

Review

# Drinking Water Contamination as a Consequence of Environmental Pollution and Its Implications for Public Health

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**Abstract:** Rapid urbanization, industrial discharge, agricultural runoff, inadequate wastewater treatment, and population growth are key drivers of poor water quality globally. Approximately 2.1 billion people still lack on-premises drinking water, and improving access to safe water and sanitation could save up to 1.4 million lives per year. Waterborne diseases account for an estimated 485,000 deaths annually, primarily from diarrheal illnesses, with the burden falling disproportionately on low-income countries. This paper presents a critical review of drinking water contamination and its impacts on human health, particularly in developing countries where modern treatment facilities are limited. The review synthesizes current evidence on the sources and health effects of contaminated drinking water, focusing on microbial pathogens and toxic chemicals, including heavy metals, pesticides, and emerging organic pollutants. A systematic search of peer-reviewed English-language articles was conducted using key terms such as “water contamination”, “toxicants”, “mechanisms of pathophysiology”, “heavy metals”, “health outcomes”, and “vulnerable population”; non-peer-reviewed and non-English studies were excluded. Findings indicate that exposure to contaminated drinking water is strongly associated with adverse health outcomes, including acute waterborne infections (diarrhea, cholera, hepatitis, and typhoid) and chronic non-communicable diseases (neurological disorders, renal disorders, cardiovascular disorders, reproductive toxicity, endocrine disruption, and cancer). Globally, unsafe water sources remain the primary risk factor for childhood diarrhea mortality. Heavy metals such as lead (Pb), even at low exposure levels, pose particular concern due to irreversible neurodevelopmental effects in children. There is therefore an urgent need to strengthen monitoring, regulation, and intervention strategies to reduce water contamination and protect public health, especially among vulnerable populations.

**Keywords:** water pollution; biological contamination; diarrhea; public health; wastewater treatment; heavy metals; lead toxicity

## 1. Introduction

Pollution remains the leading environmental cause of disease and premature mortality worldwide. Estimates from the Lancet Commission on Pollution and Health, based on data from the Global Burden of Disease Study, indicate that approximately 9 million premature deaths were attributable to pollution in 2015. A subsequent update using GBD 2019 data confirmed that this burden remains largely unchanged, equivalent to roughly one in six deaths globally, underscoring its persistent and substantial impact on public health [1,2].



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Within this broader pollution crisis, contaminated drinking water represents one of the most direct and measurable threats to human life. According to UNICEF and WHO reports for 2025, 2.1 billion people globally still lack access to safely managed drinking water, including 106 million who drink directly from untreated surface sources. A further 3.4 billion people remain without safely managed sanitation. The health consequences are severe: waterborne diseases are responsible for an estimated 485,000 deaths annually, primarily due to diarrheal diseases, with mortality rates highest in low-income countries where access to healthcare and sanitation infrastructure is limited. Furthermore, a landmark 2023 Lancet analysis estimated that 1.4 million deaths and 74 million disability-adjusted life years (DALYs) could have been prevented globally through safe water, sanitation, and hygiene (WASH) services in 2019 alone, representing 2.5% of all global deaths and 2.9% of total DALYs [3]. The current review advances the argument that drinking water contamination, driven by a complex, interacting set of environmental pollutant, including microbial pathogens, heavy metals, organic chemicals, and emerging contaminants, is one of the most critical yet insufficiently addressed determinants of global public health, especially in low- and middle-income countries (LMICs), where regulatory frameworks, water treatment infrastructure, and epidemiological surveillance remain inadequate [4]. Specifically, we contend that: (i) the health burden of contaminated drinking water spans both acute infectious diseases and chronic non-communicable diseases (NCDs), with the latter substantially underestimated due to methodological limitations in exposure assessment and disease attribution; (ii) different contaminant classes pose distinct, non-interchangeable risks that require contaminant-specific regulatory and intervention strategies rather than generic water safety approaches; and (iii) emerging contaminants, including per and polyfluoroalkyl substances (PFAS), microplastics, and antibiotic resistance genes (ARGs), along with the compounding effects of climate change, represent a growing threat that current monitoring and governance frameworks are only beginning to address. A comprehensive, analytically rigorous understanding of these contamination pathways and their mechanisms is therefore essential for designing effective prevention strategies and informing evidence-based policy. Understanding pollution as a systemic and cross-sectoral issue thus provides a conceptual foundation for examining the specific dynamics and consequences of contaminated drinking water.

### *What Is Pollution?*

Literature defines pollution as the release of unwanted waste into the air, land, freshwater, and marine environments, without considering its negative economic, ecological, or health consequences, mainly due to anthropogenic activities [5]. Pollution is increasing at an alarming rate and poses a global threat to human health and natural ecosystems. Among its various forms, air and water pollution are the most widespread in LMICs, and have increased substantially over the past century [6]. These forms of environmental pollution are associated with a range of adverse health outcomes, including the spread of infectious diseases such as typhoid, diarrhea, and cholera, as well as NCDs, including asthma, multiple cancer types, eye disorders, and CVDs [7]. Despite this, pollution has not been adequately addressed in international development and global health agendas, nor in the planning strategies of many low-income countries [8].

The current review specifically contends that drinking water contamination, driven by diverse environmental pollutants (microbial, chemical, and heavy metal contaminants), represents a critical and under-addressed public health threat, particularly in resource-limited settings, and that a comprehensive understanding of contamination pathways and mechanisms is essential for effective prevention and policy.

## **2. Methodology**

The review synthesizes evidence from studies published in national and international peer-reviewed journals, as well as reports from governmental and non-governmental organizations worldwide. The primary objective was to critically examine existing literature on water pollution, including types of contamination and their impacts on public health. A comprehensive literature search was conducted using three major electronic databases: PubMed/MEDLINE, Google Scholar, and Web of Science, covering publications from January 2000 to March 2026. Only peer-reviewed articles published in English were considered eligible for inclusion. Studies that were unpublished, preprints, or published in languages other than English were excluded. The search strategy employed a combination of keywords and Boolean operators (AND, OR), including: “pollution”, “water pollution”, “contaminated water”, “sources of water pollution”, “impact on human health”, “heavy metals”, “pesticides”, “organic pollutants”, “diarrheal disease”, “mechanism of pathophysiology”, and “toxicity of heavy metals.” Titles and abstracts of retrieved records were initially screened for relevance, followed by a detailed full-text review of potentially eligible studies. Additionally, the reference lists of selected articles were manually examined to identify further relevant publications.

### 3. Results

#### 3.1. Water Scarcity and Quality: A Global Perspective

Water is essential for all forms of life and is fundamental to human health, ecosystem stability, and food production. Once the water supplies are contaminated either physically (pH, odor, temp), chemically, and/or biologically, it has negative impacts on humans and other living systems [9]. The nature and severity of health consequences vary depending on several factors, including the chemical composition, duration of exposure, and concentration of pollutants in water. According to the 2021 World Water Development Report released by UNESCO, the global use of freshwater has increased sixfold in the past 100 years and has been growing by about 1% per year since the 1980s [10]. In the 21st century, one of the major problems is water scarcity and poor-quality drinking water (contaminated water). In support of the critical need for clean drinking water, a 2009 Gallup poll reported that drinking water pollution was considered the foremost environmental concern among Americans [11]. Furthermore, existing literature indicates that more than 80% of wastewater generated from human activities is discharged into rivers and oceans without required treatment, contributing to the transmission of over fifty water-related diseases in humans. Consequently, poor water quality is estimated to be responsible for approximately 80% of diseases and nearly 50% of child deaths worldwide, underscoring the profound public health burden associated with inadequate water management and sanitation [10,12]. Approximately 2.1 billion people (24% of the global population) lack access to safe drinking water, while 3.4 billion people lack safely managed sanitation services [13]. The most direct and severe impact of polluted water is compromised health, which affects one-third of people globally. Additional threats include human exposure to pathogens and other chemical toxicants via the food chain (e.g., irrigation of plants with contaminated water and of bioaccumulation of toxic chemicals by aquatic organisms, including seafood and fish) or during other activities (e.g., swimming in polluted surface water) [14]. This burden appears to be disproportionately higher in low-resource countries like Pakistan, where sanitation infrastructure and wastewater treatment systems are poorly developed, and public awareness regarding water quality and hygiene remains limited. Therefore, there is an urgent need to implement effective water management strategies and protective measures to address water shortages and improve the hygienic quality of drinking water supplies in Pakistan and other low-income countries. In such situations, several technologies such as ion exchange, electro-techniques, adsorption, membrane separation, and precipitation techniques have been proposed [15].

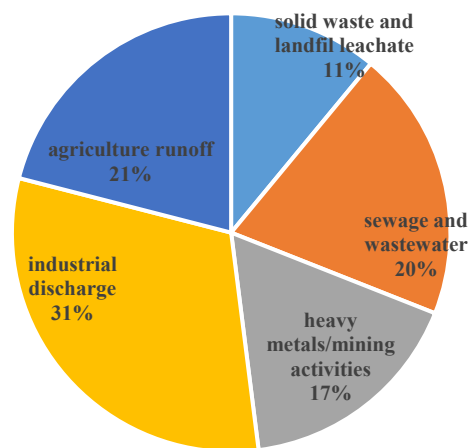
The integrated approaches combining technological solutions with policy enforcement and community engagement are essential for sustainable water quality improvement. However, globally, water quality assessment efforts have varied considerably, reflecting differences in regulatory capacity, infrastructure, research investment, and contamination priorities. In Asia, especially in South and East Asia, water quality research has been most extensive, where rapid industrialization and dense agricultural activity have driven significant contamination of both surface water and groundwater. Studies from Bangladesh, India, and Pakistan have consistently documented alarming levels of arsenic in groundwater, with tens of millions of people exposed through tube wells and hand-pumps; these findings have driven major international research efforts and shaped WHO guidelines on arsenic thresholds [16,17]. Moreover, China has invested substantially in water quality monitoring over the past two decades, and longitudinal data reveal improvements in urban surface water quality alongside persistent contamination in peri-industrial and agricultural zones [18]. The studies from Vietnam, Indonesia, and the Philippines highlight microbial contamination as the primary concern, particularly in rural areas lacking piped water infrastructure [19]. In sub-Saharan Africa, water quality assessment remains fragmented and underfunded relative to the needed scale. Available studies indicate that microbial contamination, particularly fecal coliform and *E. coli*, is near-universal in water sources, while geogenic contaminants such as fluoride (notably in the East African Rift Valley) and nitrates from agricultural runoff present distinct regional challenges [20,21].

Systematic monitoring infrastructure is limited, and many assessments rely on point-in-time surveys rather than continuous monitoring, making trend analysis difficult. In North Africa and the Middle East, water scarcity itself is the overriding concern, and quality assessments frequently highlight elevated salinity, nitrate contamination from intensive irrigation, and emerging organic pollutants in treated wastewater reused for agriculture [22]. In Europe, decades of regulatory investment under the EU Water Framework Directive (2000) have led to substantial improvements in surface and drinking water quality, with routine multi-contaminant monitoring now standard across member states. However, European studies increasingly flag emerging contaminants, particularly PFAS, pharmaceutical residues, and microplastics, as the frontier challenge, as conventional treatment systems were not designed to remove these compounds [23]. Taken together, these regional observations reveal that the contamination profiles differ markedly by geography. Therefore, common themes emerge as follows: microbial contamination dominates in lower-income settings, chemical and emerging

contaminants increasingly dominate in middle- and high-income countries, and monitoring capacity consistently lags behind the pace of new emerging contamination threats, regardless of region.

### 3.2. Sources and Types of Water Contaminants

Understanding of water pollution generally involves a scientific knowledge of the biological, chemical, and physical processes that control the movement of contaminants in the water. These contaminants include biological contaminants (microorganisms), chemical pollutants (heavy metals, pesticides, and medicines), and other new contaminants. The rate of distribution is summarized in Figure 1 [24].



**Figure 1.** Distribution rate of water contamination.

These pollutants enter the water sources through several activities, including domestic activities, agricultural runoff, industrial waste, inappropriate waste disposal, and insufficient sewage systems. These unchecked practices contaminate and pollute water supplies, endangering their safety and purity, and posing health risks [25]. The adverse human health effects are continuously being researched, and new pesticides, medications, and developing pollutants pose further difficulties to society. Additionally, sewage from cities and villages that flows directly into the sea is one of the most important sources of microplastic contamination, causing severe harm to marine life. Specifically in Asia, the water pollution has been greatly increased by the use of mineral fertilizers and pesticides in agriculture and by the operations of mining, chemical production, and other industries related to the utilization and storage of many harmful substances [26]. Other than this, various pollutants like heavy metals, oil spills, and industrial discharges are known to contaminate water sources heavily [27]. In addition to the growing pollution caused by human activities, the lack of water treatment facilities and insufficient public awareness are the major factors, among others, contributing to the increasing burden of polluted water. In the following section, we will discuss them in detail.

Chronic exposure to heavy metals and metalloids is highly toxic and is associated with significant public health risks, including carcinogenic effects [28]. However, in small amounts, they are required for maintaining good health. The most commonly found heavy metals and metalloids in wastewater include arsenic, cadmium, chromium, copper, lead, nickel, and zinc [29,30]. The primary sources of heavy metal contamination include natural processes such as soil erosion and the weathering of the Earth's crust, as well as anthropogenic activities including mining, industrial effluents, urban runoff, sewage discharge, and the use of agrochemicals such as pesticides and insecticides for crop protection and disease control [9,31].

Microbial contamination of water sources, particularly drinking water sources, is primarily caused by inadequate sewage systems, leaking sewer lines, and poorly maintained septic systems, leading to the introduction of pathogens such as bacteria (*E. coli*, *Vibrio cholerae*, *Salmonella*, etc.), viruses (hepatitis A virus, hepatitis E virus, rotavirus, etc.), parasites (*Giardia*, *Entamoeba*, *Cyclospora*, etc.), and parasitic worms (*Ascaris lumbricoides*, *Ancylostoma duodenale*, *Strongyloides stercoralis*, etc.) [32,33].

Chemical contaminants such as pesticides, on the other hand, are used to control weeds, nematodes, rodents, insects, and fungi, and are frequently used in agriculture and other industries to control pests and diseases [15]. Even though their use has improved agricultural production and pest management, it has also prompted concerns

about their fate and potential environmental and human health effects. According to the EU (European) drinking water directive, the sum of the maximum allowable concentration of pesticides in drinking water is 0.5 µg/L [34].

### 3.3. Health Risks and Disease Burden

Provision of clean drinking water is one of the major objectives of the UN Sustainable Development Goals (SDGs) [35,36]. According to the report of WHO/UNICEF, unlike LMICs, the majority of the population in high-income countries had access to safe drinking water in 2017, with less than 3% lacking access [37]. The hand-pumps are one of the commonly used methods of getting water from shallow groundwater in villages of many developing countries across Africa, Asia, and the Pacific. It is reported in previous studies that the microbial quality of hand-pumps is found to be better than uncovered surface water reservoirs like canals, but in some other cases, water from hand-pumps is found to contain significant levels of fecal coliforms and *E. coli* [38]. Microbial contamination of groundwater is usually attributed to infiltration of water containing human or livestock feces into the underlying aquifer.

### 3.4. Impact on Public Health

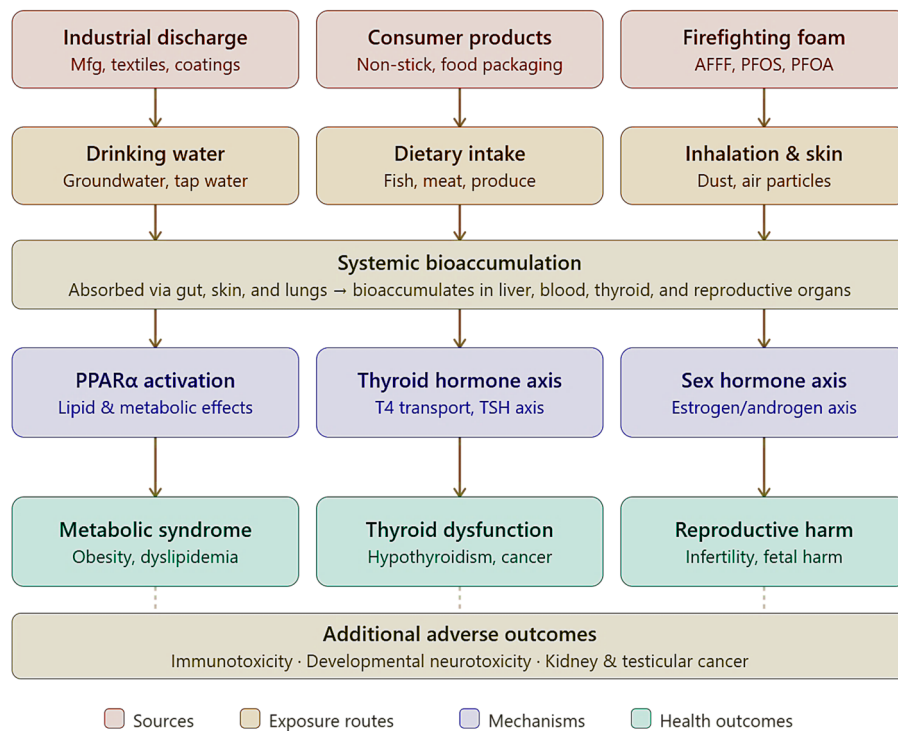
Throughout the history of human life, safe water has been a primary need. However, as the years go by, factors that threaten the availability of safe water are on the rise. In light of the rising issue, developed nations have achieved substantial advancements by purifying polluted water sources to a significant proportion, therefore making ample, clean water available for citizens [39]. Drinking water quality in less-developed countries like Pakistan is gradually deteriorating due to alarming population growth, rapid industrialization, climate change, and a lack of effective water treatment plants. Exposure to contaminated water sources presents particularly elevated health risks for vulnerable populations, including children and pregnant women. In Pakistan, the majority of the population doesn't have access to safe drinking water, and people are forced to use unsafe and unhealthy water [13]. The heavily contaminated water spreads the prevalence of waterborne diseases such as hepatitis, cholera, dysentery, cryptosporidiosis, giardiasis, typhoid, rotavirus diarrhea, intestinal worms, diarrhea, cramps, nausea, vomiting, headaches, fatigue, skin infection, gastroenteritis, joint aches, stomach pain, fever, and even death [40,41]. It has also been reported that 1–1.4 million deaths occur annually due to these waterborne diseases, and most of them are due to fecal contamination [42–44]. Diarrhea is the most common waterborne illness in rural areas. There are three types of diarrhea: acute watery diarrhea (usually lasting for several hours or days, mainly caused by *V. cholerae*), acute bloody diarrhea (caused by *Shigella spp.*), and persistent diarrhea (usually lasting for 14 days or longer). Among the diarrheas, acute watery diarrhea can be fatal, in which a person can die within hours if treatment is not given. The general treatment for diarrhea includes rehydrating with oral rehydration salt solution (ORS), consuming nutrient-rich food, and consuming zinc supplements. Cholera is another severe waterborne diarrheal disease that can also be fatal within hours if not treated. Therefore, quick treatment is crucial. Researchers estimated that there are 1.3 to 4.0 million cases and 21,000 to 143,000 deaths occur from cholera globally/year. The majority of which occur in developing countries [45,46].

Water contaminated with heavy metals poses dangerous, uncontrolled health-related threats, including neurodegeneration, headaches, liver failure, Alzheimer's disease, cancer, kidney failure, abdominal pain, higher blood pressure, mental disorders, skeletal degradation, irritability, harm to the reproductive system, and nerve damage. Hence, the regular testing of heavy metals (e.g., Lead, Arsenic) in water sources and their removal is needed [47]. Some metals, such as aluminum, can be eliminated from the human body through the excretory system. However, chronic aluminum exposure leads to accumulation in bone, brain tissue, and the liver, particularly in individuals with impaired renal function. Therefore, Aluminum is also recognized as a neurotoxin linked to dialysis encephalopathy and potentially implicated in neurodegenerative disease. Similarly, other metals tend to accumulate in body tissues and the food chain, leading to chronic adverse effects on human health [9]. They affect nearly every organ system, including the nervous system (causing neurotoxicity, cognitive impairment, and behavioral disorders), cardiovascular system (hypertension, increased risk of stroke, and coronary heart disease) [48–50]. Among the most damaging heavy metals is lead, which is known for its neurotoxicity, especially in young and growing children.

Moreover, a critical comparison of studies on pesticide-related health effects highlights notable inconsistencies that are often underemphasized in the literature. While occupational exposure studies consistently report strong associations between organophosphate exposure and neurological impairments, evidence regarding the health impacts of long-term, low-level exposure through drinking water remains comparatively limited and more heterogeneous [51]. Studies that focus specifically on drinking water exposure show weaker and less consistent effects compared to occupational studies. This is mainly because the levels of pesticides in drinking

water are usually much lower than those found in workplace exposure [52]. This distinction between exposure pathways is often not adequately addressed in review literature, which can lead to an overestimation of risks specifically associated with pesticide exposure through drinking water. Similarly, although endocrine-disrupting effects of pesticides are well established in experimental and wildlife studies, epidemiological evidence in humans remains inconsistent. These discrepancies highlight the need for more rigorous, water-specific exposure assessment studies, rather than broad extrapolation from occupational or dietary exposure data [53].

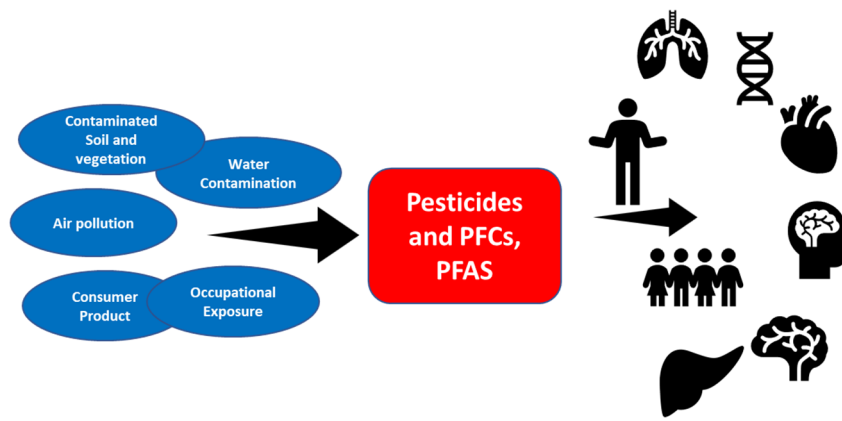
Organic pollutants such as PFAS and PFCs are predominantly found in industrial runoff, which cause serious health problems, including pre-eclampsia, birth defects, decreased human fertility, immunotoxicity, neurotoxicity, and carcinogenesis [54]. Literature indicates that pesticides are strongly associated with endocrine imbalance, immunological dysregulation, and cancer [55] (Figure 2).



**Figure 2.** Illustration of the PFAS endocrine disruption pathways.

### 3.5. Emerging Water Contaminants

Beyond the conventional categories of microbial and heavy metal contamination, increasing scientific attention has been directed toward emerging water contaminants whose environmental persistence and health impacts are increasingly recognized but remain insufficiently characterized. Among these, perfluoroalkyl and PFAS, commonly referred to as “forever chemicals”, are highly persistent synthetic fluorinated compounds that have been detected in drinking water sources worldwide [56]. Released primarily through industrial processes, firefighting foams, non-stick consumer products, agricultural runoff, pesticide-related contamination, and wastewater effluents, PFAS are characterized by their exceptional resistance to environmental degradation and significant bioaccumulative potential. These properties underlie their association with a broad spectrum of adverse health outcomes, including pre-eclampsia, congenital abnormalities, reduced fertility, immunotoxicity, neurotoxicity, endocrine disruption, and carcinogenesis [57,58] (Figure 3).



**Figure 3.** Pesticide toxicity and associated human health effects.

Microplastics and nanoplastics have emerged as significant environmental contaminants of growing global concern. These particles originate primarily from the degradation of plastic waste, synthetic textiles, and personal care products, and have been detected in diverse water sources, including tap water, bottled water, and groundwater worldwide. Their potential health impacts are increasingly being investigated, particularly their ability to adsorb and transport toxic chemical pollutants and to induce oxidative stress, inflammation, and other adverse cellular responses [59,60]. In parallel, pharmaceutical residues and their metabolites, including antibiotics, hormones, and analgesics, are increasingly detected in aquatic environments due to inadequately treated wastewater discharges and agricultural runoff. These contaminants are of particular concern because of their endocrine-disrupting properties and their role in promoting antimicrobial resistance [61]. In addition to chemical contaminants, ARGs have gained recognition as an important class of emerging biological contaminants in water systems. ARGs are disseminated primarily through wastewater effluents containing resistant microorganisms and genetic material, posing a serious public health threat by reducing the effectiveness of antimicrobial therapies, particularly in regions where waterborne infectious diseases remain highly prevalent [62]. Despite growing evidence of their occurrence, the environmental fate, transport mechanisms, bioaccumulation potential, and human health dose–response relationships of these emerging contaminants remain insufficiently understood, representing a major gap in current water safety research. Importantly, these emerging contaminant groups differ substantially in their sources, environmental behavior, persistence, and mechanisms of toxicity [63–65]. Pharmaceutical residues primarily enter aquatic systems through wastewater and agricultural discharges, where they contribute to endocrine disruption and the emergence of antimicrobial resistance [66,67]. ARGs, however, represent a distinct biological hazard because they facilitate the spread of antimicrobial resistance, thereby undermining the clinical efficacy of antibiotics, especially in low-resource settings with endemic waterborne infections [68].

### 3.6. Climate Change as a Compounding Threat to Water Quality

Climate change represents an increasingly important compounding threat to drinking water quality that has not yet received adequate attention in the literature. Rising global temperatures, shifting precipitation patterns, and increasing frequency and severity of extreme weather events are all projected to worsen water contamination risks in multiple ways [69–71]. Floods can overwhelm sewage treatment infrastructure and cause direct mixing of wastewater with drinking water sources, leading to acute surges in microbial contamination [72]. Conversely, prolonged droughts concentrate pollutants in reduced water volumes, increase the proportion of agricultural runoff relative to total water flow, and deplete groundwater reserves, forcing populations to rely on more contaminated shallow sources [73]. Warmer water temperatures accelerate the growth of harmful algal blooms and extend the geographic range and seasonal activity of waterborne pathogens such as *Vibrio* species. These dynamics are especially concerning for low-income countries, where climate vulnerability is highest and adaptive water management capacity is most limited. Integrating climate projections into water safety planning and contaminant monitoring frameworks is therefore an urgent priority for protecting public health in the coming decades.

### 3.7. Mechanisms of Toxicity and Pathophysiology of Water Contaminants

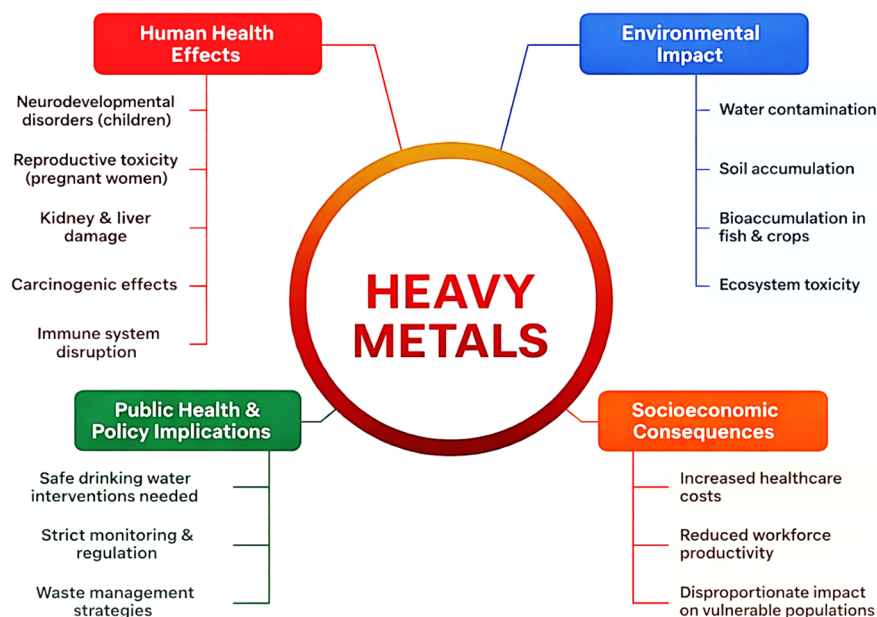
Contaminated drinking water poses significant global health risks, primarily due to the complex mechanisms of toxicity and pathophysiological effects caused by various pollutants, including microbial pathogens, toxic chemicals, and heavy metals [74,75]. In the following sections, we discuss the mechanisms of pathophysiology of microbial pathogens and chemical toxicants separately.

### 3.7.1. Mechanisms of Toxicity of Microbial Contamination

Microbial pathogens, such as bacteria (*E. coli*, *Salmonella*), viruses (hepatitis A, hepatitis E, rotavirus), and parasites (*Giardia*, *Entamoeba*), are frequently found in contaminated water, primarily due to poor sewage systems and fecal contamination from sewerage leakages [76,77]. The key mechanism of microbial toxicity for many bacterial pathogens involves the production of enterotoxins that severely affect intestinal ion transport. For example, *Vibrio cholerae* releases cholera toxin, which is known to activate adenylyl cyclase in intestinal epithelial cells, leading to an increase in cyclic adenosine monophosphate (cAMP) levels [78], which in turn induces excessive secretion of chloride (Cl<sup>-</sup>) and bicarbonate (HCO<sub>3</sub><sup>-</sup>) ions into the intestinal lumen, resulting in massive fluid loss and severe, acute watery diarrhea. Acute watery diarrhea can lead to rapid dehydration and death within hours, if left untreated [79]. Additionally, other pathogens, such as those causing shigellosis, induce acute bloody diarrhea by invading and destroying the intestinal epithelial cells, leading to inflammation and ulceration [80]. Viral infections, particularly those caused by rotavirus, also cause diarrhea by damaging the intestinal villi, impairing nutrient absorption, and enhancing fluid secretion [81]. Similarly, parasitic infections interfere with nutrient absorption and cause chronic diarrhea by damaging the intestinal lining and inflammatory responses [82]. Beyond causing acute waterborne infections, microbial pathogens can cause recurrent infections, leading to long-term health problems (chronic effects), particularly in vulnerable populations such as children. These chronic infections include environmental enteropathy, characterized by chronic inflammation and damage to the small intestine, which could lead to growth retardation and impaired cognitive development in children [83].

### 3.7.2. Mechanisms of Toxicity of Heavy Metals

Heavy metals and metalloids, including arsenic (a metalloid), lead (Pb), mercury (Hg), cadmium (Cd), chromium (Cr), and nickel (Ni), are persistent non-biodegradable environmental hazards that accumulate in water sources and are highly toxic even at low concentrations, causing toxicity in organisms via the food chain (Figure 4). The mechanisms of heavy metal-induced toxicity are diverse and often involve interfering with essential biochemical processes, such as the production of free radicals and oxidative stress, enzyme inhibition, and direct damage to cellular components [84–86].



**Figure 4.** Consequences of heavy metal contamination on health and the environment.

We discuss the pathophysiological mechanisms of some heavy metals found in the environment. (i) Arsenic (a metalloid, not a true heavy metal) is a potent toxicant that induces DNA damage and causes enzyme inhibition, especially of pyruvate dehydrogenase, and uncouples oxidative phosphorylation in mitochondria [87]. Literature reports that chronic arsenic exposure is strongly linked to skin lesions, hyperpigmentation, neurological disorders, CVD, and increased risks of skin, bladder, and lung cancers [88]. The WHO recommended safe limit for arsenic in drinking water is 10 µg/L [89,90]. (ii) Lead, a well-known neurotoxicant, is strongly associated with impaired neurodevelopment in children and various forms of cognitive degeneration; its association with neurodegenerative

conditions such as Parkinson's disease and Alzheimer's disease has been reported but remains under active investigation. The WHO guideline value for lead in drinking water is also set at 10 µg/L [91,92]. Lead toxicity is caused by its similar nature (analog) to calcium ( $\text{Ca}^{2+}$ ) and zinc ( $\text{Zn}^{2+}$ ), which interfere with cellular processes. For example, lead displaces  $\text{Ca}^{2+}$  from calmodulin and blocks  $\text{Ca}^{2+}$  flux through NMDA receptors, impairing synaptic plasticity and neuronal signaling. (iii) Mercury compounds, particularly methylmercury, are known to be highly neurotoxic [93]. It binds strongly to sulfhydryl groups of cysteine (an amino acid) in proteins, disrupting enzyme function, protein structure, and membrane integrity [94]. Mercury exposure also causes severe neurological damage, developmental abnormalities, and renal dysfunction [95–97]. Despite these toxic heavy metals, some less-addressed metals also cause severe health damage, such as cadmium, which is one of the well-known carcinogens. Overall, heavy metals contribute to systemic toxicity, including oxidative stress, chronic low-grade inflammation, endothelial dysfunction, and epigenetic alterations in DNA, which in turn induce vulnerability towards CVD, neurodegeneration, and various cancers.

As illustrated in Figure 4, heavy metals contaminate the environment through multiple anthropogenic and natural pathways, including industrial discharge, agricultural runoff, and weathering, and bioaccumulate across the food chain, ultimately reaching human populations through drinking water and food. The figure highlights the bidirectional relationship between environmental contamination and human health outcomes, including renal dysfunction, neurological damage, cardiovascular disease, and carcinogenesis, underscoring the urgency of monitoring and remediation [98]. Apart from heavy metals and biological contamination, toxic chemicals in pesticides also cause severe toxic effects to human and environmental health [99–102]. Many pesticides, such as organophosphates and DDT (organochlorine), cause neurotoxicity by inhibiting and delaying the closure of acetylcholine esterase and voltage-gated sodium channels, respectively. In general, many PFAS are known to bind peroxisome proliferator-activated receptor alpha (PPAR- $\alpha$ ), inhibit lipid metabolism, and regulate the immune system. PFAS are also known to cause birth defects and impaired human fertility [103].

### 3.8. Vulnerable Population and Health Risks

Polluted drinking water disproportionately affects vulnerable populations, particularly children and pregnant women. This increased susceptibility is attributed to several physiological and developmental factors, including higher exposure per unit body weight, immature detoxification systems (such as underdeveloped cytochrome P450 and glutathione S-transferase enzymes), increased permeability of the blood–brain barrier, rapid developmental processes, and the transplacental transfer of lipophilic contaminants from mother to fetus [83]. These factors make them more susceptible to neurodevelopmental impairments, growth stunting, and other long-term health consequences [103]. Therefore, drinking contaminated water creates a significant burden on global public health, necessitating the implementation of comprehensive strategies to protect communities and ensure sustainable access to safe drinking water [104,105].

## 4. Discussion

The findings indicate that water contamination is a multifactorial issue driven by both natural processes and anthropogenic activities, with industrial discharge, agricultural runoff, and inadequate sanitation emerging as dominant contributors. The evidence consistently shows that exposure to contaminated water is strongly associated with a wide range of adverse health outcomes, particularly gastrointestinal infections, neurological effects, and chronic toxicities linked to heavy metals and chemical pollutants. Furthermore, disparities in exposure and vulnerability highlight significant environmental health inequities, especially in low-resource settings where water treatment and regulatory enforcement remain limited. These patterns underscore the urgent need for integrated water safety management strategies and strengthened public health interventions.

In this context, it is important to distinguish between microbial and chemical contamination, as both contribute to disease burden through distinct pathways and temporal patterns of exposure. First, when comparing the relative disease burden of microbial versus chemical contamination, microbial pathogens remain the dominant cause of acute waterborne illness globally, responsible for the majority of diarrheal disease-related morbidity and mortality, particularly in children under five. However, chemical contamination (heavy metals, persistent organic pollutants, and emerging contaminants) increasingly dominates the chronic disease burden, contributing to NCDs that are far harder to attribute epidemiologically and therefore systematically undercounted. This asymmetry has important implications for prioritization: while microbial safety standards and interventions are relatively well established, regulatory frameworks for chemical and emerging contaminants remain fragmented and inconsistently enforced, especially in low-resource settings. Second, comparing different contamination pathways, agricultural runoff introduces both microbial pathogens and chemical pollutants simultaneously, making it arguably the most

complex source to regulate at the government level. Whereas industrial discharge tends to contribute higher concentrations of heavy metals and persistent organic pollutants in localized areas. The interaction of multiple contamination pathways, particularly in densely populated low-income areas, creates cumulative exposures that are not adequately captured by single-contaminant risk models. Third, the evidence base is strongest for acute infectious outcomes and weakest for chronic, low-level exposure scenarios, reflecting a systematic gap in longitudinal epidemiological research. Pathogens from fecal contamination (*Vibrio cholerae*, *E. coli*, *Giardia*, and several viruses) are mostly responsible for repeated outbreaks of diarrheal diseases, particularly in children, pregnant women, and immunocompromised individuals. Among diarrheal complications, acute watery diarrhea, such as cholera, remains lethal due to rapid dehydration. Despite the availability of effective treatments such as ORS and zinc supplementation, mortality rates are found to be high, reflecting systemic failures in the provision of safe drinking water. In developing countries such as Pakistan, surveillance systems for the supply of safe water and potential health outcomes are weak, and a large population continues to rely on unsafe water sources. Critically, the interaction of biological and chemical water pollutants with genetic, nutritional, and socioeconomic factors further complicates the disease risk landscape, necessitating multifactorial risk models rather than single-contaminant approaches. The emergence of PFAS, microplastics, pharmaceutical residues, and ARGs as additional contamination threats demands urgent attention, as conventional water treatment technologies show variable effectiveness against these compounds, and their long-term health consequences remain inadequately characterized. Climate change further compounds these risks by intensifying contamination events through flooding, concentrating pollutants through drought, and expanding the geographic range of waterborne pathogens. From a policy standpoint, the evidence reviewed strongly supports investment in: (i) routine multi-contaminant water quality monitoring, including for emerging pollutants; (ii) expanded wastewater treatment coverage with technologies appropriate for low-resource settings; (iii) stronger international regulatory standards for industrial and agricultural discharge; and (iv) longitudinal cohort studies to close critical epidemiological knowledge gaps. Without such concerted efforts, the health and developmental impacts of water pollution will continue to undermine global progress toward sustainable development and healthy longevity. According to the WHO, improving access to safe water, sanitation, and hygiene could save up to 1.4 million lives per year and prevent approximately 1000 deaths of children under five every single day.

#### *Research Gaps and Future Perspective*

Significant scientific progress has been made over recent decades in characterizing the sources, distribution, and health impacts of drinking water contaminants. Global monitoring initiatives, including the WHO/UNICEF Joint Monitoring Programme (JMP), have substantially improved our understanding of access to safe water and sanitation across regions. Epidemiological research has firmly established causal links between microbial contamination and waterborne diarrheal diseases, as well as mechanistic studies have elucidated the toxicological pathways of major heavy metals such as lead, arsenic, mercury, and cadmium. The development and widespread adoption of oral rehydration therapy (ORT) has dramatically reduced mortality from acute diarrheal illness. Advances in water treatment technologies, including membrane filtration, UV disinfection, and advanced oxidation processes, have provided effective tools for pathogen and contaminant removal. Regulatory frameworks such as the EU Water Framework Directive and the WHO drinking water quality guidelines have driven measurable improvements in water safety in many settings. Furthermore, the identification of emerging contaminants, including per- and PFAS, microplastics, and antibiotic resistance genes, represents an important frontier in water safety science. However, despite these advances, critical gaps remain. Preventing water pollution requires implementing multiple mitigation measures. Key strategies include adopting effective rainwater recharge techniques in urban areas to enhance both the quantity and quality of groundwater. Regulating wastewater discharge and improving waste management are essential to prevent future contamination. Maintaining community septic tanks and sewage systems is also essential to reduce groundwater pollution. We believe that establishing modern biological treatment facilities enables the reuse of domestic wastewater. Separating recyclable solid waste at the source, developing properly lined municipal waste disposal facilities to prevent leachate generation, and enforcing strict environmental regulations through stronger governmental oversight and effective policy implementation are also essential. Additionally, the global shortage of clean water requires more research on wastewater treatment. Limited findings are available that relate water quality surveillance data to public health outcomes and chronic NCDs, which in turn support implementing disease prevention. Research evaluating the effectiveness, affordability, and sustainability of water treatment plants in developing countries is scarce. These gaps need to be addressed through interdisciplinary research, which will be essential to improve water governance and reduce the global disease burden associated with polluted drinking water.

## 5. Conclusions

Environmental pollution and drinking water contamination represent a serious and less addressed threat to public health, particularly in developing countries where water management systems are poorly developed. The current review highlighted the microbial pathogens and toxic chemicals, including heavy metals, that continuously contaminate drinking water sources, which directly cause both acute and chronic health issues. Addressing water scarcity and safety requires a shift toward preventive and integrated approaches, including stricter regulation of pollution sources, improved sanitation and wastewater treatment, routine water quality monitoring, and increased public awareness. Strengthening these measures will play essential roles in reducing disease burden, protecting vulnerable populations, and ensuring sustainable access to safe drinking water in accordance with global public health and environmental objectives.

## Author Contributions

M.A.R.: supervision, reviewing and editing; N.B.: reviewing and editing; S.P.: conceptualization, data curation, writing the original draft preparation, software. All authors have read and agreed to the published version of the manuscript.

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The authors declare no conflict of interest.

## Use of AI and AI-Assisted Technologies

The authors declare that an AI tool (Grammarly) was used to assist with language editing and to improve the clarity, grammar, and readability of sentences wherever required. No AI tool was used to generate scientific content. All presented data is the responsibility of the authors, who carefully reviewed and approved the final version of the manuscript.

## References

1. Fuller, R.; Landrigan, P.J.; Balakrishnan, K.; et al. Pollution and health: A progress update. *Lancet Planet. Health* **2022**, *6*, 535–547. [https://doi.org/10.1016/S2542-5196\(22\)00090-0](https://doi.org/10.1016/S2542-5196(22)00090-0).
2. Landrigan, P.J.; Fuller, R.; Fisher, S.; et al. Pollution and children's health. *Sci. Total Environ.* **2019**, *650*, 2389–2394. <https://doi.org/10.1016/j.scitotenv.2018.09.375>.
3. Wolf, J.; Johnston, R.B.; Ambelu, A.; et al. Burden of disease attributable to unsafe drinking water, sanitation, and hygiene in domestic settings: A global analysis for selected adverse health outcomes. *Lancet* **2023**, *401*, 2060–2071. [https://doi.org/10.1016/S0140-6736\(23\)00458-0](https://doi.org/10.1016/S0140-6736(23)00458-0).
4. Tang, W.; Pei, Y.; Zheng, H.; et al. Twenty years of China's water pollution control: Experiences and challenges. *Chemosphere* **2022**, *295*, 133875. <https://doi.org/10.1016/j.chemosphere.2022.133875>.
5. Landrigan, P.J.; Stegeman, J.J.; Fleming, L.E.; et al. Human health and ocean pollution. *Ann. Glob. Health* **2020**, *86*, 151. <https://doi.org/10.5334/aogh.2831>.
6. World Health Organization. Ambient (Outdoor) Air Pollution. 2024. Available online: [https://www.who.int/news-room/fact-sheets/detail/ambient-\(outdoor\)-air-quality-and-health](https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health) (accessed on 15 January 2026).

7. Siddiqua, A.; Hahladakis, J.N.; Waka, A.A. An overview of the environmental pollution and health effects associated with waste landfilling and open dumping. *Environ. Sci. Pollut. Res.* **2022**, *29*, 58514–58536. <https://doi.org/10.1007/s11356-022-21578-z>.
8. Landrigan, P.J.; Fuller, R.; Hu, H.; et al. Pollution and global health, an agenda for prevention. *Environ. Health Perspect.* **2018**, *126*, 084501. <https://doi.org/10.1289/EHP3141>.
9. Kristanti, R.A.; Hadibarata, T.; Syafrudin, M.; et al. Microbiological contaminants in drinking water: Current status and challenges. *Water Air Soil Pollut.* **2022**, *233*, 299. <https://doi.org/10.1007/s11270-022-05698-3>.
10. Lin, L.; Yang, H.; Xu, X. Effects of water pollution on human health and disease heterogeneity: A review. *Front. Environ. Sci.* **2022**, *10*, 880246. <https://doi.org/10.3389/fenvs.2022.880246>.
11. Saad, L. Water Pollution Americans' Top Green Concern. 2009. Available online: <https://news.gallup.com/poll/190034/americans-concerns-water-pollution-edge.aspx> (accessed on 17 January 2026).
12. World Wildlife Fund. Water Scarcity. 2024. Available online: <https://www.worldwildlife.org/our-work/freshwater/water-scarcity/> (accessed on 22 January 2026).
13. Nada, M.J. Water contamination and disinfection: A review. *J. Pioneer Med. Sci.* **2025**, *14*, 96–102. <https://doi.org/10.47310/jpms2025140215>.
14. Schwarzenbach, R.P.; Egli, T.; Hofstetter, T.B.; et al. Global water pollution and human health. *Annu. Rev. Environ. Resour.* **2010**, *35*, 109–136. <https://doi.org/10.1146/annurev-environ-100809-125342>.
15. Raghavendra, N. Drinking water contamination and its solving approaches: A comprehensive review. *Water Air Soil Pollut.* **2024**, *235*, 639. <https://doi.org/10.1007/s11270-024-07463-0>.
16. Sultan, M.W.; Qureshi, F.; Ahmed, S.; et al. A comprehensive review on arsenic contamination in groundwater: Sources, detection, mitigation strategies and cost analysis. *Environ. Res.* **2025**, *265*, 120457. <https://doi.org/10.1016/j.envres.2024.120457>.
17. Uddin, R.; Huda, N.H. Arsenic poisoning in Bangladesh. *Oman Med. J.* **2011**, *26*, 207. <https://doi.org/10.5001/omj.2011.51>.
18. Ma, T.; Zhao, N.; Ni, Y.; et al. China's improving inland surface water quality since 2003. *Sci. Adv.* **2020**, *6*, 3798. <https://doi.org/10.1126/sciadv.aau3798>.
19. Lawrencía, D.; Maniam, G.; Chuah, L.H.; et al. Critical review of household water treatment in Southeast Asian countries. *WIREs Water* **2023**, *10*, 1640. <https://doi.org/10.1002/wat2.1640>.
20. Hlongwa, N.; Nkomo, S.P.; Desai, S.A. Barriers to water, sanitation, and hygiene in Sub-Saharan Africa: A mini review. *J. Water Sanit. Hyg. Dev.* **2024**, *14*, 497–510. <https://doi.org/10.2166/washdev.2024.266>.
21. Michel, D. Building Resilient Water Systems in Sub-Saharan Africa. CSIS. 2025. Available online: <https://www.csis.org/analysis/building-resilient-water-systems-sub-saharan-africa> (accessed on 22 January 2026).
22. Sawon, M.M.H.; Talukder, M.B.; Hossain, M.A. Food and water sustainability: Challenges and prospects. In *Food and Water Security*; Springer: Cham, Switzerland, 2026; 31–56. [https://doi.org/10.1007/978-3-032-04870-7\\_2](https://doi.org/10.1007/978-3-032-04870-7_2).
23. Nishmitha, P.S.; Akhilghosh, K.A.; Aiswriya, V.P.; et al. Understanding emerging contaminants in water and wastewater: A comprehensive review on detection, impacts, and solutions. *J. Hazard. Mater. Adv.* **2025**, *18*, 100755. <https://doi.org/10.1016/j.hazadv.2025.100755>.
24. World Health Organization. Guidelines for Drinking-Water Quality. 2017. Available online: <https://www.who.int/publications/i/item/9789241549950> (accessed on 20 January 2026).
25. Babuji, P.; Thirumalaisamy, S.; Duraisamy, K.; et al. Human health risks due to water pollution. *Water* **2023**, *15*, 2532. <https://doi.org/10.3390/w15142532>.
26. Liu, Y.; Wang, P.; Gojenko, B.; et al. A review of water pollution arising from agriculture and mining activities in Central Asia: Facts, causes and effects. *Environ. Pollut.* **2021**, *291*, 118209. <https://doi.org/10.1016/j.envpol.2021.118209>.
27. Jagaba, A.H.; Lawal, I.M.; Birniwa, A.H.; et al. Sources of water contamination by heavy metals. In *Membrane Technologies for Heavy Metal Removal from Water*; CRC Press: Boca Raton, FL, USA, 2024; pp. 3–27. <https://doi.org/10.1201/9781003326281-2>.
28. Tchounwou, P.B.; Yedjou, C.G.; Patlolla, A.K.; et al. Heavy metals toxicity and the environment. *EXS* **2012**, *101*, 133–164. [https://doi.org/10.1007/978-3-7643-8340-4\\_6](https://doi.org/10.1007/978-3-7643-8340-4_6).
29. Briffa, J.; Sinagra, E.; Blundell, R. Heavy metal pollution in the environment and their toxicological effects on humans. *Heliyon* **2020**, *6*, 04691. <https://doi.org/10.1016/j.heliyon.2020.e04691>.
30. Bello, O.S.; Agboola, O.S.; Adegoke, K.A. Sources of various heavy metal ions. In *Heavy Metals in the Environment: Management Strategies for Global Pollution*; American Chemical Society: Washington, DC, USA, 2023; pp. 59–69. <https://doi.org/10.1021/bk-2023-1456.ch004>.
31. Afzal, I.; Begum, S.; Iram, S.; et al. Comparative analysis of heavy metals toxicity in drinking water of selected industrial zones in Gujranwala, Pakistan. *Sci. Rep.* **2024**, *14*, 30639. <https://doi.org/10.1038/s41598-024-82138-8>.

32. Ashbolt, N.J. Microbial contamination of drinking water and disease outcomes in developing regions. *Toxicology* **2004**, *198*, 229–238. <https://doi.org/10.1016/j.tox.2004.01.030>.
33. Ali, D.; Ibrahim, K.E.; Hussain, S.A.; et al. Role of ROS generation in acute genotoxicity of azoxystrobin fungicide on freshwater snail *Lymnaea luteola* L. *Environ. Sci. Pollut. Res.* **2021**, *28*, 5566–5574. <https://doi.org/10.1007/s11356-020-10895-w>.
34. Panis, C.; Candioto, L.Z.P.; Gaboardi, S.C.; et al. Widespread pesticide contamination of drinking water and impact on cancer risk in Brazil. *Environ. Int.* **2022**, *165*, 107321. <https://doi.org/10.1016/j.envint.2022.107321>.
35. Shah, A.; Arjunan, A.; Baroutaji, A.; et al. A review of physicochemical and biological contaminants in drinking water and their impacts on human health. *Water Sci. Eng.* **2023**, *16*, 333–344. <https://doi.org/10.1016/j.wse.2023.04.003>.
36. Jaishankar, M.; Tseten, T.; Anbalagan, N.; et al. Toxicity, mechanism and health effects of some heavy metals. *Interdiscip. Toxicol.* **2014**, *7*, 60–72. <https://doi.org/10.2478/intox-2014-0009>.
37. Lee, D.; Gibson, J.M.; Brown, J.; et al. Burden of disease from contaminated drinking water in countries with high access to safely managed water: A systematic review. *Water Res.* **2023**, *242*, 120244. <https://doi.org/10.1016/j.watres.2023.120244>.
38. Ferguson, A.S.; Mailloux, B.J.; Ahmed, K.M.; et al. Hand-pumps as reservoirs for microbial contamination of well water. *J. Water Health* **2011**, *9*, 708–717. <https://doi.org/10.2166/wh.2011.106>.
39. Agbasi, J.C.; Chukwu, C.N.; Nweke, N.D.; et al. Water pollution indexing and health risk assessment due to PTE ingestion and dermal absorption for nine human populations in Southeast Nigeria. *Groundw. Sustain. Dev.* **2023**, *21*, 100921. <https://doi.org/10.1016/j.gsd.2023.100921>.
40. Acosta-España, J.D.; Romero-Alvarez, D.; Luna, C.; et al. Infectious disease outbreaks in the wake of natural flood disasters: Global patterns and local implications. *Infez. Med.* **2024**, *32*, 451–462. <https://doi.org/10.53854/liim-3204-4>.
41. Acheson, D.W.K. Food and Waterborne Illnesses. In *Encyclopedia of Microbiology*; Academic Press: Cambridge, MA, USA, 2009; pp. 365–381. <https://doi.org/10.1016/B978-012373944-5.00183-8>.
42. Daud, M.K.; Nafees, M.; Ali, S.; et al. Drinking water quality status and contamination in Pakistan. *BioMed Res. Int.* **2017**, *2017*, 7908183. <https://doi.org/10.1155/2017/7908183>.
43. World Health Organization. Drinking-Water. 2023. Available online: <https://www.who.int/news-room/fact-sheets/detail/drinking-water> (accessed on 21 January 2026).
44. Qamar, K.; Nchasi, G.; Mirha, H.T.; et al. Water sanitation problem in Pakistan: A review on disease prevalence, strategies for treatment and prevention. *Ann. Med. Surg.* **2022**, *82*, 104709. <https://doi.org/10.1016/j.amsu.2022.104709>.
45. Burnens, A.P.; Frey, A.; Nicolet, J. Association between clinical presentation, biogroups and virulence attributes of *Yersinia enterocolitica* strains in human diarrhoeal disease. *Epidemiol. Infect.* **1996**, *116*, 27–34. <https://doi.org/10.1017/S0950268800058921>.
46. World Health Organization. Cholera. 2024. Available online: <https://www.who.int/news-room/fact-sheets/detail/cholera> (accessed on 24 January 2026).
47. Zhang, P.; Yang, M.; Lan, J.; et al. Water quality degradation due to heavy metal contamination: Health impacts and eco-friendly approaches for heavy metal remediation. *Toxics* **2023**, *11*, 828. <https://doi.org/10.3390/toxics11100828>.
48. Generalova, A.; Davidova, S.; Satchanska, G. The mechanisms of lead toxicity in living organisms. *J. Xenobiotics* **2025**, *15*, 146. <https://doi.org/10.3390/jox15050146>.
49. Järup, L. Hazards of heavy metal contamination. *Br. Med. Bull.* **2003**, *68*, 167–182. <https://doi.org/10.1093/bmb/ldg032>.
50. Caligiore, D.; Giocondo, F.; Silveti, M. The neurodegenerative elderly syndrome (NES) hypothesis: Alzheimer and Parkinson are two faces of the same disease. *IBRO Neurosci. Rep.* **2022**, *13*, 330–343. <https://doi.org/10.1016/j.ibneur.2022.09.007>.
51. Chen, Y.; Yang, Z.; Nian, B.; et al. Mechanisms of neurotoxicity of organophosphate pesticides and their relation to neurological disorders. *Neuropsychiatr. Dis. Treat.* **2024**, *20*, 2237–2254. <https://doi.org/10.2147/NDT.S479757>.
52. Shekhar C.; Khosya R.; Thakur K.; et al. A systematic review of pesticide exposure, associated risks, and long-term human health impacts. *Toxicology Reports.* **2024**, *1*, 101840. <https://doi.org/10.1016/j.toxrep.2024.101840>
53. Chen, J.; Song, P.; Li, C.; et al. Endocrine disrupting chemicals exposure and health: An umbrella review. *Ecotoxicol. Environ. Saf.* **2025**, *302*, 118574. <https://doi.org/10.1016/j.ecoenv.2025.118574>.
54. Güzel, B. Recent advancements on per- and polyfluoroalkyl substances (PFAS) in the environment for human health: A comprehensive review. *Water Air Soil Pollut.* **2025**, *236*, 526. <https://doi.org/10.1007/s11270-025-08174-w>.
55. Ehrlich, V.; Bil, W.; Vandebriel, R.; et al. Consideration of pathways for immunotoxicity of per- and polyfluoroalkyl substances (PFAS). *Environ. Health* **2023**, *22*, 19. <https://doi.org/10.1186/s12940-022-00958-5>.
56. Wilhelm, M.; Bergmann, S.; Dieter, H.H. Occurrence of perfluorinated compounds (PFCs) in drinking water of North Rhine-Westphalia, Germany and new approach to assess drinking water contamination by shorter-chained C4–C7 PFCs. *Int. J. Hyg. Environ. Health* **2010**, *213*, 224–232. <https://doi.org/10.1016/j.ijheh.2010.05.004>.

57. Islam, M.A.; Parvin, M.I.; Nguyen, C.; et al. Per- and polyfluoroalkyl substances (PFAS) contamination in agriculture and its potential conflict with circular economy. *Environ. Pollut.* **2025**, *385*, 127036. <https://doi.org/10.1016/j.envpol.2025.127036>.
58. Muñoz-Bautista, J.M.; Bernal-Mercado, A.T.; Martínez-Cruz, O.; et al. Environmental and health impacts of pesticides and nanotechnology as an alternative in agriculture. *Agronomy* **2025**, *15*, 1878. <https://doi.org/10.3390/agronomy15081878>.
59. Rahman, S.; Saha, W.; Maysha, T.I.; et al. Prevalence and health risks of microplastics in bottled water and beverages: A food safety concern. *J. Hazard. Mater. Plast.* **2026**, *2*, 100024. <https://doi.org/10.1016/j.hazmp.2025.100024>.
60. Zhang, J.; Liu, Y.; Zhao, L.; et al. Microplastics and nanoplastics in drinking water and beverages: Occurrence and human exposure. *J. Environ. Expo. Assess.* **2024**, *3*, 24. <https://doi.org/10.20517/jeea.2024.37>.
61. Samal, K.; Mahapatra, S.; Hibzur Ali, M. Pharmaceutical wastewater as emerging contaminants (EC): Treatment technologies, impact on environment and human health. *Energy Nexus* **2022**, *6*, 100076. <https://doi.org/10.1016/j.nexus.2022.100076>.
62. Chayña, E.T.; Ferro, P.; Morales-Rojas, E.; et al. Detection of antibiotic-resistance genes in drinking water: A study at a university in the Peruvian Amazon. *Int. J. Environ. Res. Public Health* **2025**, *22*, 353. <https://doi.org/10.3390/ijerph22030353>.
63. Salvidge, R.; Hosea, L. What Are Pfas, How Toxic Are They and How Do You Become Exposed? The Guardian. 2023. Available online: <https://www.theguardian.com/environment/2023/feb/23/what-are-pfas-forever-chemicals-how-toxic-are-they-and-how-do-you-become-exposed> (accessed on 22 January 2026).
64. Dhandapani, A.; Maheshwari, M.; Rastogi, N. Degradation of microplastics and nanoplastics: An underexplored pathway contributing to atmospheric pollutants. *ACS Earth Space Chem.* **2025**, *9*, 2338–2353. <https://doi.org/10.1021/acsearthspacechem.5c00210>.
65. Mahmud, F.; Sarker, D.B.; Jocelyn, J.A.; et al. Molecular and cellular effects of microplastics and nanoplastics: Focus on inflammation and senescence. *Cells* **2024**, *13*, 1788. <https://doi.org/10.3390/cells13211788>.
66. Saradhi, T. The Hidden Environmental Impact of Pharmaceutical Waste. 2026. Available online: <https://earth.org/an-invisible-crisis-the-hidden-environmental-impact-of-pharmaceutical-waste/> (accessed on 23 January 2026).
67. Ortúzar, M.; Esterhuizen, M.; Olicón-Hernández, D.R.; et al. Pharmaceutical pollution in aquatic environments: A concise review of environmental impacts and bioremediation systems. *Front. Microbiol.* **2022**, *13*, 869332. <https://doi.org/10.3389/fmicb.2022.869332>.
68. Mutuku, C.; Gazdag, Z.; Melegh, S. Occurrence of antibiotics and bacterial resistance genes in wastewater: Resistance mechanisms and antimicrobial resistance control approaches. *World J. Microbiol. Biotechnol.* **2022**, *38*, 152. <https://doi.org/10.1007/s11274-022-03334-0>.
69. Abalasei, M.E.; Toma, D.; Dorus, M.; et al. The impact of climate change on water quality: A critical analysis. *Water* **2025**, *17*, 3108. <https://doi.org/10.3390/w17213108>.
70. Impact of Climate Change on Water Availability and Quality. Available online: <https://www.unicef.org/serbia/en/impact-of-climate-change-on-water-availability-and-quality> (accessed on April 6, 2026, from https).
71. Rosińska, W.; Jurasz, J.; Przestrzelska, K.; et al. Climate change's ripple effect on water supply systems and the water-energy nexus—A review. *Water Resour. Ind.* **2024**, *32*, 100266. <https://doi.org/10.1016/j.wri.2024.100266>.
72. Aziz, F.; Wang, X.; Mahmood, M.Q.; et al. Assessing human health risks associated with wastewater flooding. *Environ. Impact Assess. Rev.* **2025**, *115*, 108031. <https://doi.org/10.1016/j.eiar.2025.108031>.
73. Glassmeyer, S.T.; Burns, E.E.; Focazio, M.J.; et al. Water, water everywhere, but every drop unique: Challenges in the science to understand the role of contaminants of emerging concern in the management of drinking water supplies. *GeoHealth* **2023**, *7*, 2022 000716. <https://doi.org/10.1029/2022GH000716>.
74. Shekhar, C.; Khosya, R.; Sharma, A.K.; et al. A systematic review on health risks of water pollutants: Classification, effects, and innovative solutions for conservation. *Toxicol. Res.* **2025**, *14*, 014. <https://doi.org/10.1093/toxres/taaf014>.
75. Mustafa, B.M.; Hassan, N.E. Water contamination and its effects on human health: A review. *J. Geogr. Environ. Earth Sci. Int.* **2024**, *28*, 38–49. <https://doi.org/10.9734/jgeesi/2024/v28i1743>.
76. Khan, K.; Lu, Y.; Saeed, M.A.; et al. Prevalent fecal contamination in drinking water resources and potential health risks in Swat, Pakistan. *J. Environ. Sci.* **2018**, *72*, 1–12. <https://doi.org/10.1016/j.jes.2017.12.008>.
77. Nabeela, F.; Azizullah, A.; Bibi, R.; et al. Microbial contamination of drinking water in Pakistan—A review. *Environ. Sci. Pollut. Res.* **2014**, *21*, 13929–13942. <https://doi.org/10.1007/s11356-014-3348-z>.
78. Sack, D.A.; Sack, R.B.; Nair, G.B.; et al. Cholera. *Lancet* **2004**, *363*, 223–233. [https://doi.org/10.1016/s0140-6736\(03\)15328-7](https://doi.org/10.1016/s0140-6736(03)15328-7).
79. Yan, C.; Wan, W.D.; Wang, R.N.; et al. Quantitative health risk assessment of microbial hazards from water sources for community and self-supply drinking water systems. *J. Hazard. Mater.* **2024**, *465*, 133324. <https://doi.org/10.1016/j.jhazmat.2023.133324>.
80. ElNabi, M.K.A.; Elkaliny, N.E.; Elyazied, M.M.; et al. Toxicity of heavy metals and recent advances in their removal: A review. *Toxics* **2023**, *11*, 580. <https://doi.org/10.3390/toxics11070580>.

81. Rath, S. Microbial contamination of drinking water. In *Water Pollution and Management Practices*; Springer: Singapore, 2021; pp. 1–17. [https://doi.org/10.1007/978-981-15-8358-2\\_1](https://doi.org/10.1007/978-981-15-8358-2_1).
82. Goldberg, J.E. Parasitic colitides. *Clin. Colon Rectal Surg.* **2007**, *20*, 38–46. <https://doi.org/10.1055/s-2007-970199>.
83. Jayaswal, K.; Sahu, V.; Gurjar, B.R. Water Pollution, Human Health and Remediation. In *Water Remediation*; Springer: Singapore, 2018; pp. 1–17. [https://doi.org/10.1007/978-981-10-7551-3\\_2](https://doi.org/10.1007/978-981-10-7551-3_2).
84. Koyama, H.; Kamogashira, T.; Yamasoba, T. Heavy metal exposure: Molecular pathways, clinical implications, and protective strategies. *Antioxidants* **2024**, *13*, 76. <https://doi.org/10.3390/antiox13010076>.
85. Parida, L.; Patel, T.N. Systemic impact of heavy metals and their role in cancer development: A review. *Environ. Monit. Assess.* **2023**, *195*, 766. <https://doi.org/10.1007/s10661-023-11399-z>.
86. Egbueri, J.C.; Agbasi, J.C.; Khan, M.Y.A.; et al. Assessing the environmental, health, and food security implications of heavy metals in irrigation water: A multi-index analytical framework. *Anal. Lett.* **2026**, *59*, 373–408. <https://doi.org/10.1080/00032719.2025.2484451>.
87. Concessao, P.L.; Prakash, J. Arsenic-induced nephrotoxicity: Mechanisms, biomarkers, and preventive strategies for global health. *Vet. World* **2025**, *18*, 2136–2157. <https://doi.org/10.14202/vetworld.2025.2136-2157>.
88. Naujokas, M.F.; Anderson, B.; Ahsan, H.; et al. The broad scope of health effects from chronic arsenic exposure: Update on a worldwide public health problem. *Environ. Health Perspect.* **2013**, *121*, 295–302. <https://doi.org/10.1289/ehp.1205875>.
89. Tolins, M.; Ruchirawat, M.; Landrigan, P. The developmental neurotoxicity of arsenic: Cognitive and behavioral consequences of early life exposure. *Ann. Glob. Health* **2014**, *80*, 303–314. <https://doi.org/10.1016/j.aogh.2014.09.005>.
90. World Health Organization. Arsenic. 2022. Available online: <https://www.who.int/news-room/fact-sheets/detail/arsenic> (accessed on 20 January 2026).
91. Ahmad, A.; Bhattacharya, P. Arsenic in drinking water: Is 10 µg/L a safe limit? *Curr. Pollut. Rep.* **2019**, *5*, 1–3. <https://doi.org/10.1007/s40726-019-0102-7>.
92. Jarvis, P.; Fawell, J. Lead in drinking water—An ongoing public health concern? *Curr. Opin. Environ. Sci. Health* **2021**, *20*, 100239. <https://doi.org/10.1016/j.coesh.2021.100239>.
93. Rajkumar, V.; Lee, V.R.; Gupta, V. Heavy Metal Toxicity. In *StatPearls*; StatPearls Publishing: Treasure Island, FL, USA, 2026. Available online: <https://www.ncbi.nlm.nih.gov/books/NBK560920/> (accessed on 21 January 2026).
94. Shen, S.; Li, X.F.; Cullen, W.R.; et al. Arsenic binding to proteins. *Chem. Rev.* **2013**, *113*, 7769–7792. <https://doi.org/10.1021/cr300015c>.
95. Lal, S.; Singhal, A.; Kumari, P. Exploring carbonaceous nanomaterials for arsenic and chromium removal from wastewater. *J. Water Process Eng.* **2020**, *36*, 101276. <https://doi.org/10.1016/j.jwpe.2020.101276>.
96. Deng, H.; Tu, Y.; Wang, H.; et al. Environmental behavior, human health effect, and pollution control of heavy metal(loid)s toward full life cycle processes. *Eco-Environ. Health* **2022**, *1*, 229–243. <https://doi.org/10.1016/j.eehl.2022.11.003>.
97. Kubier, A.; Wilkin, R.T.; Pichler, T. Cadmium in soils and groundwater: A review. *Appl. Geochem.* **2019**, *108*, 104388. <https://doi.org/10.1016/j.apgeochem.2019.104388>.
98. Shetty, S.S.; D., D.; H., S.; et al. Environmental pollutants and their effects on human health. *Heliyon* **2023**, *9*, 19496. <https://doi.org/10.1016/j.heliyon.2023.e19496>.
99. Parlayıcı, Ş.; Bahadır, M.; Pehlivan, E. Nanoporous carbonaceous materials (biochar and activated carbon): Recent progress and potential applications for arsenic removal. *J. Dispers. Sci. Technol.* **2025**, *46*, 2026–2047. <https://doi.org/10.1080/01932691.2024.2369881>.
100. Dalla Vecchia, A.; Rigotto, C.; Staggemeier, R.; et al. Surface water quality in the Sinos River basin, in Southern Brazil: Tracking microbiological contamination and correlation with physicochemical parameters. *Environ. Sci. Pollut. Res.* **2015**, *22*, 9899–9911. <https://doi.org/10.1007/s11356-015-4175-6>.
101. Marumure, J.; Simbanegavi, T.T.; Makuvara, Z.; et al. Emerging organic contaminants in drinking water systems: Human intake, emerging health risks, and future research directions. *Chemosphere* **2024**, *356*, 141699. <https://doi.org/10.1016/j.chemosphere.2024.141699>.
102. Huang, J.; Li, J.; Meng, W.; et al. A critical review on organophosphate esters in drinking water: Analysis, occurrence, sources, and human health risk assessment. *Sci. Total Environ.* **2024**, *913*, 169663. <https://doi.org/10.1016/j.scitotenv.2023.169663>.
103. Ungureanu, L., & Mustatea, G. (2022). Toxicity of heavy metals. In *Environmental Impact and Remediation of Heavy Metals*. IntechOpen. <https://doi.org/10.5772/intechopen.102441>.
104. Joseph, L.; Jun, B.M.; Flora, J.R.V.; et al. Removal of heavy metals from water sources in the developing world using low-cost materials: A review. *Chemosphere* **2019**, *229*, 142–159. <https://doi.org/10.1016/j.chemosphere.2019.04.198>.
105. Elmadani, M.; Kiptulon, E.K.; Klára, S.; et al. Systematic review of the impact of natural resource management on public health outcomes: Focus on water quality. *Resources* **2024**, *13*, 122. <https://doi.org/10.3390/resources13090122>.