Stud Chem Environ Eng. 2023;7:100281. https://doi.org/10.1016/j.cscee.2023.100281

45. Wear SL, Acuña V, McDonald R, Font C. Sewage pollution, declining ecosystem health and cross-sector collaboration. Biol Conserv. 2021;255:109010. https://doi.org/10.1016/j.biocon.2021.109010

46. Mora A, Torres-Martínez JA, Capparelli MV, Zabala A, Mahlknecht J. Effects of wastewater irrigation on groundwater quality: an overview. Curr Opin Environ Sci Health. 2022;25:100322. https://doi.org/10.1016/j.coesh.2022.100322

47. Aind DA, Dasgupta S, Mukherjee A. Novel finding of occurrence of geogenic nickel in the arsenic-enriched groundwater of the Himalayan Brahmaputra River Basin aquifers. J Hydrol. 2025;659:133249. https://doi.org/10.1016/j.jhydrol.2024.133249

48. Laoye B, Olagbemide P, Ogunnusi T, Akpor O. Heavy metal contamination: sources, health impacts and sustainable mitigation strategies with insights from Nigerian case studies. F1000Res. 2025;14:134. https://doi.org/10.12688/f1000research.133123.1

49. Haghighizadeh A, Rajabi O, Nezarat A, Hajyani Z, Haghmohammadi M, Hedayatikhah S, et al. Comprehensive analysis of heavy metal soil contamination in mining environments: impacts, monitoring techniques and remediation strategies. Arab J Chem. 2024;17(6):105777. https://doi.org/10.1016/j.arabjc.2024.105777

50. Gad M, Gaagai A, Agrama AA, El-Fiqy WF, Eid MH, Szűcs P, et al. Comprehensive evaluation and prediction of groundwater quality and risk indices using quantitative approaches, multivariate analysis and machine learning models: an exploratory study. Heliyon. 2024;10(17):exxxx. https://doi.org/10.1016/j.heliyon.2024.exxxx

51. Zhang M, Liu R, Huang J, Si W, Wang G, Liu G. Life cycle assessment and environmental benefit analysis of a modified biochar system for heavy metal wastewater treatment. J Water Process Eng. 2025;76:108072. https://doi.org/10.1016/j.jwpe.2025.108072

52. Ghannem S, Bacha O, Fkiri S, Kanzari S, Aydi A, Touaylia S. Soil and sediment organisms as bioindicators of pollution. Ecologies. 2024;5(4):679-96. https://doi.org/10.3390/ecologies50403679

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