Bioresources Development Conference (BDC26)
NABDA
Journal of Biotechnology Research
ISSN: 1119-0531
Special Issue Vol. 5(2): (2026)

The Impact of Fluoride on Human Health: A Review

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Article ID: NJBR-BDC26-A011 | Received:13 May, 2026 | Accepted: 18 May, 2026

ABSTRACT

Fluoride is a naturally occurring element widely distributed in the Earth's crust and commonly present in groundwater and surface water systems. Its concentration in drinking water plays a significant role in determining water quality and human health outcomes. At optimal concentrations, fluoride benefits oral health by preventing dental caries and strengthening tooth enamel. However, excessive fluoride exposure resulting from natural geological processes, industrial activities, agricultural runoff, and environmental pollution can lead to serious health and ecological problems. This review examines fluoride's impact on human health, with an emphasis on sources, ecological impacts, and health implications. The review highlights that elevated fluoride concentrations in drinking water are associated with dental fluorosis, skeletal fluorosis, neurological disorders, kidney dysfunction, and other systemic health complications. International organisations such as the World Health Organisation have established guideline values for fluoride in drinking water to minimise health risks while maintaining its benefits.

Key words: Fluoride, Drinking Water, Water quality, Dental Fluorosis, Skeletal Fluorosis.

INTRODUCTION

Fluoride, the negatively charged ionic form of fluorine, is a naturally occurring element that is extensively distributed throughout the Earth's crust and commonly found in rocks, soil, groundwater, and surface water systems (Pandora *et al.*, 2024). Fluoride enters water bodies primarily through the natural weathering and dissolution of fluoride-containing minerals such as fluorite, apatite, and cryolite. In some regions, anthropogenic activities including industrial discharge, agricultural runoff, and water fluoridation programs also contribute to fluoride accumulation in drinking water sources. Due to its widespread occurrence and direct relationship with human health, fluoride concentration in drinking water has become an important global public health issue. Research conducted in Nigeria and other developing countries has shown that prolonged consumption of water containing excessive fluoride concentrations can result in several adverse health conditions, including dental fluorosis, skeletal fluorosis, and other systemic disorders (Hussain *et al.,* 2021).

Dental fluorosis is one of the most common manifestations of chronic fluoride exposure and is characterised by discolouration, mottling, and pitting of tooth enamel, especially when exposure occurs during childhood, when teeth are still developing. In more severe cases, excessive fluoride intake over a prolonged period may lead to skeletal fluorosis, a debilitating condition associated with joint stiffness, bone deformities, ligament calcification, and chronic pain. Beyond these effects, some studies have also linked elevated fluoride exposure to kidney dysfunction, neurological impairment, thyroid abnormalities, and gastrointestinal disturbances. Despite the harmful effects associated with excessive fluoride intake, the beneficial role of fluoride in promoting oral health is well recognised and extensively documented. Fluoride plays a critical role in preventing dental caries by enhancing the remineralisation of tooth enamel and reducing acid-induced demineralisation caused by oral bacteria (Pandora *et al.,* 2024). Fluoride ions interact with calcium and phosphate compounds present in tooth enamel, thereby strengthening the enamel structure and increasing its resistance to bacterial attack and acid dissolution. As a result, populations living

in areas where fluoride concentrations in drinking water are within optimal limits generally experience lower rates of dental decay among children, adolescents, and adults (Akuno, 2019). This protective effect has led many countries to adopt controlled water fluoridation programs as part of public oral health strategies.

The appropriate fluoride level varies across populations and is influenced by several environmental and socioeconomic factors, including climatic conditions, dietary habits, oral hygiene practices, nutritional status, and access to healthcare services (Abdeljawad, 2019). For instance, individuals living in hot climatic regions tend to consume larger quantities of water, thereby increasing their fluoride intake compared to those in cooler climates. Similarly, poor nutrition and inadequate calcium intake may enhance fluoride toxicity and increase susceptibility to fluorosis. To balance the beneficial and harmful effects of fluoride exposure, the World Health Organisation recommends fluoride concentrations in community drinking water supplies between 0.5 and 1.0 mg/L, which is considered sufficient to prevent dental caries while minimising the risk of adverse health effects (World Health Organisation, 2011). Concentrations above this recommended range may significantly increase the likelihood of fluorosis and other fluoride-related disorders.

In contrast, concentrations below the optimal level may reduce protection against dental decay. Rocks and minerals containing fluoride compounds contribute substantially to natural fluoride contamination through weathering and leaching processes, particularly in groundwater systems (Akuno, 2019). Seasonal variations, water temperature, soil composition, and human activities may also influence fluoride distribution in aquatic environments. Consequently, understanding how fluoride concentrations affect water quality and human health is essential for developing effective public health policies, monitoring programs, and intervention strategies that optimise fluoride exposure while minimising associated health risks.

SOURCES OF FLUORIDE IN WATER

Fluoride occurs naturally in the environment and is widely distributed in water, rocks, soil, plants, and the atmosphere. Both natural geological processes and anthropogenic activities primarily influence the presence of fluoride in water sources. Fluoride contamination of water has become a major environmental and public health concern because its concentration determines whether it exerts beneficial or harmful effects on living organisms. Understanding the various sources of fluoride in water is therefore essential for effective water quality management and public health protection.

NATURAL SOURCES OF FLUORIDE IN WATER

Natural geological processes constitute the major source of fluoride contamination in water systems worldwide. Fluoride-bearing minerals are abundant in the Earth's crust, and their gradual weathering and dissolution release fluoride ions into groundwater and surface water bodies (Edmunds and Smedley, 2013). The extent of fluoride contamination largely depends on an area's geological composition, climatic conditions, water-rock interaction, and hydrogeological characteristics. One of the major natural sources of fluoride is the weathering of fluoride-containing rocks and minerals such as fluorite (CaF_2), apatite [$Ca_5(PO_4)_3F$], cryolite (Na_3AlF_6), mica, amphiboles, and hornblende (Pandora et al., 2024). These minerals gradually dissolve when exposed to water, releasing fluoride into surrounding groundwater systems. Groundwater sources, particularly boreholes and wells, are more susceptible to fluoride accumulation because groundwater remains in prolonged contact with rocks and minerals underground, thereby increasing the rate of mineral dissolution. In many arid and semi-arid regions, high fluoride concentrations in groundwater are associated with intense evaporation and low rainfall. High temperatures increase evaporation rates, concentrating dissolved fluoride ions in groundwater aquifers (Hussain *et al.,* 2021).

Additionally, limited groundwater recharge in dry regions prolongs the residence time of water within aquifers, enhancing fluoride dissolution from geological formations. Volcanic activity is another important natural source of fluoride in water. Volcanic eruptions release fluoride-rich gases, ash, and lava into the environment, which subsequently contaminate nearby water bodies through atmospheric deposition and runoff (Fawell *et al.,* 2006). Areas located near volcanic regions often exhibit elevated fluoride levels in groundwater and surface waters due to the leaching of volcanic materials. Geothermal activities also contribute significantly to fluoride contamination. Hot springs and geothermal waters usually contain high concentrations of fluoride because heated groundwater

dissolves fluoride-containing minerals more efficiently at elevated temperatures (Edmunds and Smedley, 2013). Communities relying on geothermal water sources for domestic purposes are therefore at increased risk of fluoride exposure.

Furthermore, soil composition plays a critical role in determining fluoride levels in water. Soils derived from fluoride-rich parent materials can release fluoride into water through leaching, especially during rainfall and irrigation. In agricultural regions, infiltration of fluoride-rich soil particles into groundwater may further elevate fluoride concentrations.

ANTHROPOGENIC SOURCES OF FLUORIDE IN WATER

Beyond natural processes, human activities significantly contribute to fluoride contamination in water systems. Rapid industrialisation, urbanisation, and agricultural expansion have increased the release of fluoride compounds into the environment, affecting both surface and groundwater quality (Hussain *et al.,* 2021).

Industrial Effluents

Industrial discharge is one of the most significant anthropogenic sources of fluoride pollution. Industries such as aluminium smelting, steel manufacturing, glass production, ceramic processing, brick manufacturing, fertiliser production, and coal-fired power plants release fluoride-containing waste into the environment (Ayoob and Gupta, 2006). Wastewater from these industries often contains high concentrations of fluoride, which may enter nearby rivers, lakes, and groundwater systems if not adequately treated before disposal. Phosphate fertiliser industries are major contributors because the phosphate rocks used in fertiliser production naturally contain fluoride compounds. During fertiliser manufacturing, fluoride is released into industrial effluents and atmospheric emissions, which may subsequently contaminate water bodies through runoff and precipitation (Pandora *et al*., 2024).

Agricultural Activities

Agricultural practices also contribute to fluoride contamination in water. The use of phosphate fertilisers and certain pesticides increases fluoride concentrations in soils and agricultural runoff. Fluoride-containing fertilisers gradually dissolve and infiltrate into groundwater or are transported into nearby rivers and lakes during rainfall events (Hussain *et al*., 2021). Continuous and excessive fertiliser application may therefore lead to long-term fluoride accumulation in aquatic ecosystems. Livestock farming can further contribute indirectly to fluoride pollution through the disposal of animal wastes containing fluoride residues derived from feed supplements and water sources.

Domestic and Municipal Sources

Municipal wastewater and domestic sewage may also contribute to fluoride contamination, especially in densely populated urban areas. Household products such as toothpaste, detergents, pharmaceuticals, and cleaning agents often contain fluoride compounds that eventually enter sewage systems (Fawell *et al.,* 2006). In areas with inadequate wastewater treatment facilities, these fluoride-containing wastes may contaminate surface and groundwater resources. Additionally, improper disposal of solid wastes and landfill leachates may introduce fluoride into surrounding soils and groundwater systems. As rainwater percolates through waste materials, fluoride compounds dissolve and migrate into nearby water sources.

Artificial Water Fluoridation

In many countries, controlled fluoridation of public water supplies is intentionally carried out to reduce dental caries and improve oral health. Water fluoridation involves adding fluoride compounds such as sodium fluoride, sodium fluorosilicate, or fluorosilicic acid to drinking water systems (WHO, 2011). Although fluoridation programs provide significant dental health benefits when properly regulated, poor monitoring or excessive fluoridation may cause fluoride concentrations to exceed recommended limits, increasing the risk of fluorosis and other health complications.

Environmental Factors Influencing Fluoride Distribution in Water

Several environmental factors influence fluoride concentration and distribution in water sources. These factors include pH, temperature, alkalinity, calcium concentration, and water residence time. Alkaline water conditions generally favour fluoride dissolution from rocks and minerals, while low

calcium concentrations enhance fluoride mobility because calcium normally precipitates fluoride as insoluble calcium fluoride (Edmunds and Smedley, 2013). Seasonal variations may also affect fluoride concentrations. During dry seasons, reduced water volume and increased evaporation can lead to higher fluoride concentrations, whereas dilution during rainy seasons may temporarily reduce fluoride levels in surface waters.

INFLUENCE OF FLUORIDE ON PHYSICOCHEMICAL WATER QUALITY PARAMETERS

Effect on pH and Alkalinity

Fluoride concentration in water is closely related to pH and alkalinity. In alkaline conditions, fluoride-bearing minerals dissolve more readily, increasing fluoride concentrations in water (Edmunds and Smedley, 2013). Water bodies with high alkalinity tend to support greater fluoride mobility because hydroxyl ions enhance fluoride desorption from mineral surfaces. Consequently, groundwater in alkaline environments often contains elevated fluoride concentrations. pH changes also influence fluoride toxicity and bioavailability. Under alkaline conditions, fluoride remains more soluble and mobile, thereby increasing its persistence in water systems and its potential effects on aquatic organisms and human health (Hussain *et al.,* 2021).

Effect on Total Dissolved Solids (TDS)

High fluoride concentrations are frequently associated with increased total dissolved solids (TDS) in water. TDS refers to the total amount of dissolved inorganic and organic substances present in water, including minerals, salts, and ions. Areas with fluoride-rich groundwater often exhibit elevated TDS levels because fluoride contamination commonly occurs alongside other dissolved minerals such as sodium, calcium, bicarbonates, and sulfates (Ayoob and Gupta, 2006). Excessive TDS may reduce water palatability and its suitability for drinking and irrigation.

Effect on Electrical Conductivity

Electrical conductivity measures water's ability to conduct an electric current, which depends on the concentration of dissolved ions. Because fluoride exists as a dissolved ion, elevated fluoride concentrations increase electrical conductivity in water bodies (Pandora *et al*., 2024). High conductivity values may indicate excessive mineralisation and poor water quality, particularly in groundwater systems affected by geological contamination.

Effect on Water Hardness

Fluoride interacts with calcium and magnesium ions, which are the major contributors to water hardness. In some cases, fluoride forms insoluble compounds such as calcium fluoride, thereby influencing water hardness and mineral balance (Fawell *et al.,* 2006). Areas with low calcium concentrations are more susceptible to high fluoride mobility because calcium normally reduces fluoride solubility through precipitation reactions. Consequently, soft groundwater often contains higher fluoride concentrations than hard water.

HEALTH EFFECTS OF FLUORIDE

The World Health Organisation has established guidelines to regulate fluoride levels in drinking water, recommending concentrations that balance its protective effects against dental caries with the risk of toxicity. Understanding the health effects of fluoride is therefore crucial for developing appropriate water quality standards and preventive health strategies.

Beneficial Health Effects of Fluoride

Prevention of Dental Caries

One of the most well-established benefits of fluoride is its role in preventing dental caries (tooth decay). Fluoride enhances remineralisation of tooth enamel and inhibits the demineralisation process caused by acids produced by oral bacteria (Featherstone, 2000). Tooth enamel is primarily composed of hydroxyapatite crystals, which are susceptible to dissolution in acidic environments. Fluoride interacts with these crystals to form fluorapatite, a more stable and acid-resistant compound. This protective mechanism significantly reduces the incidence of dental caries, particularly in children and adolescents. Communities with optimal fluoride levels in drinking water have consistently shown lower rates of tooth decay compared to areas with insufficient fluoride exposure (Pandora *et al*., 2024). For this reason, controlled water fluoridation programs have been widely implemented as a cost-effective public health measure.

Role in Bone Development

Fluoride also contributes to bone mineralization by stimulating osteoblastic activity (bone-forming cells) and enhancing calcium deposition in bone tissues (Ayoob and Gupta, 2006). At low concentrations, fluoride may improve bone density and strength, which has led to its past use as a therapeutic agent for osteoporosis. However, the beneficial effects on bone are highly dose-dependent, and excessive intake may produce the opposite effect, leading to skeletal abnormalities.

ADVERSE HEALTH EFFECTS OF EXCESS FLUORIDE

Despite its benefits, chronic exposure to high levels of fluoride can result in a wide range of health problems. These effects are primarily associated with long-term consumption of fluoride-contaminated drinking water.

Dental Fluorosis

Dental fluorosis is one of the earliest and most visible signs of excessive fluoride intake. It occurs when children are exposed to high fluoride concentrations during the formative stages of tooth development, typically between infancy and eight years of age (WHO, 2011). Clinically, dental fluorosis is characterised by white streaks or opaque patches on tooth enamel, brown stains and discolouration in moderate cases. Pitting, surface irregularities, and enamel damage in severe cases. Although mild fluorosis is primarily a cosmetic concern, severe forms can compromise dental function and increase susceptibility to tooth wear. The prevalence of dental fluorosis is strongly correlated with fluoride concentrations exceeding recommended limits, particularly above 1.5 mg/L (Akuno, 2019).

Skeletal Fluorosis

Skeletal fluorosis is a more serious condition resulting from prolonged ingestion of high fluoride levels over several years or decades. It involves fluoride accumulation in bones, leading to structural and functional changes (Ayoob and Gupta, 2006). Skeletal fluorosis typically progresses in stages, including a preclinical stage with no obvious symptoms and slight biochemical changes in bones. The clinical stage involves joint stiffness and pain, reduced mobility, and muscle weakness. The advanced stage includes bone deformities, ligament calcification, and severe restriction of movement (crippling fluorosis). Skeletal fluorosis is particularly prevalent in regions with high natural fluoride concentrations in groundwater, where populations rely on untreated water sources for drinking.

Neurological and Cognitive Effects

Emerging research suggests that excessive fluoride exposure may have neurotoxic effects, particularly in children. Several epidemiological studies have reported an association between high fluoride intake and reduced intelligence quotient (IQ), impaired cognitive development, and learning difficulties (Grandjean and Landrigan, 2014). Fluoride may cross the blood-brain barrier and interfere with neurotransmitter function, oxidative stress mechanisms, and brain development. Although the exact mechanisms remain under investigation, concerns about fluoride's potential neurotoxicity have prompted increased scrutiny of fluoride exposure levels, especially in vulnerable populations.

Effects on the Renal System

The kidneys play a central role in fluoride excretion. Excessive fluoride intake can place a significant burden on renal function, particularly in individuals with pre-existing kidney disease (Fawell *et al.,* 2006). High fluoride exposure may reduce fluoride excretion efficiency, lead to fluoride accumulation, and increase the risk of toxicity. Individuals with impaired kidney function are therefore more susceptible to fluoride-related health effects, as their ability to eliminate fluoride is reduced.

Endocrine and Thyroid Effects

Fluoride has been shown to interfere with endocrine system function, particularly the thyroid gland. High fluoride concentrations may inhibit iodine uptake and disrupt thyroid hormone production, potentially leading to hypothyroidism (Susheela, 2018). Symptoms associated with fluoride-induced thyroid dysfunction include fatigue, weight gain, depression and reduced metabolic rate. In iodine-

deficient populations, fluoride's impact on thyroid health may be more pronounced.

Gastrointestinal Effects

Acute exposure to high fluoride levels can cause gastrointestinal irritation, resulting in symptoms such as nausea, vomiting, abdominal pain and diarrhoea. These symptoms are often observed in cases of accidental ingestion of high fluoride doses, such as contaminated water or industrial exposure (Ayoob and Gupta, 2006).

Reproductive and Developmental Effects

Some studies have suggested that excessive fluoride exposure may affect reproductive health and fetal development. Reported effects include reduced fertility rates, hormonal imbalances and adverse pregnancy outcomes. Fluoride may also affect fetal bone and tooth development when exposure occurs during pregnancy. However, more research is needed to fully understand these relationships and establish causal links (Meenakshi and Maheshwari, 2006).

CONCLUSION

Fluoride is an essential naturally occurring element that significantly influences water quality, ecosystem stability, and human health. At optimal concentrations, fluoride plays a beneficial role in preventing dental caries and contributes to strengthening tooth enamel and bone development. However, excessive fluoride concentrations in drinking water pose serious environmental and public health challenges. High fluoride exposure has been associated with dental fluorosis, skeletal fluorosis, neurological disorders, kidney dysfunction, and other systemic health complications.

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How to Cite This Article

Mamudu, S. B., Fabian, Z. L., Aqiba, R. U., Useni, S. S., Dalhatu, A., Azimat, A., Maspara, G. I., Japheth, J., Akinnagbe, E. S., Lumi, G. D., Nandom, N., & Umar, A. K. (2026). The Impact of Fluoride on Human Health: A Review. NABDA Journal of Biotechnology Research, 5(2), 98-103.