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Sources and Health Effects of Arsenic, Fluoride, and Nitrate in Water

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Abstract

Arsenic, fluoride, and nitrate are major inorganic contaminants in water that pose significant risks to human health. These contaminants are introduced into water sources through both natural geological processes and human activities. Arsenic is primarily released from arsenic-bearing minerals through weathering, dissolution, and erosion, while human activities such as agriculture, mining, and fossil fuel combustion further enhance its presence in water. Fluoride contamination mainly results from the dissolution of fluoride-bearing minerals such as fluorite, apatite, and topaz, whereas nitrate is largely formed through the oxidation of nitrogen oxides emitted from fossil fuel combustion, agricultural activities, and soil processes. Exposure to these contaminants leads to a range of health effects. Arsenic affects multiple organ systems, including the nervous, hepatic, renal, and cardiovascular systems, and is associated with various cancers. Prolonged exposure to elevated fluoride concentrations can lead to dental and skeletal fluorosis, while excessive intake may also adversely affect other organs and physiological systems. Elevated nitrate levels in drinking water are linked to methemoglobinemia (blue-baby syndrome) and the formation of carcinogenic N-nitroso compounds. This review summarizes the major sources of arsenic, fluoride, and nitrate contamination in water and highlights their associated impacts on human health.

Keywords: Arsenic contamination, fluoride contamination, nitrate pollution, groundwater quality, human health

INTRODUCTION

The presence of arsenic in surface and groundwater above permissible limits has emerged as a serious global public health concern [1]. Arsenic mainly appears in two inorganic forms like Arsenite [As(III)] and arsenate [As(V)] in natural water. Arsenite is approximately 50 times more toxic than arsenate and is generally more soluble under similar environmental conditions. In contrast, arsenate tends to adsorb strongly onto mineral surfaces, particularly iron oxides and hydroxides, whereas arsenite exhibits weaker adsorption behavior [2].

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Fluoride intake in humans occurs predominantly through drinking water [3]. Its impact on health is concentration-dependent: low concentrations (approximately 0.5–1.0 mg/L in drinking water) are beneficial for dental health, whereas excessive intake leads to adverse [4]. In India alone, approximately 62 million individuals, including around 6 million children, are affected by fluorosis due to elevated fluoride levels in drinking water [5]. According to WHO (2006), the permissible limit of fluoride in drinking water is 1.5 mg/L. Concentrations exceeding this threshold are associated with dental and skeletal fluorosis, as well as potential damage to the thyroid, liver, and other organs [6].

Nitrate (NO_3^-) is a common inorganic contaminant originating from agricultural activities, organic waste, and industrial discharges. It is produced through microbial transformation of nitrogenous compounds [7]. In soils, nitrogen is mainly present as ammonium (NH_4^+-N) and nitrate (NO_3^--N). While ammonium tends to bind to soil particles, nitrate is highly mobile and can easily leach into groundwater, particularly during rainfall events [8]. At a regional scale, nitrate contamination is largely influenced by fertilizer application and soil characteristics that favour leaching [9]. Considering the widespread occurrence and health implications of arsenic, fluoride, and nitrate, this review studies the major sources and associated effects on human health.

SOURCES

Arsenic

Arsenic contamination in groundwater is primarily derived from both natural and anthropogenic sources. Naturally, arsenic is released from arsenic-bearing minerals in soils and rocks through processes such as weathering, dissolution, and erosion. These processes facilitate its migration into groundwater systems. Anthropogenic contributions include agricultural practices, combustion of fossil fuels, mining and smelting activities, and various industrial operations such as glass and cement manufacturing [10].

Arsenic typically enters groundwater as As(III) and As(V) through geochemical interactions, biological processes, and environmental transformations [11]. Natural mobilization is further enhanced by volcanic activity and redox reactions, while human activities such as the use of arsenic-based pesticides, fertilizers, and improper waste disposal significantly increase its environmental load [12].

Human exposure to arsenic occurs predominantly through the ingestion of contaminated drinking water, food crops irrigated with arsenic-bearing water, and meals prepared using such water. Apart from environmental exposure, arsenic has a wide range of industrial applications. It is commonly used as an alloying component and in the manufacture of glass, pigments, textiles, paper products, metal adhesives, wood preservatives, and ammunition. Furthermore, arsenic is employed in leather tanning and, to a lesser degree, in the production of pesticides, livestock feed additives, and selected pharmaceutical formulations [13].

Fluoride

Fluoride present in groundwater is primarily derived from the weathering and dissolution of fluoride-rich minerals, including fluorite, apatite, and topaz [14]. The concentration of fluoride in groundwater is strongly influenced by the hydrogeochemical characteristics of the aquifer. Studies have reported that groundwater containing elevated fluoride levels generally exhibits low calcium and magnesium hardness along with high alkalinity. As fluoride concentrations increase, calcium and magnesium contents tend to decrease, whereas alkalinity rises. Epidemiological investigations of endemic skeletal fluorosis have further demonstrated that the adverse effects of fluoride on bones and teeth are more severe among populations consuming soft water characterized by high alkalinity and low concentrations of calcium and magnesium. The presence of calcium and magnesium in drinking water is therefore considered to reduce the bioavailability and toxicity of fluoride. In addition to mineral dissolution, the weathering of alkali, silicate, igneous, and sedimentary rocks constitutes a major natural source of fluoride in groundwater [15].

Under terrestrial conditions, fluorine behaves as a lithophile element and occurs in only a limited number of stable fluoride-bearing minerals. The most common among them are topaz $Al_2SiO_4(F,OH)_2$ and fluorite (CaF_2). Fluorine exhibits a strong affinity for substituting hydroxyl (OH^-) groups in mineral structures, leading to the formation of fluoroapatite ($Ca_{10}(PO_4)_6F_2$), which is the most abundant fluorine mineral. This substitution mechanism also contributes to elevated fluorine concentrations in amphiboles and mica group minerals. In soils, fluorine mobility is governed by several interacting factors, including clay mineral content, soil pH, and the concentrations of calcium and phosphorus. Maximum adsorption of fluorine by soil mineral components typically occurs within a pH range of 6 to 7. Additionally, in certain heavy soils, fluorine concentrations may exceed 1,000 ppm [16].

Nitrate

Nitrate contamination arises from both atmospheric and terrestrial sources. Nitrogen oxides (NO_x) released during fossil fuel combustion and soil emissions are converted into nitrate through atmospheric chemical reactions. Variations in human activities, such as increases or reductions in fossil fuel combustion, can affect the emission of NO_x and atmospheric oxidants, thus influencing the formation and deposition of atmospheric nitrate [17].

Point sources such as septic systems, sewage discharge, and industrial effluents contribute to localized nitrate contamination, particularly in shallow aquifers and private wells. Agriculture is considered the main source of nitrates. All countries, even those which do not yet have any drinking-water problems, consider agricultural sources of nitrate as a major contributor to groundwater contamination. Nitrate is brought in large quantities onto the fields in manure, especially in stockbreeding areas, and fertilizers in intensive crop-producing areas. Due to biodegradation of organic compounds in soil, naturally occurring nitrates are produced and released into the groundwater. In general, nitrate reaches groundwater and surface water along two pathways. One pathway is run-off from agricultural areas which varies with season, and depends on different factors like temperature, slope, amount of rain and type of crop. The second pathway is infiltration. In agricultural areas, nitrate infiltrates into the soil, especially during autumn and winter periods in bare fields and arable land with poor crop cover. In other areas, effluents from sewage and waste disposal also infiltrate into groundwater and thus increase the nitrate load locally [18].

EFFECTS

Arsenic

Long-term consumption of arsenic-contaminated drinking water poses significant risks to human health. Prolonged arsenic exposure can adversely affect multiple organ systems, including the nervous system, liver, kidneys, and lungs [19].

Arsenic exposure has been reported to alter the activity of antioxidant enzymes, including glutathione peroxidase and mitochondrial superoxide dismutase, particularly in the liver and lungs. Prolonged exposure to arsenic is also associated with an increased risk of cardiovascular complications, such as hypertension and other vascular disorders [20]. Continuous consumption of arsenic-contaminated drinking water may result in characteristic dermatological manifestations, including skin hyperpigmentation and hyperkeratosis, especially on the palms and soles [21]. Among the various arsenic species, inorganic arsenic is considered the most toxic and can enter the human body through ingestion, inhalation, or dermal absorption [22]. Acute arsenic poisoning commonly presents with gastrointestinal symptoms such as vomiting, severe abdominal pain, esophageal irritation, and bloody diarrhea. Chronic exposure, however, has been linked to an elevated risk of cancers affecting the skin, lungs, urinary bladder, and kidneys, along with persistent skin abnormalities, including pigmentation changes and thickening of the skin [23].

Acute arsenic intoxication typically presents with gastrointestinal symptoms, including vomiting, severe abdominal pain, and diarrhea, which may subsequently progress to neurological manifestations such as numbness and tingling of the extremities, muscle cramps, and, in severe cases, fatal outcomes. The earliest manifestations of chronic exposure to high levels of inorganic arsenic—primarily through contaminated drinking water and food—typically appear as skin abnormalities, including pigmentation changes, lesions, and hyperkeratosis of the palms and soles. These effects generally develop after prolonged exposure, often over a period of five years or more, and may precede the onset of skin cancer. Chronic exposure to arsenic is strongly associated with the development of various cancers, especially those affecting the lungs and urinary bladder. Based on extensive scientific evidence, the International Agency for Research on Cancer (IARC) recognizes arsenic and its compounds, including arsenic in drinking water, as carcinogenic to humans. In addition to carcinogenic effects, chronic ingestion of inorganic arsenic has been linked to a range of adverse health outcomes, including developmental effects, diabetes, pulmonary disease, and cardiovascular disorders. Notably, arsenic-induced myocardial infarction has been identified as a significant contributor to increased mortality [24-27].

A field investigation conducted by Kumar et al. (2021) involving the analysis of groundwater and blood samples revealed severe arsenic contamination in the study area, with groundwater arsenic concentrations reaching a maximum of 1908 μg/L [28]. While several groundwater samples exceeded the WHO guideline value of 10 μg/L for drinking water, a few samples contained arsenic concentrations below this permissible limit. Analysis of blood samples indicated that only a limited number of individuals had arsenic levels below the WHO-recommended threshold of 1 μg/L, whereas the majority exhibited elevated blood arsenic concentrations (>1 μg/L) [29]. The high levels of arsenic exposure were reflected in the widespread occurrence of arsenicosis among the affected population, particularly among individuals consuming highly contaminated groundwater. Common clinical manifestations included palmoplantar keratosis, melanosis, hyperpigmentation, raindrop pigmentation, leucomelanosis of the trunk, blackening of the tongue, and the development of tumorous skin lesions. Interviews and clinical examinations further confirmed a high prevalence of dermatological abnormalities, including keratosis of the palms and soles and various forms of skin pigmentation disorders. In addition to skin lesions, affected individuals reported several systemic health problems, including gastritis, liver dysfunction, constipation, loss of appetite, and hormonal imbalance. Notably, signs of keratosis affecting the palms and soles were also observed among children younger than 12 years of age. During the two-year study period, twelve cancer cases were documented, comprising skin cancers (including squamous cell carcinoma and melanoma), bladder, stomach, liver, and breast cancers, as well as hematological malignancies such as leukemia and lymphoma. All diagnosed cancer patients exhibited clinical features consistent with chronic arsenic toxicity.

Rahman et al. (2019) investigated arsenic contamination and its associated health effects in a village located in the Buxar district of Bihar, India. Groundwater samples were collected at random from household hand pumps spaced approximately 50 m apart [30]. Analysis revealed extremely high arsenic concentrations, with a maximum groundwater concentration of 1,929 μg/L. Blood analysis of the exposed residents also indicated substantial arsenic accumulation, with the highest recorded blood arsenic concentration reaching 664.7 μg/L. Chronic consumption of arsenic-contaminated drinking water was associated with a high prevalence of arsenicosis among the study population. Frequently observed clinical manifestations included hyperkeratosis of the palms and soles and hyperpigmentation of the skin. In addition, several individuals presented with enlarged cervical nodules suspected to be associated with lymphoma. The affected population also reported a wide range of systemic health disorders, including gastritis, flatulence, constipation, anemia, loss of appetite, breathlessness, and neurological impairments. Furthermore, the study documented multiple cancer cases, including breast, liver, gallbladder, thyroid, and colorectal cancers, highlighting the serious health consequences of prolonged exposure to arsenic-contaminated groundwater.

Fluoride

The health effects of fluoride are concentration dependent. While a fluoride concentration of around 1 mg/L in drinking water is considered beneficial for reducing the incidence of dental caries [26]. excessive fluoride intake may lead to toxic effects. Long-term exposure to fluoride concentrations ranging from 0.9 to 1.2 mg/L can cause mild dental fluorosis, with disease severity varying according to total fluoride intake from drinking water and other sources. At higher concentrations, fluoride primarily affects the skeletal system, and chronic consumption of water containing 3–6 mg/L fluoride has been associated with skeletal fluorosis, a condition characterized by abnormal changes in bone structure and increased skeletal fragility

Exposure to excessive fluoride during childhood, particularly while teeth are developing, can cause dental fluorosis, which is manifested by enamel discoloration ranging from white opaque streaks to brown or black mottling [27]. Chronic ingestion of high levels of fluoride may further progress to skeletal fluorosis, a debilitating condition characterized by pain and stiffness of the joints, muscle weakness, headaches, and gastrointestinal symptoms during its early stages. Continued fluoride accumulation leads to osteosclerosis, calcification of connective tissues, and damage to the spine, major joints, muscles, and nervous system. Since both dental and skeletal fluorosis are irreversible, limiting fluoride exposure remains the most effective preventive measure. The World Health Organization recognizes long-term consumption of fluoride-rich drinking water as the primary cause of these disorders.

Teotia et al. (1981) reported that the severity of chronic fluoride toxicity is governed primarily by the total daily fluoride intake and the duration of exposure to fluoride-rich drinking water, whereas the contribution of dietary fluoride is generally considered to be comparatively low. Daily fluoride intake is largely influenced by two factors: the fluoride concentration in drinking water and the quantity of water consumed each day. Water consumption, in turn, varies according to several physiological and environmental factors, including body size, dietary habits, ambient temperature, and the level of physical activity. In regions with hot climatic conditions, such as many parts of India, agricultural workers may consume as much as 8 L of water per day, thereby increasing their fluoride intake. Furthermore, the predominantly water-based cooking practices common in Indian households contribute additional fluoride exposure, as most staple foods are prepared using water.

Nitrate

Although nitrate exhibits relatively low toxicity, its conversion to nitrite following ingestion poses significant health risks. Bacterial activity in the mouth and gastrointestinal tract reduces nitrate to nitrite, which oxidizes hemoglobin to methemoglobin, thereby decreasing the oxygen-carrying capacity of blood. While most nitrite is subsequently converted back to nitrate, the remaining fraction can continue to promote methemoglobin formation. Excessive methemoglobin levels (>10%) may cause methemoglobinemia (blue baby syndrome), particularly in infants, resulting in cyanosis and impaired oxygen transport (WHO, 2017). Bottle-fed infants are at greater risk because of their higher water intake relative to body weight and the incomplete development of enzyme systems involved in methemoglobin reduction.

In addition, nitrate can participate in the formation of N-nitroso compounds, including nitrosamines and nitrosamides, which are recognized carcinogens. These compounds are formed through reactions in the acidic environment of the stomach and have been linked to increased cancer risk [31].

CONCLUSIONS

- Arsenic, fluoride, and nitrate contamination in water arises from a combination of natural geochemical processes and anthropogenic activities. Arsenic is mobilized from mineral sources through weathering and redox reactions, while human activities such as agriculture, fossil fuel combustion, and industrial processes significantly enhance its concentration in groundwater. Chronic arsenic exposure is associated with severe health effects, including cardiovascular diseases, skin lesions, and various cancers.
- The dissolution of fluoride-bearing minerals, such as fluorite, apatite, and topaz, is a major natural source of fluoride contamination in groundwater. Lower concentrations of calcium and magnesium with higher alkalinity in soft water enhance fluoride toxicity. Fluoride mobility is governed by clay mineral content, soil pH and concentrations of calcium and phosphorous.

Decreasing levels of fluoride cause dental caries whereas increased level can cause dental and skeletal fluorosis.

- Nitrate contamination is largely driven by agricultural practices, atmospheric deposition, and waste disposal systems. Due to its high mobility, nitrate easily leaches into groundwater. Once ingested, it can be converted into nitrite, which interferes with oxygen transport in blood, leading to methaemoglobinaemia, especially in infants. Additionally, nitrate contributes to the formation of carcinogenic N-nitroso compounds.
- Overall, the widespread occurrence and serious health impacts of these contaminants highlight the need for continuous monitoring, improved water management practices, and effective mitigation strategies to protect public health. Integrated approaches including source control, advanced water treatment technologies, and continuous monitoring are essential to mitigate the risks posed by these contaminants.

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