THE SOIL POLLUTION

Fluoride Contamination in Drinking Water and Its Pathological Impacts on Human Dental and Skeletal Systems: A Systematic Review

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Published November 2026

Abstract

Fluoride is a naturally-occurring mineral that can be found in drinking water sources, including groundwater. When present at the correct levels, fluoride contributes to the prevention of dental caries, but it can have harmful health impacts when present in high levels and for extended periods, especially on dental and skeletal tissues, when consumed in drinking water. A systematic review is intended to assess the scientific literature available on fluoride contamination in drinking water and its pathological effects to human dental and skeletal systems, with a critical evaluation. The review addresses the link between fluoride concentration, exposure time and health consequences. Dental fluorosis can occur: enamel discoloration, hypomineralization, mottling and, in severe cases, damage to the enamel surface may occur as a result of excessive fluoride intake during tooth development. Likewise, high levels of fluoride in the long-term may cause skeletal fluorosis that is linked to higher bone density, osteosclerosis, joint stiffness, chronic pain, limited mobility and skeletal deformities. The studies showed that the severity of the fluorosis is dependent on dose, age, nutritional status, climatic factors and susceptibility. Epidemiological data show positive correlations between high fluoride concentration of drinking water and dental and skeletal fluorosis, especially in communities relying on naturally occurring groundwater fluoride. The World Health Organization (WHO) has recommended a guideline fluoride level of 1.5 mg/L for drinking water, but the fluoride exposure conditions must also be taken into account, as well as the total fluoride intake. The study emphasizes the need for routine surveillance and mapping of fluoride polluted areas, and the application of successful defluoridation methods to reduce the health hazards associated with fluoride and ensure public health protection.

Keywords: Fluoride contamination; drinking water; dental fluorosis; skeletal fluorosis; enamel hypoplasia; osteosclerosis; fluoride toxicity; public health; review

1 Introduction

1.1 Background of fluoride and its occurrence in nature

Fluoride is an inorganic naturally occurring ion of the element fluorine that is present in earth's crust, soil, rocks and water bodies. It enters the environment, mainly by weathering and dissolution of the fluoride bearing minerals fluorite (CaF_2), fluorapatite [$Ca_5 (PO_4)_3F$] and certain mica minerals, as well as by weathering and dissolution of cryolite (Na_3AlF_6). The geological formation in which groundwater is found can be a source of fluoride enrichment if the water remains in contact with the minerals for a long time.Geological sources of fluoride enrichment can include prolonged contact between groundwater and geological formations containing mineral sources of fluoride. Water quality conditions, such as geology, groundwater chemistry, water pH, water temperature, and other dissolved ions, greatly influence the concentration of fluoride in drinking water (Ayoob & Gupta,

2006). The sources of fluoride in the environment vary in concentration and the presence of fluoride in drinking water has important health implications. When present in small amounts, fluoride is beneficial to dental health as it increases the hardness of tooth enamel and decreases the risk of dental caries. But high fluoride levels in water can have negative health impacts, especially dental and skeletal fluorosis, if consumed over long periods of time. Hence, the knowledge of the natural occurrence, environmental distribution and health effects of fluoride is very important for the safety of drinking water.

1.2 Sources of fluoride contamination in drinking water

The sources of water contamination by fluoride include natural geological processes, but also human activities. These sources make different contributions in different geographic areas depending on the level of industrial activity and environmental conditions.

1.2.1 Natural sources (rocks, minerals and groundwater)

The primary sources of fluoride contamination in groundwater are believed to be natural geological sources. When the fluoride-rich minerals (fluorite, apatite and amphiboles) dissolve, fluoride ions are released into surrounding groundwater. High evaporation rates, low rates of groundwater recharge, high pH and long residence time of water in the rocks can also increase fluoride levels, especially in arid and semi-arid areas. High pH and low calcium availability in groundwater can promote dissolve and accumulation of fluoride. This means that people who use untreated deep well or borehole water for drinking and other purposes might suffer long-term exposure to high fluoride levels (Ayoob & Gupta, 2006).

1.2.2 Anthropogenic sources (industrial discharge, fertilizers and other activities)

Fluoride contamination may also be caused by human activity in surface and ground water. Some industrial processes like those for the manufacture of phosphate fertilizers, aluminium, glass, brick and some chemical industries may emit effluents containing fluoride in the environment. The application of phosphate fertilisers containing fluoride impurities can be a source of agricultural activities. Inappropriate handling of industrial waste and poor wastewater treatment can be additional sources of elevated fluoride levels in water resources. Many areas with high fluoride groundwater concentrations have naturally high concentrations, however, human activities can also cause local contamination and raise the potential for human exposure.

1.3 Importance of fluoride in human health

Fluoride is a key component of dental health, especially as teeth are forming and also in the life cycle. It encourages remineralisation of enamel, increases resistance to acid mediated mineral dissolution of enamel and reduces the activity of specific oral bacteria that produce acids. Such mechanisms help to prevent dental caries and maintain healthy teeth. Fluoride can be found in drinking water, toothpaste, mouthwash and some foods.

WHO (2022) has recommended a guideline concentration for fluoride in drinking water of 1.5 mg/L (ppm). This value takes into account the benefits versus the potential risks of consuming too much fluoride. The correct concentration, however, is dependent on climatic conditions, water use and fluoride sources from other water supplies. Therefore, continuous monitoring of drinking water fluoride concentrations is crucial, particularly in those communities relying on groundwater as their main source of drinking water.

1.4 Beneficial and harmful effects of fluoride

The effect of fluoride on human health is double-sided based on the concentration, exposure time, and the way in which it's consumed. Fluoride can significantly benefit the teeth when used at the proper concentrations, by promoting remineralization of the enamel and limiting the formation of dental caries. It strengthens the enamel and increases resistance to acids formed by oral microorganisms that is critical to maintaining tooth integrity. Therefore, fluoride exposure in a controlled manner, e.g., through drinking water and dental hygiene products, is considered to be a very good preventive strategy against tooth decay. But high and long term fluoride intake can lead to fluorosis, a long term problem of minerals in the tissues, especially the teeth and bones. Dental fluorosis occurs when there is an excess of fluoride during tooth formation, causing a disturbance in enamel mineralization. It manifests as white faint lines or as opaque patches, or in severe cases as brown coloration, enamel pitting and structural damage. A flux results in abnormal bone mineralization, increased bone density, joint stiffness, chronic pain, limited mobility and, in late stages, skeletal deformities. Children who ingest excessive levels of fluoride during tooth formation are more likely to develop dental fluorosis, while adults who ingest excessive amounts of fluoride over prolonged periods are more likely to develop skeletal effects (World Health Organization[WHO], 2022).

1.5 Global distribution of fluoride contamination in drinking water

Drinking water contamination with fluoride is a major environmental and public health problem in several regions of the world. Countries like India, China, Pakistan, Bangladesh, Ethiopia, Kenya, Tanzania, Mexico, Argentina, and some parts of the United States have reported naturally-occurring fluoride in their groundwater. Geological formations, climatic environment, groundwater chemistry and water rock interaction are significant factors that are linked to the geographical distribution of fluoride contamination. The arid and semi-arid regions are especially sensitive since, due to high evaporation rates and low groundwater recharge, fluoride may build up in groundwater.

In Africa, fluoride levels have been reported to be high in volcanic rocks and volcanic activity in Ethiopia, Kenya and Tanzania. Likewise, some parts of China and South Asia have fluorosis as a public health problem caused by the drinking of fluoride-contaminated water.Likewise, long-term exposure to fluoride contaminated groundwater causes endemic fluorosis in some parts of China and South Asia. Levels of contamination are not uniform across the country nor are they the same in adjacent communities. WHO (2022) recommends fluoride concentration of 1.5 mg/L for drinking water use, and high concentrations, especially when in use for a long time, can lead to skeletal fluorosis.WHO (2022) recommends that the fluoride concentration in drinking water should be 1.5 mg/L, and higher concentrations can lead to dental fluorosis, while very high concentrations can lead to skeletal fluorosis with long-term exposure. These differences highlight the need for regional monitoring of water quality and for designing regional strategies to defluoridate the water.

1.6 Fluoride contamination in India

India is one of the countries where naturally occurring fluoride contamination in groundwater is a significant problem. It is especially pronounced in dry and semi-dry areas where underground water resources are heavily utilized for potable and household uses. Several States including Rajasthan, Gujarat, Andhra Pradesh, Telangana, Karnataka, Tamil Nadu, Madhya Pradesh, Haryana, Punjab, Uttar Pradesh and Bihar have reported water fluoride level exceeding the recommended guideline for drinking water. This contamination is related to geological formation with fluoride bearing minerals, lack of ground water recharge and extended interaction between water and rock (Ali et al., 2019).

Ali et al. (2019) carried out a systematic review and meta-analysis that included 63 studies and 57,381 samples of groundwater samples, and found that the mean fluoride concentration for the Indian groundwater samples was 2.37 mg/L. The study further revealed that the fluoride levels were significantly higher in rural areas as compared to urban areas. A more recent country-wide assessment of groundwater based on around 660,000 observations indicated that concentration of fluoride was significantly variable in both spatial and temporal domains: 8.65% of pre-monsoon samples and 7.10% of post-monsoon samples above the guideline value of 1.5 mg/L (Saha et al., 2024).

However, the effects of over exposure to fluoride in India are more pronounced in those communities who rely on untreated groundwater. Exposure to polluted water over time may cause dental fluorosis in children and skeletal fluorosis in adults, which may impact the health, working productivity and well-being of individuals. The state of Uttar Pradesh is also one of the states with fluoride-contaminated groundwater, and region-wise assessment and regular monitoring is of significance from the public health perspective.

In response to this, the Government of India launched the National Programme for Prevention and Control of Fluorosis (NPPCF) which works on the principles of disease surveillance, laboratory diagnosis, health education, prevention and clinical management of the affected people. The programme also focuses on the surveillance of the fluoride concentration of the drinking water and on efforts to make alternative water sources available (Directorate General of Health Services, 2025).

In general, fluoride pollution is a significant crossroads of environmental pollution, groundwater quality and human health. It is affected by the concentration, duration and age of exposure, as well as nutrition and the environment. Thus, systematic monitoring of fluoride concentrations in drinking water and their relationship with dental and skeletal deformities is vital to planning preventive and public health measures.

2 Review of literature

2.1 Physicochemical properties of fluoride

Fluoride is the ion form of a very reactive halogen, fluorine, in group 17 of the periodic table. Present in the environment, especially in rocks, minerals, soil and in groundwater. Fluoride has a high electronegativity and is easily combined with other elements such as calcium, sodium and magnesium. It is normally found as the fluoride ion (F-). Concentrations in groundwater are dependent on geology, pH, temperature and water – rock interactions. Fluoride has beneficial effects at suitable concentrations for dental health, but may be toxic to humans if present at high concentrations for extended periods of time (WHO, 2017).

2.2 Sources and mechanisms of fluoride contamination in groundwater

Groundwater may be contaminated with fluoride by natural and anthropogenic sources. Sources: Dissolution of minerals containing fluoride, like fluorite, apatite and mica. The origins of high fluoride levels are geochemical, such as mineral weathering, ion exchange and long-term interaction between groundwater and fluoride bearing rocks. Sources include industrial effluents, phosphate fertilization, aluminium production and some mining operations. In areas where the geology is characterized as containing fluoride and where other available sources of drinking water are scarce, groundwater contamination can be important (Ayoob & Gupta, 2006).

2.3 Fluoride concentration in drinking water and permissible limits

The concentration of fluoride in drinking water is a significant indicator of fluoride exposure to humans. Considering its health effects, the WHO guidelines are 1.5mg/L fluoride in drinking water. The Bureau of Indian Standards (BIS) prescribes 1.0 mg/L as acceptable limit and 1.5 mg/L as the permissible limit in the absence of alternative source in India (BIS, 2012). In the event that these concentrations of fluoride are exceeded, the water may be more likely to cause dental and skeletal fluorosis, especially in populations that drink contaminated groundwater for a long period.

2.4 Human exposure pathways and fluoride absorption

Fluoride is a ubiquitous contaminant in which human exposure primarily occurs through drinking water, food, beverages, dental products, and in some occupations. In areas of fluoride endemicity drinking water is usually the primary source. Once swallowed, soluble fluoride is absorbed primarily in the stomach and small intestine, with about 75–90% of it absorbed. Chemical form, gastric acidity, and calcium and other dietary factors are all important to absorption (National Research Council, 2006).

2.5 Fluoride metabolism, distribution, and excretion

Once absorbed, fluoride is carried in the bloodstream to other parts of the body. 99% of retained fluoride is deposited in mineralized tissues, especially in bones and teeth. A fraction of fluoride absorbed is incorporated into developing teeth and skeletons and the other fraction is excreted primarily via the kidneys in urine. Fluoride retention and elimination is affected by renal function, age and skeletal development (National Research Council, 2006).

2.6 Mechanism of fluoride toxicity in the human body

Fluoride toxicity occurs when excessive fluoride levels are deposited in the mineralized tissues and disrupt normal physiological functions. Too much fluoride in dental tissues will interfere with the function of the ameloblast leading to enamel under-mineralization and dental fluorosis. White streaks, opaque patches, brown discoloration and, in more severe cases, enamel pitting may be seen clinically. Fluoride ion replaces calcium and hydroxyapatite in the bone resulting in changes to bone mineralization, density, and remodelling. If it builds up over time it can lead to osteosclerosis, stiffening, bone pain, and bone deformity. Too much fluoride can also cause oxidative stress and disrupt enzyme functions in cells(National Research Council, 2006; WHO, 2022).

2.7 Factors influencing fluoride toxicity

There are a number of biological, nutritional and environmental factors that can affect fluoride toxicity: Age/gender: Children are especially vulnerable to dental fluorosis due to the fact that teeth are still developing. Overexposure with excessive fluoride for long periods of time can cause skeletal fluorosis in adults. Susceptibility may differ between males and females as a result of differences in exposure and physiology. Nutritional status: Malnourished people and those with low levels of certain minerals may be more susceptible to fluoride toxicity. Both the quality of diet and the effect of the diet on fluoride absorption, retention, and action on mineralized tissues can have an impact. Duration of exposure: Fluoride can accumulate and cause chronic dental and skeletal problems when high levels of fluoride are present continuously over a number of years. Total fluoride intake: Fluoride from food, beverages, using dental products and other environmental sources will affect toxicity in addition to drinking water concentration. Calcium and vitamin D status: Calcium affects the

absorption of fluoride by forming poorly soluble compounds and vitamin D is important for calcium and phosphorus metabolism and bone mineralization. Deficiencies can have negative impacts on bone health. Daily fluoride intake may be higher in warmer climates due to the increased water used. Other factors such as geological characteristics, groundwater chemistry and local dietary habits also affect exposure levels. In general, fluoride toxicity is a complex process, affected by factors such as dosage, exposure period, nutritional status, and susceptibility (WHO, 2017, 2022).

3 Pathological impacts of fluoride on the human dental system

3.1 Introduction to dental fluorosis

Fluorosis of the teeth is a developmental defect of the enamel that results from too much fluoride during tooth development. It is most common when fluoride is consumed in drinking water, food, or other sources when a child is still in their developing permanent teeth. If fluoride levels are higher than recommended, they could affect normal enamel development, causing changes in the appearance, structure and mineralization of enamel. Dentally, fluorosis appears as white opaque patches, brown coloration and severe cases, as pitting and enamel damage (DenBesten & Li,2011).

3.2 Mechanism of fluoride-induced enamel toxicity

Too much fluoride disrupts the biological mechanism of amelogenesis, which is the formation of enamel. In this process, ameloblasts control the secretion and maturation of enamel proteins and the deposition of minerals into enamel. Ameloblast activity is affected by high fluoride concentrations, intracellular signalling is disturbed, and removal of enamel matrix proteins is affected. This makes it impossible for enamel crystals to form properly, which makes it more porous and less complete (DenBesten & Li, 2011).

3.3 Clinical manifestations of dental fluorosis

Dental fluorosis appears in different intensities, depending on the dose, time and stage of development of fluoride exposure.

- **Mild:** Small white opaque lines or spots on the surface of the tooth enamel, but no structural damage.
- **Moderate:** White discoloration is more extensive and may have some brown staining and increase in enamel opacity.
- **Severe:** Surface irregularities, enamel pitting, brown or dark discoloration and loss of enamel structure.

3.4 Histopathological changes in dental enamel

Histopathologically, fluorotic enamel is characterized by its increased subsurface porosity and irregular mineral distribution. The outer enamel layer can be relatively mineralized while the deeper layers of enamel are hypomineralized. These changes alter the translucency of the enamel and give the typical white opaque appearance to the enamel that is associated with the fluorosis lesion.

3.5 Effects on ameloblasts and enamel mineralization

The cells that develop the enamel are highly specialized cells called ameloblasts. They become affected by excess fluoride by affecting their metabolic functions, protein secretion and maturation

activities. This disturbance causes not only a delay in the growth of enamel crystals, but also an impediment in the deposition of calcium and phosphate, resulting in muscle degradation of enamel and its compromising integrity.

3.6 Changes in enamel structure, porosity, and hardness

Changes brought about by fluoride result in higher porosity, especially at the subsurface level of enamel. Extensive fluorosis may cause the enamel to be less hard and less mechanically strong, predisposing it to post-eruptive enamel breakdown, abrasion and surface damage.

3.7 Dental fluorosis and its impact on oral health and quality of life

Dental fluorosis may have an impact on dental health and mental health. Severe cases can lead to increased tooth sensitivity, enamel breakdown and even esthetic issues. Discoloration may have a damaging impact on self-esteem, social interaction, and self-confidence, especially in children and adolescents. As such, dental fluorosis is not only a clinical dental disease, but it is also a public health problem in fluoride contaminated groundwater communities.

3.8 Diagnostic criteria and assessment methods

Dental fluorosis is usually diagnosed by visualizing the tooth enamel in the clinic. There are two popular assessment techniques.

- **Dean's Fluorosis Index:** This index was developed by Dean (1942) to categorize dental fluorosis as normal, questionable, very mild, mild, moderate, and severe. It has been extensively adopted in epidemiological surveys for the assessment of fluorosis prevalence and severity.
- **Thylstrup–Fejerskov Index (TFI):** This index determines the clinical appearance and the level of enamel changes on a scale from 0 to 9, where 0 represents no changes and 9 represents the most severe fluorosis. It offers more specific evaluation of lesions of the teeth and severity of the lesions (Thylstrup & Fejerskov, 1978).

A high exposure of fluoride at the time of tooth development can cause substantial changes in enamel structural integrity, mineralization, and formation. Early diagnosis, periodic monitoring of fluoride concentrations in drinking water and preventive measures are crucial to mitigate dental fluorosis burden.

4 Pathological impacts of fluoride on the human skeletal system

4.1 Introduction to skeletal fluorosis

Skeletal fluorosis is a chronic metabolic bone disease due to exposure to high levels of fluoride for long periods of time, mainly drinking water. Fluoride also deposits in mineralized tissues, such as bone and teeth, with changes in bone structure, density and normal function. The severity of SF is dependent upon the level of fluoride, duration of exposure, nutritional condition, age, and susceptibility of the individual. Consumption of fluoride containing groundwater over a long time is a serious public health issue in endemic areas (WHO, 2022).

4.2 Mechanism of fluoride accumulation in bones

Once ingested, fluoride travels into the bloodstream and is transported in the blood to all parts of the body. The body stores about 99% of the fluoride that it retains in calcified tissues, including bones

and teeth. Fluoride gets trapped into hydroxyapatite crystals and substitutes the hydroxyl groups of hydroxyapatite with fluoride groups to create fluorapatite. Ongoing deposition affects the mineralization and remodeling of bone, which can lead to excessive bone deposition and abnormal skeletal architecture (National Research Council, 2006).

4.3 Effects of fluoride on bone metabolism

Excessive fluoride exposure is a factor that impacts osteoblasts (bone forming cells) and osteoclasts (bone breaking cells). Fluoride could encourage osteoblastic activity, which leads to the formation of more bone, and more mineral material per bone unit. Too much stimulation can upset the bone formation to resorption ratio, however, causing abnormal and weak bone. Therefore, it does not necessarily equate with good bone strength.

4.4 Histopathological and radiological changes in bones

Histopathology can show change in trabecular architecture, abnormal mineralization, increased osteoid formation, and cortical thickening. Generalized osteosclerosis, increased bone density, calcification of the interosseous membranes and ligamentous ossification are common radiological features. These abnormalities can be similar to other skeletal conditions, sometimes making the diagnosis in the clinic difficult.

4.5 Clinical manifestations of skeletal fluorosis

The clinical symptoms typically develop in three phases:

- **Early stage:** Joint pain that is frequent or persistent, as well as joint stiffness, muscle weakness and back and extremity discomfort.
- **Moderate stage:** Continuous joint stiffness, lack of joint motion, decreased flexibility, and some radiological changes of increased bone density.
- **Advanced stage:** Severe deformities of the skeleton, limited mobility, stiffness of the spine and neurological problems due to compression of the surrounding neural structures.

4.6 Osteosclerosis and abnormal bone formation

Advanced skeletal fluorosis is characterised by osteosclerosis. Glycoside is a drug used to treat diabetes, which can have the adverse effect of causing excessive fluoride poisoning, causing thickened and denser bones. However, the microarchitecture of these bones may have changed and the mechanical efficiency may have decreased, making them more susceptible to skeletal complications.

4.7 Effects on joints, ligaments, and mobility

Fluoride poisoning can lead to calcification and ossification of ligaments, joint capsules and interosseous membranes. These alterations make joints more inflexible and cause chronic pain, stiffness and limited motion. Involvement of the spine can significantly affect a person's functional capacity and independence in life.

4.8 Neurological complications associated with advanced skeletal fluorosis

In advanced skeletal fluorosis, neurological effects can occur when an excess of bone formation and/or ligament calcification constrict the opening of the spinal canal or the neural foramina. When the

spinal cord and nerve roots are compressed it can cause numbness, tingling, muscular weakness, trouble walking and in severe cases, paralysis.

4.9 Effects on bone strength and skeletal architecture

Fluoride-induced osteosclerosis may result in a higher radiologic score, but not necessarily better bone quality. Inappropriate mineralization and changes in the arrangement of the trabeculae might affect the mechanical strength and elasticity of the bone and lead to pain, deformity and limited mobility.

4.10 Diagnostic methods for skeletal fluorosis

Diagnosis includes clinical history, fluoride concentration assessments of drinking water, urinary fluoride estimation and radiological examination. X-rays of the spine, pelvis and forearm are used to help identify osteosclerosis, cortical thickening, and ligament calcification. Serum and urine fluoride levels can help detect over-exposure. Differential diagnosis is important as it can be mistaken for inflammatory joint diseases such as ankylosing spondylitis (Padhan & Maikap, 2022).

The case reported by Padhan & Maikap (2022) showed that the disease process of skeletal fluorosis can mimic spondyloarthritis and hence it is important to have a combination of four factors such as exposure history, dental examination, biochemical investigations and radiological findings for a proper diagnosis.

5 Systemic and biochemical effects of excessive fluoride exposure

Fluoride can cause a number of systemic and biochemical disturbances in addition to its known effects on teeth and bones when the exposure is excessive due to drinking water contamination. After gastrointestinal absorption, fluoride is transported to the bloodstream where it is distributed throughout the body, where it concentrates significantly in mineralized tissues, especially bones. High levels of fluoride in the body for long periods have been linked to alterations in cell signalling and metabolic disturbances, organ dysfunction and oxidative stress. There is strong evidence from experimental studies for these biological effects, with some evidence more robust than others for particular organ systems and human populations (Johnston & Strobel, 2020; Pal et al., 2023).

5.1 Effects on calcium and phosphorus metabolism

Fluoride disrupts the calcium and phosphorus metabolism and the calcium deposition process, alters bone remodelling, and affects the calcium resorbing and depositional cells. Too much fluoride can change the availability of calcium and disrupt the balance of the osteoblast and osteoclast functions. These changes may impact the bone mineralization, density and structural integrity. It may also lead to skeletal fluorosis – a condition of abnormal bone formation, increase in bone density, stiffness in the joints, and limitation of motion, which is likely to happen with prolonged exposure to the hazard (Johnston & Strobel, 2020).

5.2 Oxidative stress and cellular damage

Oxidative stress is one of the major mechanisms involved in fluoride-induced toxicity. Over-exposure to fluoride can cause excessive production of reactive oxygen species (ROS) which can lead to lipid peroxidation, protein oxidation and DNA damage. At the same time, it can inhibit the activity of antioxidant enzymes, such as superoxide dismutase (SOD), catalase (CAT), and glutathione peroxi-

dase (GPx). This imbalance between oxidants and antioxidants leads to the damage of cellular membranes and organelles which may trigger inflammation and apoptosis (Pal et al., 2023).

5.3 Effects on kidney and liver functions

Kidneys are a major pathway for the loss of fluoride in the urine and therefore are highly susceptible to chronic exposure to fluoride. High fluoride content can lead to renal tubular damage, cause oxidative stress and change urinary excretion which can impact creatinine and urea levels. Likewise, hepatic toxicity due to fluoride has been found to be linked with mitochondrial dysfunction, lipid peroxidation, changes in enzyme activities, and changes in liver cell structures. However, animal evidence from experimental studies is more robust than the human evidence of these organ-specific effects (Pal et al., 2023).

5.4 Endocrine and hormonal disturbances

High fluoride levels can affect the regulation of the body, especially the thyroid gland. There have been reports of epidemiological studies showing an association between TSH levels and fluoride exposure. But the results of studies on triiodothyronine (T3) and thyroxine (T4) are inconclusive. Other metabolic pathways and calcium dependent cellular signalling pathways may also be affected by changes in hormonal regulation related to fluoride (EFSA, 2025).

5.5 Effects on reproductive and developmental health

Excessive exposure to fluoride has also been found to impact reproductive health in experimental studies, through a disruption of steroid hormone production, sperm quality, ovarian function, and development of reproductive tissue. Some possibilities have been suggested: oxidative stress and changes in cellular signalling. Developmental effects have also been assessed, but with limited conclusions for reproductive toxicity in humans, requiring additional epidemiological studies (Pal et al., 2023)

5.6 Molecular and cellular mechanisms of fluoride toxicity

Mitochondrial dysfunction, disruption of intracellular calcium regulation, enzyme inhibition, alteration of gene expression, and activation of apoptotic pathways are all involved in the molecular aspects of fluoride toxicity. Fluoride may also alter the balance of pH and electrolytes in cells, which in turn will impact normal metabolism. All these mechanisms can be said to account for why an excessive exposure may result in pathological changes in several organ systems over time (Johnston & Strobel, 2020).

6 Prevention, control and management of fluoride contamination

Prevention and management of fluoride contamination of groundwater is crucial for controlling dental and skeletal fluorosis, especially for groundwater-dependent populations. Continuous water quality monitoring, suitable defluoridation technology, availability of alternative safe drinking water sources, nutrition improvement and community involvement are essential for management. A multi-sectorial approach with the participation of the local community, researchers, health authorities and government bodies is required to reduce long-term fluoride exposure and to ensure public health.

6.1 Monitoring of fluoride concentration in drinking water

It is important to monitor the water supply for fluoride concentrations on a regular basis, in order to detect contaminated sources and to avoid over-exposing water consumers to fluoride. Groundwater wells, handpumps, borewells and public water-supply systems should be sampled regularly. Fluoride concentration is measured by using Fluoride ion-selective electrode, ion chromatography and colourimetric techniques. Geographic Information Systems (GIS) can also be used to define areas at risk from fluoride and develop a spatial distribution map. The surveillance allows authorities to determine high risk areas and take preventive measures accordingly before fluorosis develops (WHO, 2022).

6.2 Drinking-water quality standards and WHO recommendations

The WHO has recommended guideline value of 1.5 mg/L (ppm) for fluoride in drinking water. The actual risk is, however, dependent on the amount of fluoride ingested, climate, water consumption and dietary practices (WHO, 2022). According to IS 10500:2012, the acceptable limit is 1.0 mg/L while the permissible limit is 1.5 mg/L in the absence of any other source of water in Indian context. Hence, there is a need for regular assessment against national and international standards to ensure the safety of drinking water.

6.3 Defluoridation techniques

Defluoridation is the process of removing excessive fluoride from the drinking water using physical and chemical processes. There are a number of techniques:

- **Nalgonda technique:** Developed in India for the removal of fluoride by coagulation, flocculation, sedimentation and filtration using aluminium salts, lime, bleaching powder. It is fairly cost-effective and can be used at the community level (Nawlakhe et al., 1975).
- **Activated alumina adsorption:** Fluoride ions are adsorbed on the porous surface of the activated alumina. Its efficiency is influenced by pH, contact time and adsorbent properties. It is to be replaced or regenerated periodically.
- **Reverse osmosis:** This is a membrane process for eliminating fluoride and some dissolved contaminants which involves pressurizing water. But a number of factors need to be taken into account such as the maintenance of the membrane, energy usage and waste disposal.
- **Ion exchange:** Fluoride ions are exchanged for other ions through the use of special anion exchange resins. It can effectively treat the method, but needs to be regenerated and maintained properly.
- **Bone char and other adsorption methods:** Fluoride can be removed by surface adsorption using bone char, modified clays and other adsorptive materials. The efficiency is dependent on the quality of the materials used, their operating conditions, and their treatment capacity.

6.4 Alternative safe drinking-water sources

Alternative source of safe drinking water is an important preventive measure in fluoride-endemic areas. Alternative water resources such as rainwater harvesting, treated surface water, community water-supply systems and groundwater sources that have naturally low fluoride levels can help decrease reliance on contaminated borewells. Alternative sources need to be tested for fluoride and other chemical and microbiological contaminants before they can be distributed. Rain water harvesting is especially beneficial in rural areas where the fluoride content in ground water is high.

6.5 Nutritional interventions and public health awareness

The nutritional improvement is a supportive measure to minimize the negative impacts of fluoride toxicity. For good bones and teeth it is important to have a well-balanced diet that includes sufficient calcium, vitamin D, vitamin C and minerals. Encourage the consumption of milk, green leafy vegetables, fruits and calcium containing foods especially in children and during pregnancy. Periodic water testing and safe drinking water practices should be emphasized, as should public awareness programmes educating communities on fluoride exposure, symptoms of fluorosis, and safe drinking water practices. The reduction of fluoride exposure should not be the sole means of nutritional intervention.

6.6 Government policies and community-based interventions

Government programs are needed to help manage fluoride contamination by monitoring water quality, providing treatment facilities, supporting health-care programs, and educating the public. The National Programme for Prevention and Control of Fluorosis (NPPCF) in India emphasizes surveillance, diagnosis, treatment, rehabilitation and awareness in fluoride affected districts (Directorate General of Health Services, 2025). The involvement of the community through the village level water committees, local health workers and educational institutions can facilitate implementation and maintenance of defluoridation systems.

6.7 Sustainable strategies for fluoride-contaminated regions

Sustainable, affordable and locally appropriate interventions are needed for the long term management of fluoride contamination. This includes the incorporation of rainwater harvesting, decentralized water-treatment systems, regular groundwater assessment, better sanitation infrastructure and community involvement in water resources management. In resource-poor areas, solar-powered treatment systems and materials from the local community could be more cost effective options. In addition, linkage of water-quality monitoring and health-checking can aid early detection of fluorosis cases. Equitable access to safe drinking water, environmental protection, and ongoing public health education should be accorded special attention in the management of the system for sustainability. In general, the prevention and control of fluoride contamination can only be achieved through the implementation of a multi-disciplinary approach, which encompasses scientific monitoring, technological interventions, nutritional improvement, government policies and community involvement. All these measures can significantly lower fluoride exposure and avoid dental/skeletal fluorosis in vulnerable groups.

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