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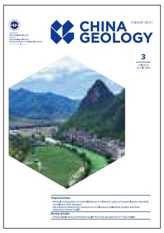

Chemical elements and human health from the perspective of “One Health”

Qing Wen[a], Li-yue Zhang[a], Ming-xin Liu[a], Wen-bing Ji[b], Chang Li[a], Tao Yu[a, d,*], Qi-feng Tang[d,*], Hui Lu[a], Qing-ye Hou[c, d], Zhong-fang Yang[c, d]

[a] *School of Science, China University of Geosciences, Beijing* 100083, *China*
[b] *Nanjing Institute of Environmental Sciences, Ministry of Ecology and Environment, Nanjing* 210042, *China*
[c] *School of Earth Science and Resources, China University of Geosciences, Beijing* 100083, *China*
[d] *Key Laboratory of Ecogeochemistry, Ministry of Natural Resources, National Research Center for Geoanalysis, Beijing* 100037, *China*

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ABSTRACT

Human activities are closely related to geological environments or those influenced by geological factors, which can significantly impact human health. Previous studies have predominantly focused on isolated spheres or single environmental indicators, lacking research on the multifactorial influences affecting the overall geographic environment. From the “One Health” perspective, this paper synthesizes natural environmental factors across the lithosphere, hydrosphere, atmosphere, and pedosphere, encompassing the sources, forms, concentrations, and bioavailability of chemical elements, as well as pollutants and their associations with human health. Comprehensive natural environmental factors, based on GeoHealth, are intimately connected to human health. Under the pressures of future population growth and rapid industrial development, the relationship between the global geological environment and human health will become increasingly prominent. Therefore, it is crucial to pay close attention to health-based thresholds and promptly implement pollution prevention and control measures.

1. Introduction

Health and longevity are global pursuits, and the factors affecting human health are among the most prominent research topics in modern science. Despite ongoing debates, researchers in relevant fields have reached a consensus that human health is influenced by a combination of environmental, genetic, lifestyle, and socioeconomic factors (Lavezzi AM and Ramos-Molina B, 2023). Among these, environmental factors are particularly crucial because humans are highly sensitive to their surroundings. The term “environment” refers to the Earth’s surface, which humans depend on for survival and development, encompassing both natural and human-made components. The natural environment consists of rocks, soil, water, air, biota, and other constituents (elements). Numerous studies have indicated (Kennedy EM et al., 2018) that the totality of the lithosphere, hydrosphere, atmosphere, and pedosphere, is a primary determinant of human health. This is in line with the World Health Organization’s (WHO) One Health concept of optimizing human and ecosystem health by integrating a number of domains (Mumford EL et al., 2023) (One Health Action Commission, OHAC), which provides an important perspective for analyzing the transboundary impacts of geological elements on human health. This approach emphasizes the interconnections between human, animal, and environmental health and can link geochemical processes to biological outcomes. By studying the transport of chemical elements in the soil, lithosphere, hydrosphere and atmosphere and their bioaccumulation through the food chain, the impact on public health is revealed. In recent years, the One Health approach has been applied to multidisciplinary studies and systematically applied to assess the multifactorial impacts of environmental elements on health, integrating geochemical data with epidemiological modeling in order to develop more effective pollution prevention and control strategies (Oltean HN et al., 2025).

First author: *E-mail address*: 2019230041@email.cugb.edu.cn (Qing Wen).

* Corresponding author: *E-mail address*: yutao@cugb.edu.cn (Tao Yu); tangqifeng@mail.cgs.gov.cn (Qi-feng Tang).

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As awareness of the Earth's environment and human health has grown, research at the intersection of health and geology has surged. Hamilton EI et al. found (Hamilton EI et al., 1973) that the elemental composition of human tissues is similar to the average composition of the Earth's crust, indicating that the elements constituting the human body are primarily derived from the environment. The unique content and distribution of trace elements in the geological environment profoundly impact human health. Uneven distribution of elements in the natural environment can lead to endemic diseases, such as selenium deficiency in a diagonal band from northeast to southwest China leading to Keshan disease and Kashin-Beck disease, and motor neuron disease in calcium- and zinc-deficient areas of sub-Saharan Africa (Gashu D et al., 2021). Conversely, specific concentrations of elements can promote regional health and longevity, as observed the selenium content of the soil in Bama County and the longevity zone of Chongqing city in China, are in the selenium-enriched range (Zhang W et al., 2023). Additionally, there are many elements/substances that have a negative impact on human health, such as heavy metal cadmium poisoning that causes itai-itai disease, lead poisoning that causes mental abnormalities in children (Naranjo VI et al., 2020), mercury poisoning that causes Minamata disease, etc. Airborne pollutants, such as sulfur dioxide (SO_2), nitrogen oxides (NOx), and tobacco smoke can cause cancer, or cardiovascular, prenatal central nervous system, and respiratory health problems when ingested. Extensive research has shown that among all chemical elements, selenium (Se), cadmium (Cd), copper (Cu), zinc (Zn), and calcium (Ca) are most closely related to health (Rayman MP, 2000, 2008, 2020; Rasin P et al., 2025).

Currently, there is substantial research on factors influencing human health. However, most studies have focused on single environmental factors, and research on the relationship between health and chemical elements has primarily employed correlation analyses, lacking a multifactorial approach to the overall geographic environment, making it difficult to fully describe the complex interactions between the ecological environment and human society. Secondly, existing research lacks a systematic summary of how environmental elements in the lithosphere, hydrosphere, atmosphere, and pedosphere affect human health through synergistic or antagonistic effects. Health is a critical indicator of environmental quality. Given the close relationship between human health and the geographic environment, cross-circuit collaboration through the "One Health" approach is an important solution to the study of the environment and human health. One Health is dedicated to achieving sustainable coordination and synergistic enhancement of human, animal, and environmental health. By focusing on the human-animal-environment interface, it fosters interdisciplinary and cross-regional collaboration to address environmental risk factors threatening human health, thereby promoting the integrity and resilience of global ecosystems. This review comprehensively collated relevant literature through systematic searches of published academic papers, research reports, and online information released by governmental and non-governmental organizations. Data were electronically acquired from databases including Web of Science (WoS), PubMed, Springer, among others. The literature search employed multiple keyword combinations aligned with the review's thematic focus. In WOS, the following search terms were applied: (One Health) AND (soil OR water OR atmosphere OR rock) AND (exposure) AND (human health). Articles containing keywords such as elements, exposure sources, human health, and health impacts were subsequently analyzed. This study based on a GeoHealth framework, primarily focuses on indicators of environmental exposure affecting health. This paper advocates for the integration of rocks, soil, water, and air within the "One Health" framework, using the lithosphere, pedosphere, hydrosphere, and atmosphere as entry points to advance transdisciplinary collaboration across geographic and institutional boundaries. It comprehensively reviews the relationship between geological environmental factors in the lithosphere, hydrosphere, atmosphere, and pedosphere and human health.

2. Elements affecting human health in four circles

2.1. Rocks and human health

Different regions have different natural background environments and the chemical composition of surface materials is very diverse due to the different compositions of the various minerals that make up the rocks. Bedrock is transferred to other materials through erosion, weathering and soil-forming process properties and, to varying degrees, to the water that passes through these solid-phase resources.

2.1.1. Black shale and potentially toxic elements

Black shale is a sedimentary rock mainly composed of siliceous, argillaceous, carbonate rocks, and some metamorphic rocks, formed in relatively deep anoxic marine basins. Black shale serves as a significant geological source of Cd. Soils developed from black shale with high geochemical background are typically characterized by enriched organic matter and sulfide minerals, coupled with severe acidification, which collectively enhance Cd bioavailability and consequently elevate environmental risks. In Luzhai, Guangxi, soils in black shale-exposed areas exhibit significant Cd enrichment and pronounced acidification (Duan YR et al., 2020). Similarly, in Wushan County, Chongqing, soils derived from black shale formations demonstrate exceedances of multiple heavy metal thresholds, including Cd, Ni, and Zn, with Cd concentrations reaching up to 59.7 mg/kg (Liu YZ et al., 2015, 2017, 2019).

Globally, elevated Cd concentrations are most closely associated with black shale. Black shale is widely distributed around the world, with the South China black shale formation being one of the largest black shale areas on Earth, extending approximately 1600 km from southwest to east along the

Yangtze River. Studies indicate that the main carriers of potentially toxic metals in black shale are sulfide minerals, which are easily oxidized in the surface environment, releasing Cd and other potentially toxic elements and posing a risk of acid rock drainage. These elements are often transported in dissolved form through surface water or groundwater and can be adsorbed onto organic and clay minerals or iron/manganese hydroxides, or retained in the surrounding soil or sediment by forming secondary minerals (Liu YZ et al., 2015, 2017, 2019). These elements can then be taken by the human body, leading to environmental pollution and threatening human health. Table 1 summarizes the major distribution areas of black shale worldwide and their ecological and human health risks. It could be inferred that the incidence of cancer and disease is associated with black shale ore mining and rock weathering.

2.1.2. Granite and radioactive substances

Granite is the most abundant intrusive igneous rock in the continental crust. Studies have found that natural radioactive nuclides (including ^{238}U, ^{226}Ra, ^{232}Th, and ^{40}K) are widely distributed in most granites. High concentrations of radioactive uranium and thorium have been observed in granite regions in Guangzhou, China, the Czech Republic, the Iberian Peninsula, the Central Alps, the Jura of Switzerland, northern Estonia, and volcanic regions of Italy (Grzywa-Celińska A et al., 2020). Assessing these natural radioactive elements can estimate the radiation hazard index and their impact on human health. Long-term inhalation of radioactive nuclides and exposure to high-radioactivity substances can affect human organs, and timely monitoring of radioactive substance release into the environment can provide appropriate protection for humans.

2.1.3. Heavy metal pollution in karst area carbonate rock soil

Karst areas are among the most ecologically fragile geomorphological regions in the world, characterized by high geological background values of heavy metals. Due to shallow soil, low organic matter content, and high pH, agricultural soils are sensitive to heavy metal pollution, posing significant threats to the environment and human health. The metal concentrations in carbonate rocks in the crust are usually low (averaging 0.035 mg/kg), such as Cd, Pb, Cr, Cu and Zn. However, soils formed from carbonate rocks may enrich Cd by one or more orders of magnitude compared to the parent rock. The southwestern karst region of China, which is the largest continuous karst terrain in the world, has extensive carbonate rock, forming a Cd anomaly zone over 200000 km^2. The enrichment is attributed to the unique geochemical behavior of trace metals in soil formation processes in the carbonate rock area, where trace metals have lower mobility because they are adsorbed onto clay minerals or iron-manganese oxides or captured into their lattices (Wen YB et al., 2020). Soils developed from carbonate bedrock are initially alkaline but become more acidic during weathering and soil formation, resulting in lower bioavailability of heavy metals in the soil.

2.1.4. Mineral dust

Agricultural production tillage, unpaved roads, construction sites, and wind erosion of bare fields release mineral dust into the atmosphere, which affects human health. Globally, wind from arid regions' dry soils is the main carrier of particulate matter and atmospheric pollution. Dust particles in such winds are mainly oxides, salts, and clays, typically less than 10 μm in diameter, and have undergone intense weathering. For example, dust storms from the Sahara Desert in Africa travel across the Atlantic Ocean with the trade winds to North America, where they are associated with increased Hg, Se, and lead content in the soil (Münzel T et al., 2018). Due to the toxicity of particulates, dust from Africa is also associated with an increase in cardiopulmonary deaths in Europe from air pollution. Since wind-borne dust can be transported long distances, pleistocene loess deposits from western Xinjiang Province, China, and dust from Mongolian mineral soils have been found to increase the risk of acute myocardial infarction in Japan (Lelieveld J et al., 2015). Coal formed from peat deposits is the second largest global energy

Table 1. Global distribution of black shale and health risks.

Distribution areas	Ecological and human health risks	Literature sources
Talvivaara Region, Finland	Geochemical weathering of black shale significantly increases Pb, Cu, manganese, nickel and Zn concentrations in local river sediments	(Maier WD et al., 2015)
Central Korea	Soil Se concentration in black shale development is as high as 72.6 mg/kg, much higher than the world average soil Se content (0.20 mg/kg)	(Park M et al., 2010)
Southern Shaanxi, China	Consistency between the geological distribution of black shale and the geographical distribution of endemic diseases	(Du YJ et al., 2018)
Guangxi, China	Cd bioavailability in soils from karst areas is high, exhibiting geochemical background level concentrations as high as 2.67 mg/kg	(Wen YB et al., 2020)
Three Gorges Region, China	Cd intake in adults through Cd-rich vegetables is 234 μg per day, which is significantly higher than the reference dose (60 μg for a 60 kg adult).	(Liu YZ et al., 2015, 2017, 2019)
Midwest Basin, USA	As concentrations were as high as 95 mg/kg, while the metal contaminated underground aquifers.	(Ayotte JD et al., 2017)
Jamaica	Elevated Cd concentrations were also detected in urine samples from people in areas naturally high in Cd.	(Wright PRD et al., 2010)
United Kingdom	Se-rich soil linked to black shale	(Parnell J et al., 2016)
Sweden	Burning and processing of black shale has resulted in the detection of up to 200 μg/L of uranium in groundwater	(Åström ME et al., 2009)

source. During transportation and combustion, coal releases substantial particulates in the form of aerosols, containing elements such as As, Cs, F, Se, and Hg. Inhalation of coal dust poses risks to human health, with studies showing that coal miners who inhale coal dust long-term have a four-fold higher incidence of black lung disease compared to the global average (Akbar KA and Kallawicha K, 2024). Additionally, individuals with indirect exposure to coal are also susceptible to respiratory and cardiovascular diseases, systemic inflammation, and neurological disorders.

2.2. Soil and human health

2.2.1. Beneficial mineral derived elements in soil

Approximately 78% of the global per capita calorie consumption comes directly from crops grown in soil, with an additional nearly 20% derived from terrestrial food sources indirectly dependent on soil. This process is based on the cycling of materials in the soil. Soil is a crucial component of the natural environment, serves as the material foundation for all living organisms. Most elements in the soil can be recycled and reused repeatedly. In more detail, the elements absorbed by plants from the soil enter the food chain, these elements form the main components of the cellular tissues of plants and animals, and the death and decay of organisms and their tissues return them to the soil, where they are decomposed by soil micro-organisms and the elements are released into the environment and taken up again by plants and animals, thus constituting a cycle. It is through this cycle that mineral derived elements in the soil affect human health. Over two-thirds of the world’s population lacks one or more essential mineral derived elements in their diet.

In 1996, The WHO declared Se to be an essential micronutrient for human health based on its observed benefits (Rayman MP, 2000, 2008, 2020). The range between dietary deficiency (<60 μg/d) and toxicity (>400 μg/d) of Se is quite narrow (NHC, 2018), making it one of the elements most closely related to health. Regions in China known for their long-lived populations, such as Bama in Guangxi and Hotan in Xinjiang, have soil Se levels significantly higher than other areas. Studies have indicated a similarity in distribution between the proportion of people aged 90 and above, and Se content in the soil in China, showing a significant positive correlation between background Se levels in soil and longevity indices (Huang B et al., 2009). Furthermore, the concentration of Se in soil largely determines the Se intake of the local population through edible plant tissues or the food chain. It is estimated that 500 million to 1 billion people worldwide have insufficient Se intake, with plants contributing approximately 60% of the daily dietary Se intake, followed by meat and seafood (Kieliszek M, 2019). For normal adults, the WHO recommends a daily Se intake of 30–40 μg/d, with an upper tolerable intake level of 400 μg/d. Due to geological and climatic factors, Se concentrations in soil vary greatly worldwide. Using Rayman’s naming convention, global Se belts can be categorized as “toxic,” “high,” “highly-adequate,” “adequate,” and “deficient” (Rayman MP, 2000, 2008,2020) (Table 2).

Since mineral elements ultimately originate from the soil, there are variations in the mineral nutritional status of different regions, especially where the soil-water-plant-human linkage is fairly direct. Despite China ranking fourth globally in Se reserves (only behind Canada, the United States, and Belgium)(Gupta M and Gupta S, 2017), a geographical low-Se belt stretches from Heilongjiang Province in the northeast to Yunnan Province in the southwest, affecting 71.2% of China’s land (Zhu YG et al., 2009). Se deficiency in humans primarily leads to two endemic diseases: Keshan disease (KD) and Kashin-Beck disease (KBD), and in general the local distribution of these two diseases is directly related to the geographic pattern of soil Se deficiency. Keshan disease presents as an endemic cardiomyopathy in humans, and has been recorded in 329 counties and 16 provinces in China. Kashin-Beck disease is an endemic osteoarthropathy that is distributed similarly to KBD, with cases recorded in 335 counties and 15 provinces in China. The Songnen Plain in northeastern China is located in a low-Se geological zone at the Se-deficient and Se-marginal areas, and is one of the regions in China where Se deficiency-related diseases were first identified. Residents in this area have a higher incidence of KD and KBD (Yang CM et al., 2021).

According to Sun GX et al., Se deposition and volatilization are key factors controlling the distribution of Se in surface soil (Fig. 1), playing a crucial role in the Se balance in terrestrial environments (Sun GX et al., 2010, 2016). The wet deposition from the East Asian summer monsoon and the

Table 2. Regional division of global selenium belt.

Selenium belt	Intake (μg/d)	Region	Literature sources
Toxic	>720	Enshi County, Hubei Province Ziyang County, Shaanxi Province	(Qin HB et al., 2013) (Cui ZW et al., 2017)
High	200–720	North America Venezuela	(Han S et al., 2019) (Winther KH et al., 2020)
High–adequate	100–200	Spain Japan	(González S et al., 2006) (Hu XF et al., 2017) (Miyazaki Y et al., 2002)
Adequate	30–100	Australia New Zealand Saudi Arabia	(Lyons GH et al., 2005) (Thomson CD, 2004) (Al-Ahmary KM, 2009)
Deficient	＜30	United Kingdom Finland Canada	(Darling AL et al., 2010)

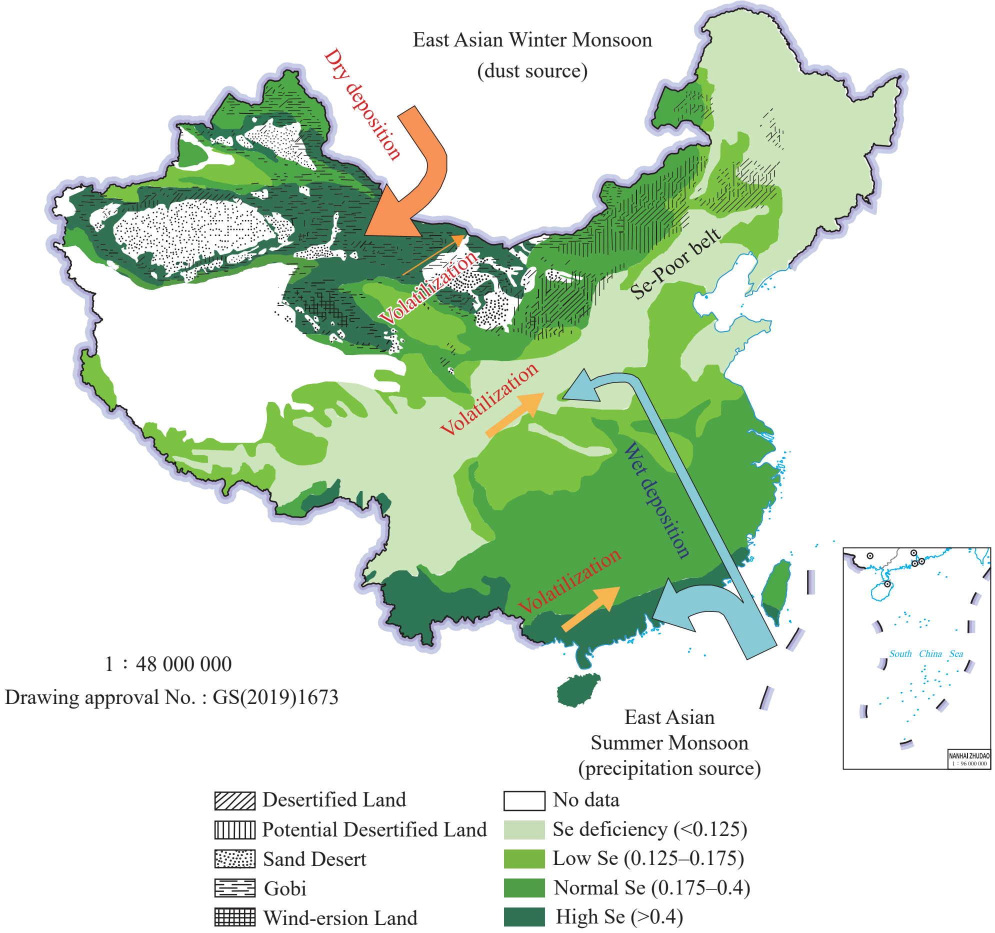

Fig. 1. Selenium deposition and volatility in China (after Sun GX et al., 2010, 2016).

dry deposition from the East Asian winter monsoon are the primary reasons for Se enrichment in southeastern and northwestern China. In central China, the soil Se volatilization rate is similar to the deposition rate, indicating that volatilization offsets deposition, making the net Se input to the soil negligible. The surface soil Se content is close to or slightly higher than that in the bedrock, and significantly lower than in the northwestern or southeastern regions (Sun GX et al., 2010, 2016). This is the main reason for the existence of the low-Se belt. A study using machine learning algorithms predicts that due to climate change, Se species will shift towards more oxidized forms, which bind less strongly in soil and leach more easily with precipitation. This will result in a 55% to 80% decrease in soil Se concentrations by the end of the 21st century (Feinberg A et al., 2021). Therefore, sustainable fertilizer management strategies must be developed to counteract the reduction in atmospheric nutrient supply and ensure future food security and nutrition.

Se-rich soils mainly originate from certain types of sedimentary rocks. Excessive exposure and absorption of Se can also adversely affect human health. For example, in Punjab, India (Chawla R et al., 2020), the high Se content in soil and water leads to mustard and wheat plants containing Se at levels of 931 mg/kg and 390 mg/kg respectively. Consuming these Se-rich crops increases dietary Se intake and accumulation in the human body, with Se potentially substituting sulfur in amino acids (cysteine and methionine), leading to the production of malformed proteins and resulting in Se toxicity. However, reports of Se toxicity in humans are limited because high Se concentrations in the environment and food are rare.

Zn is an essential trace element for all life forms, involved in the production of various enzymes and proteins in both plants and animals. It is known as an anti-aging element. Zn deficiency in humans is a global public health issue, with one-third of the world’s soils being Zn-deficient, affecting approximately 17% of the global population and contributing to 4% of global child morbidity and mortality. This is more prevalent in regions with high cereal consumption and low consumption of animal products. Soil Zn deficiency is mainly caused by low Zn solubility and high Zn fixation rates. Factors such as extreme soil weathering, high effective phosphorus, high clay content, prolonged waterlogging, and high soil organic matter content reduce the bioavailability of Zn, resulting in generally low Zn content in plants. Phytates and other elements also affect Zn absorption in the human body. Phytates strongly bind with Zn in the body, limiting its bioavailability. Elements like Ca can form insoluble complexes with phytates and Zn. Cu shares transport proteins with Zn and affects the redistribution of Zn in plants, further inhibiting Zn absorption and significantly impacting human health. Although Zn is crucial for humans, the daily intake for adults should not exceed 40 mg/d (Zia MH et al., 2020). Very high intakes of Zn, which have occurred due to inappropriate use of Zn supplements, can interfere with Cu metabolism and deplete the body of Cu. Chronic exposure to excess Zn can reduce immune function and HDL cholesterol. This indicates that, apart from Zn deficiency, potential toxicity at high exposure levels must also be monitored.

Numerous other mineral derived elements in soil, when present in insufficient or excessive amounts, can lead to diseases and endanger human health. For instance, Cu is an essential micronutrient for both human and plant growth. The Cu content in soil depends on complex processes among parent materials and their physicochemical properties, as well as additions from agronomic practices or industries. Research indicates that Cu content decreases with increasing pH and clay content, and Cu has a high affinity for organic matter, making it less likely to leach from the soil profile and more likely to accumulate in surface soil. Long-term accumulation in farmland can increase the risk of toxicity in crops. Generally, Cu content in crop tissues is sufficient within the range of 5.00–30.00 mg/kg (Tóth G et al., 2016). Deficiency can cause severe diseases like anemia, while excess Cu can lead to liver diseases and Alzheimer’s disease and potentially cause neurodegeneration.

Ca is the fifth most abundant inorganic element, constituting about 2% of the total body weight and involved in various biological structures and physiological processes (Sharma D et al., 2017). Dietary intake is necessary to meet the body’s Ca needs, with recommended daily intake for adults ranging from 800 mg/d to 1300 mg/d. Bangladesh, South Africa, India, Vietnam, South Korea, and China are currently the most affected by Ca deficiency, with intake levels between 25% and 33% of the recommended levels (Balk EM et al., 2017). Insufficient Ca intake leads to multiple diseases, affecting the level of health of the human body, which in turn causes an economic burden on individuals and an economic cost to the country. Therefore, it is crucial to focus on the factors that influence Ca intake. Cereals are the primary food source in these countries. Ca deficiency in field-grown crops is rare, with crop Ca content is directly related to soil pH. Crops grown on acidic soils have higher Ca availability, and increasing soil pH improves the relationship between extractable soil Ca and crop Ca content. Crops grown on calcareous soils contain higher Ca levels than those on non-calcareous soils. Additionally, Ca provides significant protection against Cd toxicity in crops. Lower doses of Ca promote Cd uptake and translocation in crops, but higher doses reduce root Cd uptake. Studies have shown that increasing Ca content in rice plants significantly reduces Cd accumulation. The distribution and bioavailability of iron in the environment directly influence human health. The two principal subtypes of chronic inflammatory bowel disease (IBD) are Crohn’s disease (CD) and ulcerative colitis (UC). Europe, Australia, and North America are among the regions with the highest incidence rates (Weidner J et al., 2024), demonstrating 10 to 30 cases per 100000 individuals. Among IBD complications, anemia emerges as the most prevalent manifestation, observed in approximately one-third of patients. Anemia manifests when the human body exhibits reduced erythrocyte counts or diminished hemoglobin concentrations. Consequently, iron deficiency persists as a global health challenge requiring coordinated multinational mitigation efforts. Fig. 2 illustrates the roles of different elements in human health.

2.2.2. Harmful heavy metal elements in soil

In recent years, soil heavy metal (HM) pollution has become a global environmental issue. Heavy metals in agricultural soil have received extensive attention due to their impact on the quality and safety of agricultural products and human health. Cd, arsenic (As), and mercury (Hg) have been proven to be highly toxic, non-degradable, and capable of accumulating in the human body, leading to irreversible health impacts. These elements are listed among the top 20 hazardous substances by the U.S. Environmental Protection Agency (EPA) and the Agency for Toxic Substances and Disease Registry (ATSDR) (Yang QQ et al., 2018). According to the latest national soil pollution survey in China, the overall soil environment is poor, with severe pollution especially in the central and southwestern regions. It is estimated that 19.4% of agricultural soil samples exceed the limit values, with heavy metals accounting for the majority (82.4%) of the pollutants, and Cd being the most prevalent (7%).

Cd is a toxic heavy metal. The chronic Cd poisoning disease, Itai-Itai disease, was first discovered in Toyama Prefecture, Japan, in the early 20th century. This disease was caused by Cd-contaminated soil, leading to severe health problems. Cd competes with Ca and other nutrients in the human body, and the local residents consumed rice that lacked essential minerals, leading to kidney damage, osteoporosis, and cancer from prolonged consumption. The WHO and the Food and Agriculture Organization (FAO) recommend a maximum tolerable intake of Cd at 70 μg/d. Studies on Itai-Itai disease patients estimate the cumulative Cd intake to be 2.6 g for mild cases and 3.3 g for severe cases. At the current rate of Cd intake in China (15.3 μg/kg body weight/month), it would take the general population over 100 years to reach a cumulative intake of 2.6 g, but it would take only 47–76 years for farmers in polluted areas who rely on self-grown rice to reach this level (Wang P et al., 2019). Fig. 3 illustrates the uptake and translocation of Cd in rice.

Rice is the largest contributor to dietary Cd intake, accounting for 56% of the total intake in China. Rapid industrialization worldwide has led to severe heavy metal contamination in agricultural soils. In China, 2.2%–10% of surveyed rice samples exceeded the maximum permissible Cd level (0.2 mg/kg) (Song Y et al., 2017), with 56%–87% of field survey samples from polluted areas in southern China exceeding the food limit. The Cd content in grains from these polluted areas is comparable to or higher than those in the Itai-Itai disease region during the peak of chronic Cd poisoning in Japan, highlighting the severity of the current situation in China. Due to Cd's long biological half-life in the human body (10 to 35 years), its health risks are insidious and require constant vigilance. The accumulation of Cd in soil has raised global concerns about food safety, prompting many countries to set stringent thresholds for soil Cd levels (Tables 3 and 4).

From 1990 to 2015, the average Cd content in rice and rice consumption rates indicate that for an adult weighing 60 kg, the Cd intake from rice alone in China ranges from 2.9–7.0 μg/kg body weight/month (116 g of rice per day in the north) to 7.7–18.7 μg/kg body weight/month (316 g of rice per day in the south). The dynamics of Cd content in rice are governed by multiple factors (Fig. 4). The latest national soil pollution survey shows that since the early 1980s, soil Cd concentrations in northern, northeastern, and western China have increased by 10%–40% on average, and by over 50% in coastal and southern regions (Shi JD et al., 2023). The increase in soil Cd is primarily due to local mining and smelting activities and irrigation with contaminated water. Atmospheric deposition and the application of phosphate fertilizers also add Cd to the soil. Soil acidification can significantly increase the solubility of Cd: A one-unit decrease in soil pH can increase Cd solubility by 4–5 times.

As is a naturally occurring environmental pollutant and a class I carcinogen, affecting millions of people worldwide,

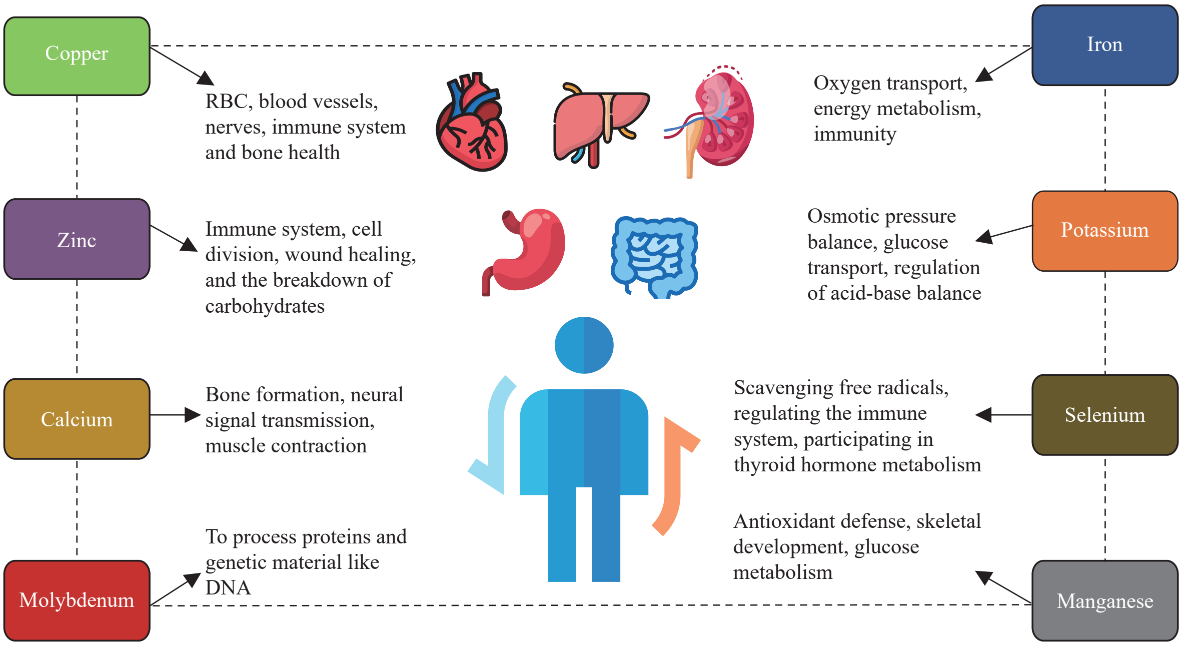

Fig. 2. Role of various elements in human health.

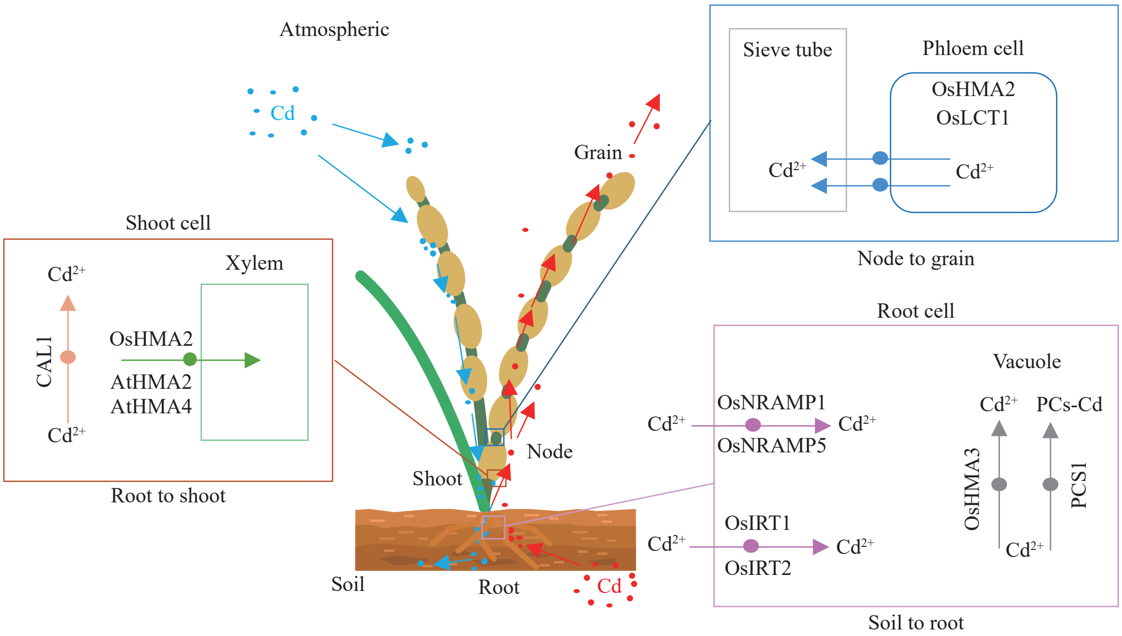

Fig. 3. Uptake and translocation of Cd by rice.

particularly in India, Bangladesh, China, parts of South America, and Southeast Asia. Among them, Asia is the most severely affected region. Particularly in South Asia, Bangladesh and West Bengal, India are facing the world's most severe public health crisis due to excessive As levels in groundwater (Bhowmick S et al., 2013). In China, regions such as the North China Plain and Yunnan Province are affected by dual As sources from both sedimentary layers and mining activities. South American countries such as Chile and Argentina have become significant polluted zones due to volcanic rock's naturally high As background and lithium mining activities (Aullón Alcaine A et al., 2020). In North America and Europe, As pollution primarily relates to historical mining activities, such as mining areas in the southwestern United States and industrial legacies along Hungary's Danube River basin (Gati G et al., 2016). Additionally, East African Rift Valley regions, such as Tanzania, have emerged as As-fluoride co-contaminated areas due to mining activities and related operations (Mng'Ong'o M et al., 2021). Studies have reported that inorganic forms of As, such as arsenite (As(III)), due to its high binding affinity with biological molecules such as sulfhydryl groups, are 60 times more toxic than arsenate (As(V)). Major crops that accumulate As in soil include barley, beans, corn, and rice, with rice absorbing ten times more As than other crops. This is due to the reduction and dissolution of iron oxides/hydroxides under anaerobic conditions, leading to higher mobility of arsenite (As(III)), and the unique physiological functions of rice plants that enable them to absorb high concentrations of As from the soil. Therefore, dietary As exposure has become a major risk source in Asian rice-growing regions such as China and Vietnam, as well as in seafood-consuming areas of Europe and America (Noh CH et al., 2023). Long-term intake of As-contaminated foods such as rice and seaweed may lead to chronic poisoning. Studies have demonstrated significant associations between As exposure and global health issues including skin cancer, bladder cancer, cardiovascular diseases, and diabetes. Typical cases of As-induced endemic diseases include skin keratosis in Bangladesh, lung cancer in Chile, and Blackfoot disease in the Taiwan (China). The WHO recommends a level of 0.2 mg/kg for As in rice. Carey M et al. suggested that (Carey M et al., 2015) rinsing rice multiple times before cooking can reduce As content in grains by up to 60%, thereby lowering the risk of human exposure to As from rice.

Table 3. Threshold values of Cd content in agricultural soils in different countries.

Country	Soil Cd thresholds (mg/kg)	Literature sources
Canada	0.5	Kubier A et al., 2019
Switzerland	0.8	
Germany	0.4–1.5	Lalor GC, 2008
Netherlands	0.8	Tang X et al., 2016
Romania	5.0	
Russia	0.3	
Poland	3.0	
United States of America	1.0	Mubeen S et al., 2023
Mexico	37	Liao X et al., 2023
United Kingdom	3.0	Cupit M et al., 2002
Denmark	0.5	
Finland	0.5	
Austria	1.0	
New Zealand	1.8	Abraham E, 2020
Kenya	0.7	Mungai TM et al., 2016
Brazil	0.3	de Souza RE et al., 2024

Table 4. Cd content limit values in Chinese soils.

Soil type or use	pH				Source
	⩽5.5	>5.5–6.5	>6.5–7.5	>7.5	
Paddy field	0.3	0.4	0.6	0.8	GB15618–2018
Others	0.3	0.3	0.3	0.6	

Hg is found in soils formed from parent materials high in organic matter and has a strong affinity for organic matter. However, anthropogenic activities like gold mining and coal combustion can lead to extensive soil Hg pollution. The eastern part of North America, Western Europe, and the East Asian industrial belt have become major pollution zones due to historical emissions. Additionally, tropical regions such as the Amazon Basin and Southeast Asia have emerged as pollution hotspots primarily because of gold mining activities (Velásquez Ramírez MG et al., 2021). Hg can be methylated by soil organisms, making it mobile in the soil, which can lead to surface water contamination and the formation of highly toxic methylmercury that plants can absorb. Humans can accumulate Hg in brain tissue through drinking contaminated water or consuming contaminated plants or animals, causing damage to the central nervous system, cardiovascular diseases, and other health issues.

2.3. Drinking water and human health

2.3.1. Beneficial trace elements in water

In natural water systems, the changing chemical composition of water is largely controlled by geological factors, with the geochemistry of rock weathering determining the release of elements into the water. When dilute rainwater of the sodium chloride type containing carbon dioxide enters the soil zone, carbon dioxide from decaying organic matter is further dissolved in the infiltrating water to form carbonic acid. In the unsaturated zone of soils and sedimentary rocks, this weak acid dissolves soluble Ca and magnesium carbonates, such as calcite and dolomite, thus releasing high concentrations of Ca and magnesium. In crystalline igneous and metamorphic rocks, the silicates weather slowly in the presence of carbonic acid, releasing low concentrations of Ca, magnesium, potassium, and sodium in water that percolates into the soil or groundwater. These water contains beneficial elements such as Se, Ca, and strontium (Sr), which are essential for human growth. The quality of drinking water from different environments can directly affect local human health. For instance, a study indicated that the Se concentration in the drinking water of the longevity region of Chongqing is significantly higher than in non-longevity areas

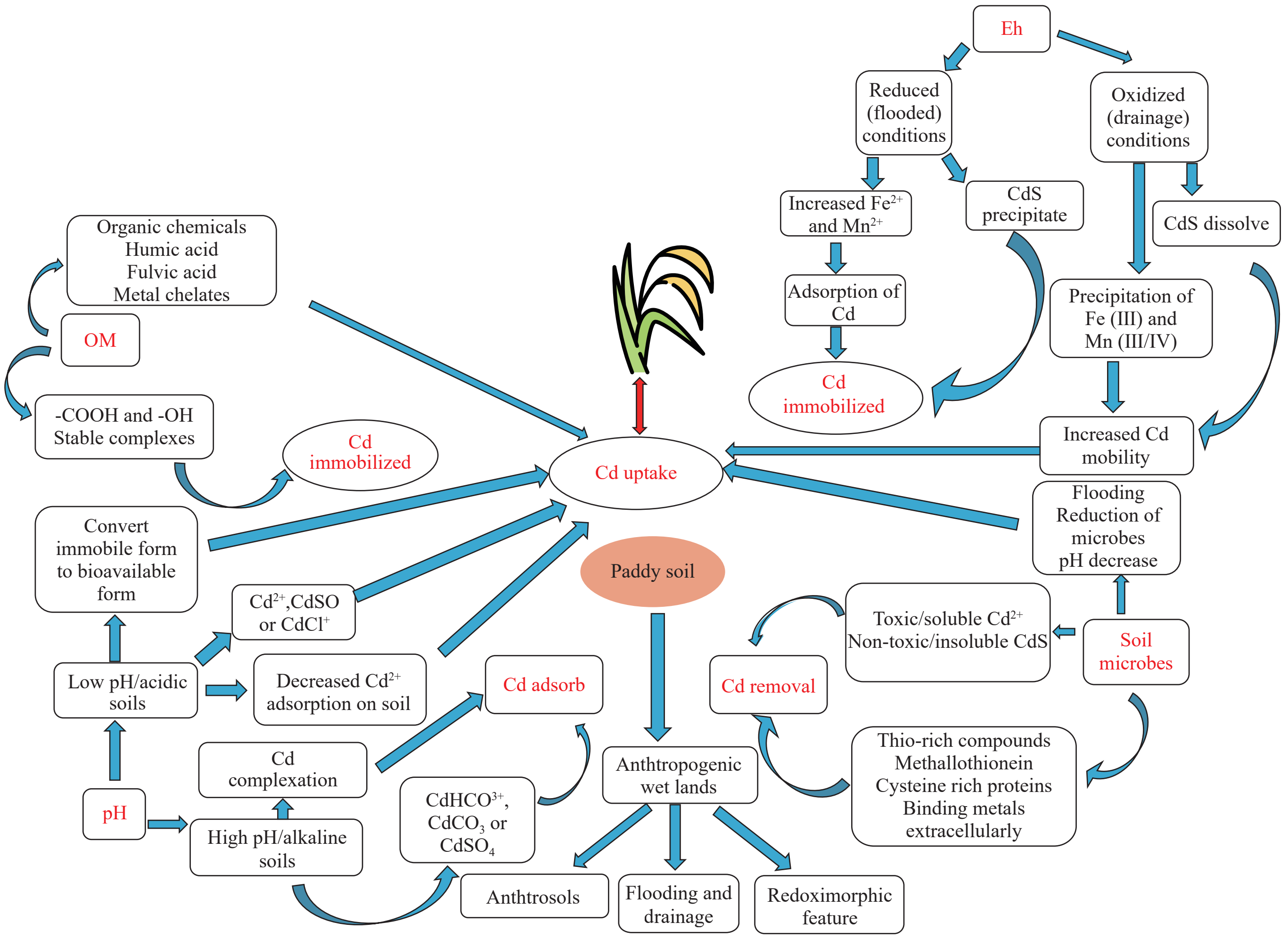

Fig. 4. Cd dynamics in paddy soil (after Riaz U et al., 2020).

(Liu YL et al., 2018). The drinking water in the longevity region of Nicoya Peninsula, Costa Rica, is rich in Ca and magnesium (Rosero-Bixby L et al., 2014). Researchers in Taiwan, China, confirmed that Ca in drinking water could reduce the risk of death from various diseases (Yang CY et al., 2006). Studies on longevity factors in other regions of China have shown a positive correlation between strontium in drinking water and longevity (Deng QC et al., 2018).

However, excessive levels of certain elements can pose health risks. For example, the element fluorine has long been recognised to have benefits for dental health, but more than 200 million people worldwide are thought to be drinking water with fluoride in excess of the WHO guideline value, resulting in chronic endemic fluorosis (Ahmad Dar F and Kurella S, 2024).

2.3.2. Harmful heavy metals in water

Statistical data indicates that about 14% of the world's population lacks access to clean drinking water, and 32% lack adequate sanitation facilities. Approximately 5 million people die annually from waterborne diseases, and by 2025, most of the world's population is expected to live in countries experiencing moderate to severe water scarcity (Patel B et al., 2023). The presence of heavy metals in water has become a growing concern, with 35 metals identified as health threats, 23 of which are heavy metals. Heavy metal (HM) pollution in aquatic environments is a critical issue due to their potential toxicity and accumulation in water. Numerous studies have highlighted the various impacts of heavy metals in drinking water, with As and Cd being extensively researched due to their public health implications.

Currently, 107 countries have recorded moderate to excessive As levels in groundwater. Global surveys have identified severe As contamination in groundwater in large alluvial plains, delta plains, and sedimentary inland basins, especially in arid and semi-arid regions (Schaefer MV et al., 2017). High-As groundwater is more likely to form and persist in geologically young aquifers (Quaternary) (Valskys V et al., 2022). In aquifer systems, water-rock interactions are the primary source of As release. As is rare in most igneous and metamorphic rocks but is widespread in marine shales and some iron-rich sedimentary rocks. The amount of As released from minerals into groundwater depends on mineral types, pH, redox conditions, and the presence of other ions that promote As desorption from secondary minerals. Additionally, research has shown that anoxic conditions in aquifers can lead to heavy metal contamination in drinking water, a problem faced by many coastal areas like Greece due to seawater intrusion. Thus, aquifer management or supplementing aquifers with uncontaminated water can reduce As pollution (Haugen EA et al., 2021).

The WHO has set a provisional guideline value of 10μg/L for As in drinking water. It is estimated that about 57 million people worldwide drink groundwater with As concentrations exceeding WHO's recommended standard (Shaji E et al., 2021). Smith AH et al. reported that (Smith AH et al., 1999) drinking 1 liter of water containing 50 μg of As daily could result in 13 out of 1000 people developing cancer. As inhibits the mitochondrial electron transport chain (ETC) and the activity of antioxidant enzymes, leading to excessive reactive oxygen species (ROS) accumulation, which induces oxidative damage to lipids, proteins, and DNA. This further triggers mitochondrial dysfunction, resulting in the release of cytochrome c into the cytoplasm and ultimately leading to cellular apoptosis. This could potentially contribute to the development of Parkinson's disease. Concentrations of As in the groundwaters of the Bengal Basin span some four orders of magnitude, with occasional extremes above 1000 μg/L. Recognised health problems include skin disorders and internal cancers. Additionally, most crops and various types of vegetation are highly susceptible to As-contaminated water, affecting root development, biomass, germination, cell expansion, nutrient and water absorption, respiration, and photosynthesis, which can lead to reduced yields and productivity. Fig. 5 illustrates the biogeochemical cycle of As.

The sources of heavy metal pollution in water are diverse. Cd enters surface and groundwater through industrial wastewater, widespread use of pesticides, and domestic sewage discharge. For example, Dhaka, Bangladesh, is a sewage discharge point for the region, and the surrounding rivers show high levels of Cd and other heavy metals (Ahmad MK et al., 2010). Geological sources of Cd can also elevate Cd levels in water and sediments, such as observed in groundwater within Sweden's black shale deposits, where Cd concentrations are significantly higher than reference samples. In Finland's Talvivaara region, rich in Cd-bearing black shale, the Cd concentration in river sediments is noticeably higher than in gneiss, granite, or quartzite areas (Liu YZ et al., 2015, 2017, 2019). Heavy metals can accumulate to toxic levels under these specific environmental conditions. Cd and its compounds are highly water-soluble, promoting their high bioavailability and bioaccumulation. Chowdhury S et al. examined heavy metal levels in drinking water in many developing countries and found that Cd exposure poses severe threats to human health (Chowdhury S et al., 2016). In aquatic ecosystems, Cd exposure increases reactive oxygen species (ROS) formation in cells, leading to oxidative damage in biological systems. To minimize the impact of heavy metals, regulatory bodies have proposed maximum allowable limits for drinking water (Table 5).

Furthermore, certain elements in drinking water can interact with each other. Simultaneous exposure to multiple heavy metals can have synergistic or antagonistic effects on human health. Antimony can exacerbate As toxicity in terms of genetic toxicity and metabolism (Wysocki R et al., 2023), while Zn can reduce As toxicity. The WHO recommends a daily intake of 15 mg of Zn to mitigate the adverse effects of As on health.

2.4. Atmosphere and human health

The atmosphere is a fundamental environmental element for human survival, and exposure to risk factors in the atmosphere can significantly impact human health.

2.4.1. Air Pollutants

With rapid economic development, the emission of environmental pollutants has drastically increased, leading to severe global air pollution issues. The International Agency for Research on Cancer (IARC) classifies outdoor air

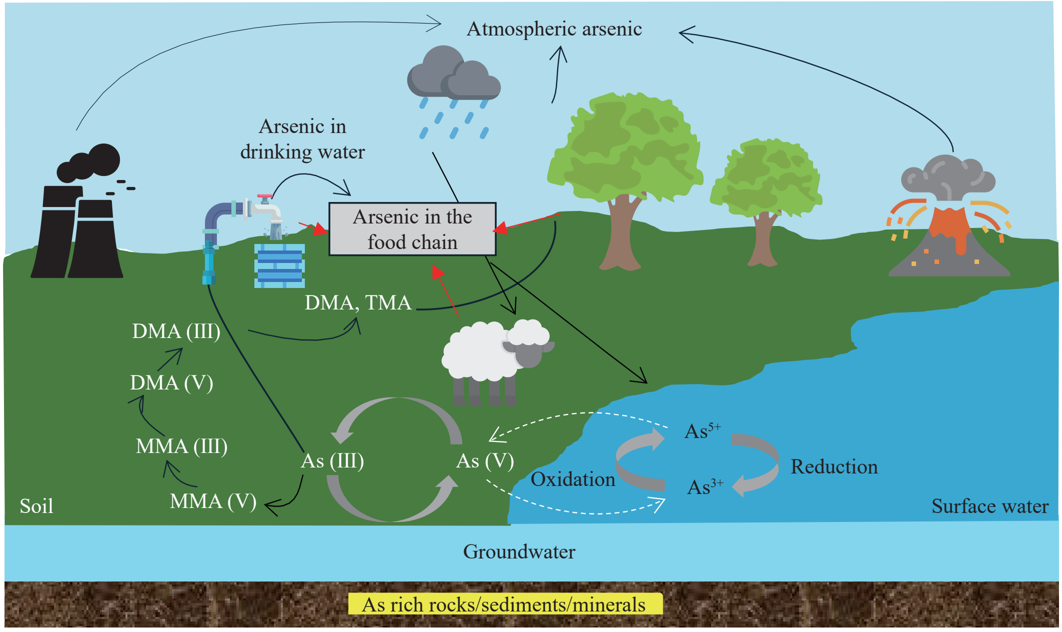

Fig. 5. Biogeochemical cycle of As.

pollution as a human carcinogen (Group 1) (Loomis D et al., 2013). Long-term exposure to particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and ozone (O_3) has been shown to cause various diseases, shorten life expectancy, and increase the risk of health hazards. The environmental air quality standards for different pollutants are listed in (Table 6).

Particulate matter (PM) is a widespread air pollutant consisting of a mixture of solid and liquid particles suspended in the air, with complex chemical compositions and a wide range of particle sizes. PM can be directly emitted as primary particles or formed as secondary particles through atmospheric oxidation and transformation of gaseous pollutants. For instance, NO_x from vehicle exhaust and SO_2 from burning sulfur-containing fuels are primary precursor gases that condense into liquid nitrate and sulfate compounds in the atmosphere. The commonly used indicators related to health are the mass concentrations of particles with diameters of 10 μm (PM_{10}) and 2.5 μm ($PM_{2.5}$). Studies have shown that for every 10 $\mu g/m^3$ reduction in $PM_{2.5}$ concentration, the lifespan of lung cancer patients increases by 0.35 years, and for every 10 $\mu g/m^3$ increase in $PM_{2.5}$ concentration, the related mortality rate increases by 2.8% (Ma YX et al., 2023). When $PM_{2.5}$ concentrations reach 10 $\mu g/m^3$ (the WHO air quality guideline [AQG] level set in 2005), the total number of deaths caused by $PM_{2.5}$ exposure is nearly halved, with the most significant impact in Southeast Asia and Africa (Yu P et al., 2022). The increase in PM concentrations is closely associated with a decrease in life expectancy, with PM_{10} having a more pronounced impact. Reducing inhalable particulate air pollution levels benefits public health.

Nitrogen oxides are a significant component of ambient air pollutants, with health risks generally arising from nitrogen dioxide (NO_2) or its reaction products, including O_3 and secondary particles. Evidence from multi-city studies in different geographic locations indicates that NO_2 concentrations between 12 $\mu g/m^3$ and 32 $\mu g/m^3$ significantly affect mortality rates from various diseases. For example, a pilot study in Korea found a strong association between NO_2 and deaths from cardiovascular and respiratory diseases (Hwang J et al., 2020). The primary source of NO_2 is vehicle emissions, and countries must actively adopt strategies to reduce air pollution and NO_2 levels to improve air quality and promote human health.

Sulfur dioxide (SO_2) is a common atmospheric pollutant produced naturally by geothermal activities, primarily from volcanoes, or anthropogenically from burning coal and oil. SO_2 can directly impact human health, being associated with cardiovascular and respiratory diseases. In China, for instance, for every 10 $\mu g/m^3$ increase in SO_2 concentration, the associated hospitalization rate increases by 0.63% (Wang LJ et al., 2018). SO_2 can also combine with other gases or particles to form secondary pollutants like sulfates, which are major contributors to smog. Long-term exposure to high concentrations of pollution poses health hazards.

Table 5. Maximum allowable concentrations of various elements in drinking water.

Element	Threshold (mg/L)			Hazard Intensity Score (HIS)
	WHO	USEPA	China Drinking Water Standards (GB5749–2022)	
Copper	3	1.3	1.0	807
Zinc	5	5	1.0	915
Arsenic	0.05	0.01	0.01	1674
Cadmium	0.1	0.005	0.005	1320
Mercury	0.0001	0.002	0.001	1458
Selenium	0.04	0.01	0.01	–

Meteorological factors and their interactions with air pollutants also affect human health. A national time-series analysis conducted in 128 counties in China from 2013 to 2018 found that high-temperature conditions significantly enhanced the impact of ozone on cardiovascular and respiratory disease mortality rates. A study by Meng in developing regions of Asia demonstrated that (Meng X et al., 2012) extreme high temperatures increased the mortality rate associated with PM_{10}-related diseases.

2.4.2. Heavy metals in atmospheric particulate matter

Particulate matter in the air often accumulates harmful substances, such as heavy metals, polycyclic aromatic hydrocarbons, and viruses. Inhaling these particulates can adversely affect human health, with heavy metals in particulates being identified as decisive factors for various diseases. For example, Nawrot T et al. found that (Nawrot T et al., 2006) long-term exposure to heavy metals (Cd, Cr, Ni) associated with particulate matter significantly impairs lung function and can even lead to lung cancer. Heavy metals in atmospheric particulates originate from multiple pollution sources, such as fuel combustion, resuspended dust, and geological sources, releasing different types and quantities of heavy metals. The bioavailability of heavy metals in particulate matter varies depending on the pollution source. For instance, heavy metals in particulates from residential areas are more bioavailable in the respiratory system than those from commercial and industrial areas because these particulates leach more heavy metals into Gamble solution

Table 6. Ambient air quality standards of pollutants.

Pollutant name	Average sampling time	Concentration limit			
		USEPA		MEPRC	
SO_2	24 hours	350	$\mu g/m^3$	150	$\mu g/m^3$
	1 hour	100		500	
NO_2	24 hours	–		80	mg/m^3
	1 hour	150		200	
O_3	Maximum 8 hours per day	160		160	$\mu g/m^3$
	1 hour	250		200	
Particulate matter (particle size less than or equal to 10 μm)	annual average	12		70	
	24 hours	150		150	
Particulate matter (particle size less than or equal to 2.5 μm)	annual average	15		35	
	24 hours	35		75	

(Huang H et al., 2018). Although the total concentrations of Cd and lead in vehicle emissions are lower than those from coal combustion, they exhibit higher bioavailability. Particulates collected near lead smelters are rich in Pb and Cd, but the inhalation bioavailability of these metals is relatively low. Therefore, accurately assessing the bioavailability of heavy metals in particulate matter from various pollution sources is crucial. The toxic effects of inhaled heavy metals in particulate matter should be included in the health risk assessment of atmospheric pollution.

2.4.3. Airborne radiation

Radon is a naturally occurring radioactive gas and the most prevalent natural radiation source that humans are exposed to (Maier A et al., 2021). Radon is present in almost all outdoor air, albeit at low concentrations, with an average global atmospheric concentration of 10 Bq/m^3 (Grzywa-Celińska A et al., 2020). Radon is a decay product of uranium and thorium found in soil and rocks, with its release depending on geological formations. Research has found higher radon concentrations in regions with granite, metamorphic igneous rocks, and shale with uranium deposits. Radon enters residential buildings from the ground due to pressure differences and accumulates in the lowest levels, easily entering the human body through respiration. Exposure to high radon levels can cause various cancers and genetic mutations, threatening human health. The IARC has reported the relationship between radon exposure and lung cancer risk, classifying radon as a Group 1 carcinogen (Tchorz-Trzeciakiewicz DE and Klos M, 2017). The International Atomic Energy Agency (IAEA) has set annual average radon concentration limits of 300 Bq/m^3 for residential and public buildings and 1000 Bq/m^3 for workplaces (Grzywa-Celińska A et al., 2020).

Thorium (Th), a naturally occurring radioactive element in the Earth’s crust, is also recognized as an emerging environmental contaminant. Studies have revealed that the distribution of thorium isotopes is highly heterogeneous. The highest soil thorium concentration has been detected in Muong Hum, Lao Cai Province, Vietnam, with an activity level of 8948 Bq/kg (Duong NT et al., 2021). With increasing exploitation of rare earth metals and the implementation of thorium-based nuclear reactors, the ecological and human health risks associated with thorium exposure are escalating. Thorium can be absorbed into the systemic circulation through gastrointestinal ingestion, inhalation, or percutaneous absorption via dermal wounds, subsequently inducing hepatic and pulmonary injury in humans. According to the WHO, the recommended contamination threshold for thorium in drinking water is 246 μg/L. Exceeding this level may pose significant health hazards to humans.

3. Transportation and exposure of elements in different layers

3.1. Coexistence and transport of elements

The composition and content of elements in soil have a profound influence on other environmental layers (Fig. 6). Rock is the parent material of soil development. The enrichment and deficiency of elements in rock will lead to the enrichment and deficiency of elements in weathered soil. SO_2 and NO_x undergo oxidation reactions in the atmosphere, converting into highly acidic substances that subsequently dissolve in raindrops to form acid rain. During atmospheric deposition, particulate matter can be transported hundreds of kilometers via air currents, leading to acidification of soils and water bodies as well as ecosystem destruction. The following Table (Table 7) summarizes the main sources and contribution of heavy metals in soils of China.

The table indicates that there are differences in the sources of heavy metals among different study areas, but on a national scale, soil heavy metals primarily originate from atmospheric deposition and soil-forming parent materials. Corresponding studies in Europe have also shown that agricultural soils are subjected to high inputs of heavy metals from atmospheric deposition (Tabors G et al., 2023). Heavy metals in atmospheric deposition exhibit high mobility and bioavailability, readily accumulating in the food chain and ultimately posing adverse effects on human health, thus necessitating increased attention.

In addition, the change of soil environmental quality also controls the water environmental quality. Heavy metals can enter aquatic systems from soils through a variety of diffusion pathways, such as surface runoff, soil leaching, and groundwater flow. Surface runoff occurs when soils become saturated or when rainfall intensity exceeds infiltration rates. The amount and rate of metal fluxes in surface runoff depend primarily on the form and concentration of metals in the soil, rainfall intensity and watershed characteristics. Surface runoff is predominantly into rivers, so the instantaneous response to changes in metal concentrations in rivers can be used as an indicator of surface runoff processes. Soil leaching is the process of downward transport of dissolved metals through percolating water in the soil profile. Groundwater flow is a soil water process in which infiltration water accumulates along the upper surface of the less permeable layers of the soil and moves downward laterally. The relative contribution of soil leaching or groundwater flow to the transport of heavy metals is highly dependent on soil properties and topographic and meteorological conditions. Zheng XY et al. found that groundwater flow from acidic mine wastewater in Yangquan, Shanxi Province is the main input pathway of heavy metals in the Shandi River basin (Zheng XY et al., 2023). A nationwide modelling report from the Netherlands indicates that soil leaching is an important contributor to Cd (20%), Zn (40%) and Pb (40%) in surface water (Bonten LTC et al., 2008). When heavy metals, agrochemicals and industrial pollutants, among others, migrate from the soil profile to the aquifer through these pathways and result in the contamination of drinking water sources, they threaten human health.

The transport and bioavailability of elements in terrestrial and aquatic systems are dependent on their chemical form, whereas the transport of soil heavy metals is controlled by a

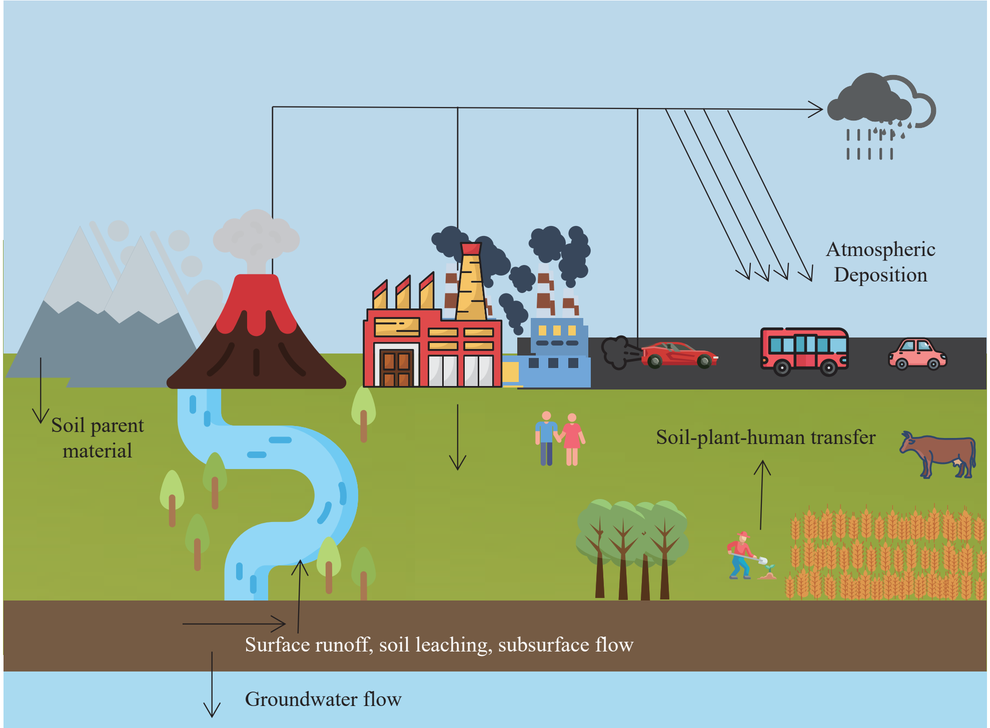

Fig. 6. Transport of environmental elements in rocks, soil, water, and atmosphere.

number of environmental parameters such as geological features, soil characteristics such as soluble ligand concentrations, soil matrix composition (oxides, clays, and organic matter), pH, temperature, and redox potential (Kicińska A et al., 2022). When heavy metals enter the subsurface environment, they change their morphology through adsorption/desorption, complexation/dissociation, and precipitation/dissolution reactions with soil components. For example, under acidic conditions, the dissociation of iron oxides, clay minerals and layered silicates, as well as the oxidation of sulphide minerals (pyrite), can accelerate the release of As from sediments. In addition, the increase/decrease of soil redox potential (Eh) can regulate a range of biogeochemical reactions. For example, some variable heavy metals such as Hg, As, Cr and Fe may undergo valence changes in the redox potential range, and inorganic forms of Hg and As can be converted to methylated forms under anaerobic conditions. Organic matter in the soil, especially humic and xanthic acids has a high adsorption capacity for many pollutants, including heavy metals, which reduces the uptake of heavy metals by plants, immobilizes them in the soil and reduces the migration of heavy metals to groundwater). Geological features also play a crucial role, especially the geological configuration of the rock type. For example, in carbonate environments, conduit flow occurs along larger fractures and openings, leading to increased dissolution of carbonate rocks and further providing physical access to groundwater flow. All of these features directly influence the pathways and rates of heavy metal transport.

3.2. Exposure to contaminants

Exposure pathways are the ways in which environmental pollutants enter the human body as part of metabolic processes. Different environmental pollutants have different exposure pathways to the human body, and understanding these pathways is important for assessing the potential risk they pose to human health. The environmental pollutants mainly discussed in this paper can be categorised into the following different types (Table 8).

Previous studies have found that exposure pathways play an important role in determining the severity of human exposure to contaminants, the distribution of contaminants in the body, and the potential health consequences that may result from these exposures (Sharma AK et al., 2023). Fig. 7 illustrates the relationship between the environmental media discussed in this paper and the exposure pathways, with ingestion of water or food, inhalation of air, and dermal contact being the main three exposure pathways.

3.2.1. Ingestion

Oral ingestion of contaminated food and water has been identified as the main route of human exposure to heavy metals. Wu JH and Sun ZC assessed the potential risk to groundwater in the alluvial plain region of west-central China and indicated that oral ingestion is the main exposure pathway for contaminants ingested in water by residents in this region, providing a good basis for ensuring safe drinking water and environmental protection of water resources in densely populated areas (Wu JH and Sun ZC, 2016). The food chain is one of the most important routes of contamination exposure, and people living in areas with high As levels in drinking water are at increased risk of cancer.

3.2.2. Inhalation

Inhalation is one of the most important routes of exposure

Table 7. Sources and contribution proportions of soil pollutants in China.

Area	Location	Sources (Contribution%)	References
Northeast China	Fine River Basin, Shenyang	Industrial sources (36.5), Atmospheric deposition (23.5), Agricultural sources (20.8), Soil parent material (19.2)	Ning CP et al., 2017
	Lalin River Basin	Soil parent material (38.0), Pesticide and fertilizer application (32.6), Coal burning and industrial emission sources (29.4)	Li J et al., 2016
	Upstream of Songhua River	Ore dressing, highway traffic, and waste discharge (39.31), Comprehensive pollution from soil parent material, fertilizer, and residential coal burning Source (23.93), Iron ore mining and transportation (22.89), Rock weathering and biological action (13.87)	Ai JC et al., 2014
North China	Chaohe River Coast, Beijing	PCA/MLR: Mining activities (33), Soil parent material (29), Traffic emissions (27), Coal burning (11). PMF: Mining activities (35), Coal burning (26), Soil parent material (22), Traffic emissions (17)	Li YX et al., 2013
	Shunyi District Farmland, Beijing	Natural sources (76.0–78.6), Atmospheric deposition (15.5–16.4), Fertilizers and pesticides (5.9–7.7)	Lu AX et al., 2012
	A suburban farmland, Tianjin	Industrial waste (46), Irrigation water (29), Atmospheric dust deposition (9.2), Inorganic fertilizer (7.3), Organic fertilizer (4.3)	Li X et al., 2016
East China	Changxing County field, Huzhou, Jiangsu	Pb from factory (55.37), Agricultural activities (29.28); Cd from factory (65.92), Agricultural activities (21.65), Soil parent material (12.43)	Xue JL et al., 2014
	Baguazhou, Nanjing, Jiangsu	Atmospheric deposition (33), Fertilization (30.8), Industrial emissions (25.4), Soil parent material (10.8)	Hu WY et al., 2018
	Changshu Town, Jiangsu	Natural sources (45.4), Waste incineration and textile printing & dyeing industry (28.3), Electroplating and livestock breeding (21.0), Traffic exhaust (5.3)	Zhang YX et al., 2018
	Lujiang, Anhui	Parent material sources (47), Mining activities (25), Industrial activities (28)	Wu J et al., 2022
Central China	Changsha, Liling, Liuyang city, Hunan Province	Atmospheric deposition (51.21–94.74), Fertilizers (3.36–48.20), Irrigation water (0.58–12.85)	Yi KX et al., 2018
	Lianyuan City, Hunan Province	Natural sources (33.6), Atmospheric deposition (26.05), Industrial activities (23.44), Agricultural activities (16.91)	Liang J et al., 2017
	Wuhan East Lake Hi-Tech Development Zone, Hubei	Electronic industry (67), Soil parent material (16), Other sources (9), Urban atmospheric deposition (mainly vehicle exhaust) (8)	Qu MK et al., 2013
South China	Northern Guangdong	Industrial sources (Pb: 68.1, Cd: 32.2), Urban sources (Pb: 10.1, Cd: 20.0), Soil parent material (Pb: 9.6, Cd: 12.4 by Stochastic Gradient Boosting), Agricultural sources (Pb: 7.4, Cd: 11.7), Atmospheric sources (Pb: 3.1, Cd: 10.7), Water sources (Pb: 1.7, Cd: 13.0)	Wang Q et al., 2015
	Northeastern Yangshuo County, Guangxi	Mining, smelting, and transportation activities (51.3), Atmospheric deposition (20.5), Soil parent material (13.1), other natural sources (15.1)	Pan YX et al., 2024
Northwest China	Urban Area of Xi’an	Natural sources (26–77), transport sources (3–54), fossil fuel combustion (1–21), other sources (4–16)	Chen XD and Lu XW, 2017
	Hexi Corridor, Gansu Province	Traffic (Pb: 77.48, Zn: 32.12), Industrial (Cr: 48.84, Ni: 54.12), Agricultural (Cu: 42.67, Zn: 36.07)	Guan QY et al., 2018
Southwest China	Chongqing	Industrial Emissions, Coal Burning, and Agricultural Activities (Cd: 87.5, Zn: 87, Ni: 73.3, Cu: 69.6, Cr: 63.9), Industrial and Agricultural Activities (Hg: 90.3)	Li SY and Jia ZM, 2018
	Pb-Zn Mining Area, Huize County, Yunnan	Coal Burning and Fertilizer Application (68.26), Industrial Activities (16.32), Mining and Soil Parent Material (15.42)	Lu X et al., 2018

to air pollutants. Due to their small size, atmospheric pollutants can be inhaled directly by the human body and pose a risk to human health by accumulating in the respiratory tract and potentially crossing the blood-brain barrier when the production of fine particulate matter in the air increases (Shetty SS et al., 2023).

3.2.3. Dermal contact

Dermal contact with harmful chemicals in the environment such as pesticides, chemical solvents, and naturally occurring toxic minerals such as naturally occurring Hg, Pb, or silver during agricultural or industrial activities can directly penetrate the skin and enter the bloodstream, resulting in toxic effects on human health. These effects vary from short-term symptoms to long-term chronic diseases and even carcinogenic effects. The occupational nature of this type of exposure is highly characterised and can be the subject of targeted studies. Differences in exposure levels and health effects across population groups with distinct demographic characteristics are presented in Table 9. Current research predominantly focuses on single-exposure pathway investigations, while largely neglecting comprehensive studies on the combined effects of multi-pathway exposures such as inhalation and dermal contact. Furthermore, most existing studies on heavy metals and human health rely on analyses of total heavy metal concentrations in soils, failing to adequately account for bioavailability.

4. Pollution mitigation policy

Environmental pollution is a global issue. To minimize health hazards associated with environmental contaminants, it must adhere to the “One Health” concept and integrate comprehensive governance measures for soil, water, and air pollution (Fig. 8). Moreover, the relevant policies operate across global, regional, and national levels, designed to address the interconnected health challenges of humans, animals, and the environment through cross-sectoral coordination mechanisms. The WHO has outlined two long-term “One Health” goals in its 2030 Agenda: (1) Improved health of humans, animals, plants and the environment while identifying sustainable system-wide One Health solutions that allow our ecosystems to thrive in harmony. (2) Reduced risk and impact of health threats at the human-animal-plant-environment interface using a One Health approach efficiently, effectively and equitably (WHO, 2022). To enhance the global public health governance framework and capacity development, and to foster collective responses to public health security challenges, Hainan has established various collaborative projects with domestic and international universities, including the co-creation of the One Health Research Center (Liang TC et al., 2023).

The control of environmental pollution is not achieved by a single entity, and in the context of global environmental pollution, international organizations and agencies such as the World Health Organization, the United Nations and the Food and Agriculture Organization must work together, develop a unified agenda for soil, water and air governance policies to achieve sustainable development and safeguard human health and well-being.

Table 8. Classification of environmental pollutants.

	Classification	Content	Sources
Pollutants	Soil pollutants	As, Cd, Hg and other heavy elements	Pesticides Mining and industrial activities Chemical spills
	Water pollutants	As, Cd and other heavy elements	Agricultural runoff Domestic and industrial wastewater
	Air pollutants	Dust, particulate matter, SO_2, NO_x, radon	Industrial exhaust Automobile exhaust Radiation

5. Conclusions

This study has explored the impact of geological environmental factors on human health by comparing health indicators such as chemical elements in the soil, rock, water, and atmosphere under a “One Health” perspective. However, there are several limitations and uncertainties in this research.

Firstly, human health is influenced by a complex interplay of genetics, natural environment, and socio-economic conditions. Therefore, other factors may confound discussions on the relationship between the environment and human health.

Secondly, although the authors attempted to evaluate environmental quality from a nutritional perspective, such as discussing concentrations of chemical elements in the environment, the authors have not comprehensively assessed environmental characteristics. Future research needs more indicators to establish a holistic evaluation method.

Moreover, different components in the environment have both synergistic and antagonistic effects on human health, making it challenging to determine relationships between soil and diseases. Additionally, due to variations in geological and climatic conditions, the data summarized in this paper may not comprehensively include situations from all global regions. Therefore, based on the common characteristics of population health and longevity, studying the global environmental factors affecting health and longevity is of great significance.

In recent years, emerging pollutants in the environment have received widespread attention from researchers, such as

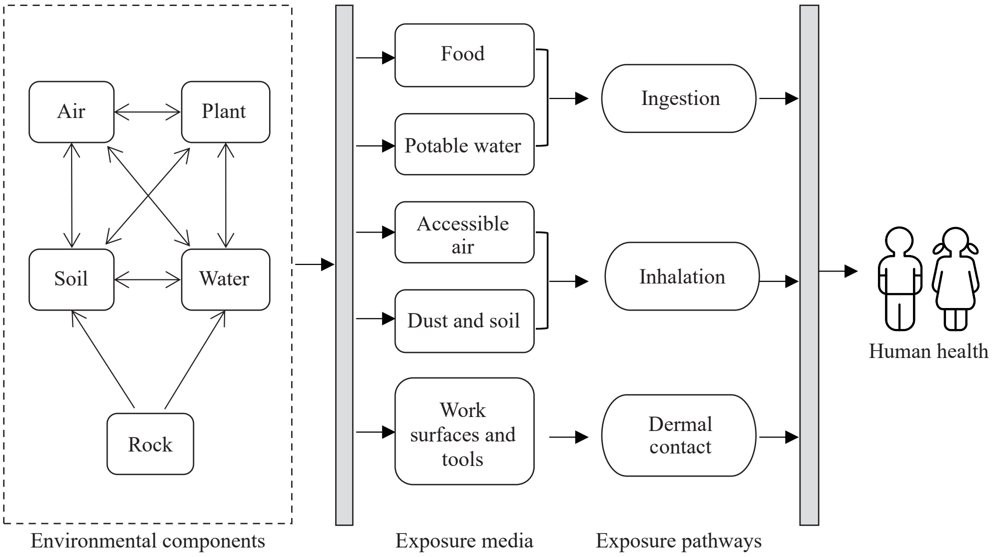

Fig. 7. Environmental components and major exposure pathways.

perfluorinated compounds (PFCs), microplastics (MPs), and nanoplastics (NPs). PFCs, due to their strong carbon-fluorine bonds, exhibit high persistence in degradation, leading to their accumulation in the environment and biological tissues. MPs, known for their high persistence and extreme distribution, act as carriers for toxic chemicals in natural ecosystems through direct and indirect pathways, impacting human health.

Future research efforts should focus on studying the environmental behavior of these emerging pollutants and the human health risks they pose. Understanding their persistence,

Table 9. **Differences between demographic groups and health impacts.**

Classification	Demographic characteristics	Exposure pathways	Typical pollutants	Health effects	References
Pedosphere	Children	Ingestion dermal contact	Pb, Cd	Neurodevelopmental disorders	Ma CC et al., 2021
	Farmers	Inhalation| ingestion	As	Cardiovascular diseases	Kumar S et al., 2019
	Low-income populations	Inhalation ingestion dermal contact	As, Pb, Cd	Renal tubular dysfunction	Atikpo E et al., 2021; Hernández-cruz EY et al., 2022
Lithosphere	Occupational workers	Inhalation ingestion	As, Hg	Silicosis	Calao-Ramos C et al., 2021
	Indigenous peoples	Inhalation ingestion	As, Cu	Liver fibrosis	Renu K et al., 2021
Hydrosphere	Fishermen	Ingestion	Hg, As	Neurological damage	González-Feijoo R et al., 20244
	Rural low-income populations	Ingestion	As, F, Cr	Skin cancer	Podgorski J and Berg M, 2020; Kumar A et al., 2024
	Urban low-income residents	Ingestion	Cr	Liver injury	Ahmad A et al., 2020
Atmosphere	Children Elderly population	Inhalation	PM$_{2.5}$	Asthma	Zhang YY et al., 2022
	Transportation workers	Inhalation	O$_3$, PM$_{2.5}$	Lung cancer	Yu ZG et al., 2022
	Low-income groups	Inhalation Dermal contact	NO$_x$, PM$_{2.5}$	Bronchitis	Qing Y et al., 2021

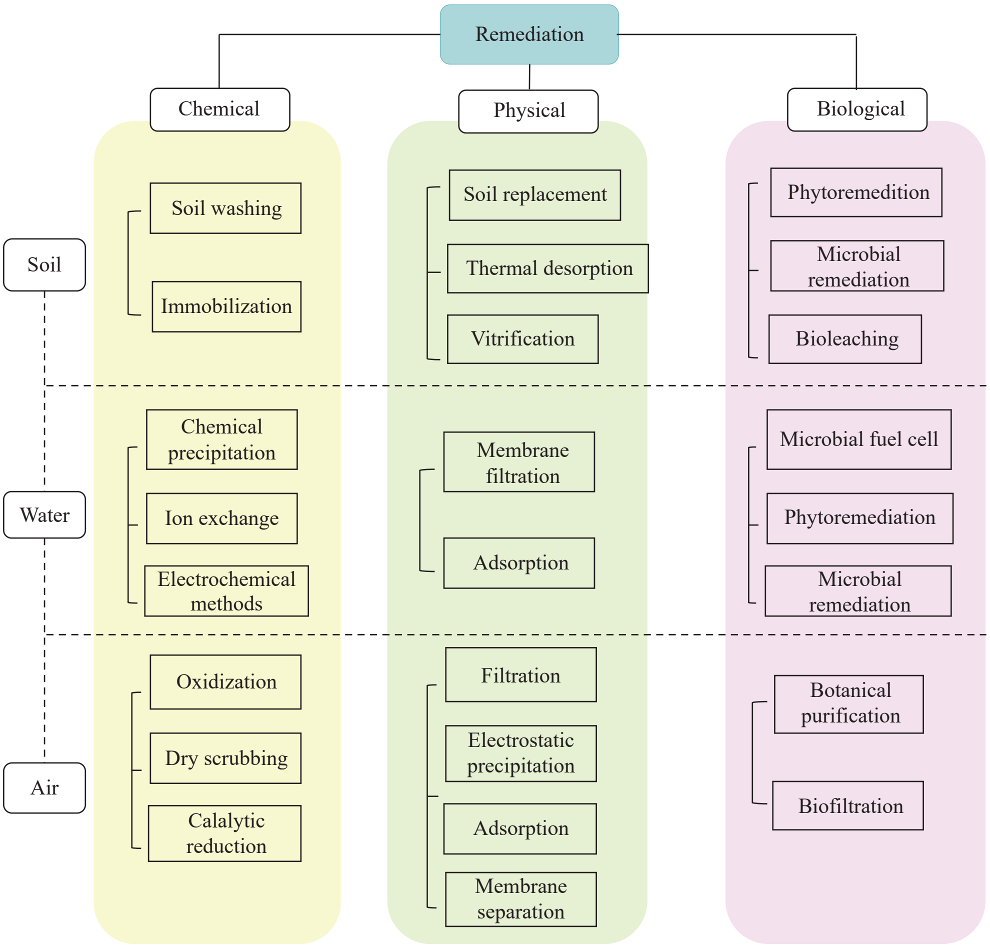

Fig. 8. Classification of heavy metals remediation approaches.

bioaccumulation, and potential health impacts will be crucial for developing effective policies to mitigate their adverse effects on both environmental and human health.

In brief, while this study provides valuable insights into the impact of geological environmental factors on human health, addressing the identified limitations and exploring new emerging pollutants are essential for advancing our understanding and safeguarding public health globally.

CRediT authorship contribution statement

Qing Wen: Conceptualization, Investigation, Writing - original draft, Writing - review & editing, Methodology, Visualization. Li-yue Zhang: Investigation, Resources, Visualization. Ming-xin Liu: Investigation, Resources, Visualization. Wen-bing Ji: Investigation, Resources. Chang Li: Investigation, Resources. Tao Yu: Conceptualization, Visualization, Methodology, Writing - review & editing, Project administration, Supervision. Qi-feng Tang: Supervision, Investigation, Funding acquisition. Hui Lu: Investigation, Resources. Qing-ye Hou: Supervision, Investigation. Zhong-fang Yang: Writing - review & editing, Supervision.

Declaration of interests

The authors declare no conflicts of interest.

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