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REVIEW ARTICLE

The Fluoride Menace: Sources of Pollution, Environmental Impact and Health Risks

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ABSTRACT

Fluoride exposure unleashes a devastating triple threat to global health, ecosystems, and biodiversity, imperilling the very foundations of our planet. Rampant industrialization and naturally occurring geological sources have catastrophically amplified fluoride contamination, poisoning soil, plants, and water bodies, with dire consequences for human and environmental well-being. Chronic fluoride ingestion can lead to debilitating fluorosis, disrupt aquatic food chains, and compromise agricultural productivity. The consequences of fluoride pollution are far-reaching, causing respiratory distress, reduced biodiversity, and detrimental effects on livestock, including decreased milk production and locomotor disorders. This comprehensive study undertakes a systematic evaluation of fluoride pollution sources, health impacts, and environmental consequences. Key findings highlight the urgent need for mitigating fluoride contamination in subsurface water sources, safeguarding public health, and protecting ecosystems. This research provides a critical framework for policymakers, scientists, and stakeholders to address the complex challenges posed by fluoride pollution.

Keywords: *Fluoride, Ecosystem, Catastrophically, Livestock, Public Health*

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INTRODUCTION

Water, covering approximately three-quarters of the Earth's surface, is a vital element essential to all aspects of life. However, the accelerating pace of industrialization, rapid population growth, unregulated urban expansion, and intensive agricultural practices – including widespread fertilizer and pesticide use – have severely depleted and degraded water and soil resources. Groundwater has become a crucial alternative to surface water, serving as a reliable and often preferred source for industrial, agricultural, and human consumption. In developing nations, groundwater serves as the primary source of potable water. Despite Earth's abundant water resources—1386 million km^3—only 31.1% of freshwater (approximately 10.63 million km^3) is stored in groundwater. However, global groundwater supplies are dwindling, particularly in Asia, Africa, and North America [1]. Geographical, economic, and budgetary constraints hinder access to clean drinking water in various regions worldwide. Alarmingly, projections suggest that over 50% of the global population may face clean drinking water scarcity by 2025 [2].

Fluoride contamination poses a significant threat to groundwater quality globally, affecting approximately 200 million people across 29 countries, including India, who consume water exceeding 1.5 mg/L [3]. Various institutions, including the World Health Organization (WHO), UNICEF, and the Bureau of Indian Standards (BIS), have established permissible fluoride limits in potable water, ranging from 0.5 to 1.5 mg/L. The alarming reality is that 200 million people worldwide rely on water sources polluted with high fluoride levels [4]. Nations such as India, China, Argentina, Mexico, and several African countries are vulnerable to fluorosis-related illnesses (Figure 1). India and China account for the bulk of fluorosis cases in Asia [5]. Fluoride contamination ravages the environment, primarily through human activities—chemical fertilizers, pesticides, industrial and sewage discharge, incineration releases, and excessive groundwater pumping—and natural sources, where meteoric water and surface runoff interact with fluoride-bearing minerals [6]. This toxic legacy has far-reaching consequences, crippling plant growth through physiological, biochemical, and molecular disruptions, devastating soil microbial activity, and troubling human health with increased risks of hypertension, neurological disorders, kidney damage, lung cancer, etc. [7] (Table 1).

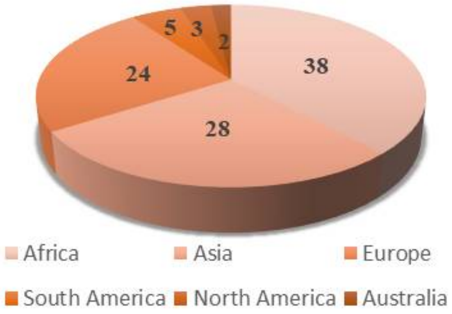

Figure 1: A pie chart showing the number of the countries in the continents affected by fluorosis

In India, fluorosis is endemic in 19 states, with five states—Andhra Pradesh, Rajasthan, Punjab, Uttar Pradesh, and Gujarat—exhibiting hyperendemic fluorosis in over half of their districts [8]. Rajasthan's unique geology, dubbed the "Mineral Museum," contributes to its high fluoride levels [9]. Fluoride's presence in natural elements profoundly impacts living organisms. Consumable water is a primary source of fluorosis, making it a significant public health concern. Residents relying on natural resources are more vulnerable due to economic and educational challenges.

The toxicological threshold for fluoride poisoning is quantified at 1 mg F/kg body mass, with potentially hazardous doses approximated at 5 mg F/kg [10]. Fluorosis can occur even in areas with ideal or barely detectable fluoride levels, emphasizing the need for comprehensive monitoring and mitigation strategies. The World Health Organization identifies arsenic and fluoride as the two most hazardous inorganic toxins harming human health. Addressing this issue requires thorough monitoring and mitigation strategies to ensure safe drinking water. This paper provides a comprehensive review of fluoride pollution sources, encompassing both natural and anthropogenic origins, and its far-reaching environmental and health implications, including impacts on water, air, soil, plants, aquatic life, and human physiology, highlighting the associated health risks. Drawing on expertise from diverse fields, our analysis synthesizes data from reputable international and national organizations, peer-reviewed literature, and authoritative websites.

Table 1: Flow chart illustrating the Impact of fluoride.

IMPACT OF FLUORIDE

Groundwater Quality	Air Quality	Human Health	Animals: Aquatic life and Birds	Plants	Quality of Soil and Microbial Activity in Soil
• Its presence causes high bicarbonate alkalinity and low calcium in water • Quality of drinking water compromised especially in the areas where groundwater contamination	• HF in the air can reach up to the stratosphere and also alters the quality of air • Atmospheric residence of Fluoride is >500 years	• Dental caries and discoloration • Skeletal fluorosis • Social impact • Neurological impairment or paralysis • UTI and hypocalcaemia	•Hoof abnormalities •Swollen joints •Bone ageing and fluoride intake are found related in birds	• Leaf tip burn • Leaf necrosis • Root and shoot growth retarded • Plant germination delayed	• Detrimental impact on soil ecology and microbial activity • Increases pH of soil • Stressing plant's growth

SOURCES OF FLUORIDE

Fluoride pollution poses a pressing global concern, disproportionately affecting millions in developing nations where water fluoride levels often surpass the recommended 1.5 mg/L threshold [11]. Topographical, financial, and economic challenges compound this issue, hindering access to clean drinking water and making it difficult for developing nations to meet regulatory standards.

Fluoride enters the environment through both natural and anthropogenic sources (Table 2). Natural weathering and dissolution processes release fluoride from fluoride-bearing rocks and minerals, such as fluorspar, cryolite, apatite, mica, and others, into groundwater [6]. Fluoride content varies significantly across rock types. Killas contains the highest concentration (1,873 mg/kg), followed by schist (1,703 mg/kg), gneiss (1,563 mg/kg), and granite (1,043 mg/kg)

[12]. Volcanic rocks exhibit exceptionally high fluoride levels, reaching 2,000 mg/kg, while alkaline igneous rocks contain 1,300 mg/kg [13]. Human activities, particularly industrial processes like coal-fired power plants, steel and aluminum production, glass manufacturing, and fertilizer use, substantially contribute to fluoride pollution. These pollutants accumulate in soil, plants, and water sources through dust, rain, snow, or fog. Fertilizer leaching contaminates soil with fluoride levels as high as 255 mg/kg, while natural sources like gneiss and granite rocks contain concentrations exceeding 5,000 mg/kg [14]. Groundwater contamination remains the primary source of fluoride exposure, followed by phosphatic fertilizer contamination of agricultural products and fluoride entry through food, cosmetics, aerosols, and other sources [15]. GIS mapping has been utilized to study fluoride pollution in regions like Chennai, Tamil Nadu, and Dhanbad, Jharkhand, providing valuable insights into its distribution [16]. Seasonal variations, such as high evapotranspiration during pre-monsoon periods, temporarily precipitate fluoride salts in upper soil layers, exacerbating soil and groundwater contamination during monsoons [17]. Even seemingly innocuous products, like toothpaste, contribute to fluoride pollution, with concentrations reaching 800-1,000 parts per million [18].Ultimately, both natural and anthropogenic factors play critical roles in contaminating environmental components with fluoride, drawing attention to the complex interplay between human activities and natural sources in perpetuating fluoride pollution.

Table 2: Common sources of Fluoride in Environment

Sources of Fluoride

Natural Sources

- Water and drinks
- Geogenic Source's weathering
- Volcanic Eruptions
- Marine Aerosols
- Salts
- Groceries
- Soil

Anthropogenic Sources

- Drugs and agents used in Dentistry
- Fluoride fertilizers
- Burning of coal
- Fluoride mouth rinse
- Fluoride varnish
- Fluoride foam and gel
- Filling materials and fissure sealents
- Medicines
- Industry release
- Beverages

Fluoride pollution originates from natural sources, including high-fluoride rocks and soil, which contaminate groundwater as water flows through them, dissolving fluoride in the process [7]. Research reveals that fluoride-containing minerals in host rocks weather naturally, releasing fluorine due to its high solubility, which progressively dissolves into groundwater sources, where it is detected as a trace element. Fluoride predominantly affects groundwater in dry and semiarid regions, particularly where aquifers comprise unconsolidated rock fragments with varying calcium content, ranging from bedrock to alkaline groundwater [19]. Common minerals contributing to fluoride in groundwater include topaz

($Al_2(SiO_4)F_2$), cryolite (Na_3AlF_6), villiaumite (NaF), fluorite (CaF_2), sellaite (MgF_2), and fluorapatite ($Ca_5(PO_4)_3F$) [20]. Fluoride (F^-) can also be a substitute for hydroxide (OH^-) in the crystalline structures of minerals like mica and amphiboles [21]. Extensive research has elucidated the mechanisms underlying fluoride dissolution into water, highlighting the complex interplay between geological processes and groundwater contamination.

Drinking Water

Fluoride is a naturally occurring element commonly found in drinking water, accounting for 75-90% of human exposure, primarily through consumption of water with excessive fluoride levels [22]. Fluoride concentrations in water sources vary significantly due to geological and environmental conditions, which are mostly attributed to fluoride-rich soil, volcanic activity, and anthropogenic influences. Ali *et al.*, [23] and Raghav *et al.*, [24] reveals a wide range of fluoride concentrations across different water sources. Naturally occurring water contains 0.02-0.2 ppm, while river water exhibits a broader range of 0.0-6.5 ppm. Groundwater, a primary drinking water source in many regions, has fluoride concentrations spanning 0.1-8.7 ppm. Seawater typically contains higher fluoride levels, averaging 1.4 ppm. The fluoride concentrations in lakes, rivers, and canals are contingent upon the topography of their respective catchment regions. The fluoride concentration in subterranean water and aquifers is reliant upon the mineral content of the rocks that the water crosses [25]. Furthermore, the practice of community water fluoridation is acknowledged to significantly contribute to enhancing oral health by reducing the incidence of dental caries. Increased fluoride concentrations in drinking water are associated with decreased calcium and magnesium hardness and elevated alkalinity [26]. Furthermore, an individual's water intake varies based on diet, physical activity, humidity, temperature, and overall health. The variability in fluoride levels across water sources accentuates the critical need for monitoring and controlling fluoride exposure to mitigate adverse health effects associated with overexposure.

Food Source

A comprehensive review of research articles reveals that shellfish and tea are notable natural sources of fluoride [24]. While fluoride is present in trace amounts in various foods, plant-based items such as cereals, fruits, and vegetables tend to have higher concentrations [5]. This is attributed to the ability of plants to absorb fluoride from contaminated soil, resulting in increased fluoride content in crops. Table (3) provides a detailed breakdown of fluoride concentrations in specific foodstuffs. All plant life assimilates fluoride from soil and water, with *Coriandrum sativum* (Coriander) and *Spinacea oleracea* (Spinach) exhibiting the highest fluoride levels among field-grown vegetables [27]. Tea leaves are significant fluoride sources, particularly when brewed with high-fluoride water, which can multiply fluoride intake. Furthermore, various food products contain fluoride, including dental products (toothpaste), tea and coffee, pork and poultry, grapes (raisins, wine, grape juice), sodas, tap water, artificial sweeteners, potatoes, infant meals [28].

Table 3: Fluoride content in dietary items.

S.No.	Foodstuff	Fluoride concentration (ppm)	References
1	Spinach (*Spinacea oleracea*)	9.87-29.15	[27]
2	Cabbage (*Brassica oleracea*)	4.25-11.30	[29]
3	Cow milk	1.73-6.87	[30]
4	Red gram (*Cajanus cajan*)	2.34-4.84	[27]
5	Apple (*Mallus*)	1.05-2.20	[30]
6	Green tea leaf (*Camellia sincnsis*)	72.62-89.02	[31]
7	Peas (*Pisum sativum*)	10.77	[30]
8	Bajra (*Pennisetum glaucum*)	2.76-3.84	[32]
9	Snacks	0.22-0.40	[33]
10	Grapes (*Vitis Vinifera*)	0.84-1.74	[34]
11	Rice (*Oryza sativa*)	0.51-5.52	[35]
12	Soybean (*Glycine max*)	4	[30]
13	Coriander (*Coriandrum sativum*)	4.28	[36]

Volcanic Activities

Volcanic eruptions, such as those in Japan, can contaminate groundwater with fluoride, posing a significant health risk. Research has shown that volcanic ash, like that from the Sakurajima eruption, contains alarming levels of fluoride, averaging 788.1 mg/kg [37]. Volcanic activity releases hazardous gases, including hydrogen fluoride (HF) and trace elements, before and during eruptions. This has led to widespread endemic fluorosis in volcanic regions globally, particularly in East Africa, India, and China, affecting millions. The occurrence of fluorides in water near volcanic regions depends on the prevalence of air pollutants emitted by volcanic gases. This aligns with the results from the micro-basins surrounding the Galeras Volcano, notably the Rio Azufral and Rio Cariaco in the municipality of Consaca (Narino), which have comparable amounts of 0.8 mg/L [38]. Local rock formations may alter as a result of plate tectonics and volcanic activity, exposing the water source primarily aquifers to fluoride-rich rocks and raising the fluoride content [39].In Kyushu Island, Japan, a direct link between volcanic activity and human fluorosis was first identified. The Aso volcano's emissions have been tied to the debilitating condition known as "Aso volcano disease," impacting entire communities living near the volcano's base [40]. Over the past two decades, ashfall leachate analyses have emerged as a crucial method for assessing the potential environmental release of toxic elements derived from volcanism during rainfall events following eruptive activities [41]. Multiple studies have revealed a detailed widespread fluorine overdose mortality among grazing animals in regions of Iceland or New Zealand that have experienced volcanism or are blanketed in recently accumulated ashfall [42]. According to the study findings of Sanchez-Espana *et al*., [43], there were water-soluble salts such as fluorides, chlorides, and sulfates in the ashfall that the Tajogaite volcano (Canary Islands, Spain) produced during its 2021 outburst. These elements can be released during consecutive rainfall episodes, which can have negative impacts on human health (possible contamination of groundwater used for water supply) and the environment (accumulation in soils, plants, livestock, or aquatic biota). Therefore, it should be carefully examined since it impacts significant economic sectors like agriculture as well.

Practices in Agriculture

Agricultural practices, particularly the use of phosphate fertilizers, significantly contribute to fluoride contamination in soil and groundwater. These fertilizers contain leachable fluoride levels ranging from 25 to 52 mg/kg, posing a substantial risk to environmental health [44]. Phosphate fertilizers are identified as a primary source of fluoride pollution in agricultural areas, due to trace amounts of fluoride impurities. Research highlights a direct correlation between fertilizer application and groundwater contamination in various agricultural regions. Fluoride is a significant geogenic contaminant that pollutes the soil root zone. Fluoride readily integrates into the human and cattle food chain via bioaccumulation in flora. Additionally, phosphate fertilizers, herbicides, pesticides, burning biomass, and human activity in industrial processes like making bricks, ceramics, and aluminum can all release fluoride into the environment. In an attempt to increase productivity and meet the need for food, the use of chemical fertilizers and pesticides has proliferated by farmers and the widespread application of chemical fertilizers by farmers to their crops is the main source of fluoride increment in soil in rural India [45].

Industrial Processes

Environmental concerns are raised by airborne fluoride emissions since the majority of plants are phytotoxic to it [46]. Although research has been done on the transmission of fluoride in the air, the general pathways are still unclear. Zhao *et al*., [47] through their studies investigated that the direction of the wind can affect ground-level fluoride concentrations, the dispersion of fluoride is strongly influenced by distance from the emission source. greatest levels of fluoride are found in the vicinity of the facility that produces pollution and exposure duration can affect the patterns of airborne fluoride pollution. Yang *et al*., [48] confirm that the northern Helan Mountains, China have much greater topsoil acidity and fluorine and sulfate concentration than control points of interest. Additionally, pasture has a greater fluorine level than both the Chinese fluorine standard values. The lengthy history of coal mining and spontaneous combustion in the area might cause this. Industrial fluoride emissions, particularly from the alumina-to-aluminum conversion process using cryolite as a flux, pose a significant health risk to smelter workers, leading to industrial fluorosis [49]. Susheela *et al*., [50] revealed alarming fluoride levels in smelter workers, with significantly higher urine and serum fluoride concentrations ($p<0.001$) compared to non-smelter workers. Additionally, elevated fluoride levels were detected in their nails ($p<0.001$). While industrial emissions are a primary source of fluoride exposure for smelter workers, dietary factors also play a crucial role in increasing fluoride levels within the body. The consumption of fluoride-rich foods contributes substantially to overall fluoride intake. Factories pollute a variety of natural resources, including soil, air, reservoirs, flora, herbage, ecosystems, and more, by releasing fluoride into the surrounding environment as gases and particulates/dust, furthermore, the manufacturing of steel, iron, aluminum, zinc, phosphorus, chemical fertilizers, oil refineries, bricks, glass, plastic, cement, and hydrofluoric acid are among the most frequent sources of industrial fluoride emissions, as are coal-fired power plants [51].

IMPACT OF FLUORIDE

Impact on groundwater quality

Water, essential for life's sustenance since its inception, supports over 1.5 billion people relying on groundwater as their primary drinking water source. India, the world's largest consumer of groundwater, exemplifies the critical role groundwater plays. However, inadequate wastewater management from urban, industrial, and agricultural activities threatens groundwater quality globally. In India, approximately two-thirds of rural inhabitants depend on groundwater for drinking water (Figure 2). Fluoride contamination in groundwater primarily results from chemical reactions, such as decomposition and dissolution, and interactions with water [52]. Phosphate fertilizers used in agriculture often harbor high fluoride levels, potentially seeping into groundwater and surface water [53]. Lack of monitoring allows fluoride to remain undetected in groundwater sources until examined, due to its colorless, tasteless, and odorless nature. High bicarbonate alkalinity and low calcium levels exacerbate fluoride contamination. Geogenic fluoride contamination in drinking water is the primary source of human fluoride intake. Inadequate access to clean drinking water due to groundwater pollution sparks disputes, potentially escalating into socioeconomic crises and conflict [54]. An estimated 200 million people worldwide, including 62 million Indians, including 6 million children, suffer from fluorosis as a result of drinking water that contains excessive levels of fluoride. Tectonics, weathering, soil type, water physicochemical characteristics, and rock type are the determinants of fluoride pollution in groundwater [55].

Elevated groundwater fluoride levels have been linked to various health disorders across several regions. Notably, in India, 48 groundwater sources exceeded the maximum allowable limit of 1 mg/L, set by the Bureau of Indian Standards and the World Health Organization. A staggering 69% of 1,136 participants in a study conducted by Arif *et al.*, [56] suffered from dental fluorosis, with 22% classified as mild and 6.5% as severe. The severity of this issue is compounded by the variability of fluoride concentrations in water, which are influenced by the geological composition of the underlying rocks. As surface water sources, such as ponds, lakes, dams, and reservoirs, provide drinking water for both humans and wildlife, assessing fluoride levels in these persistent sources is crucial.

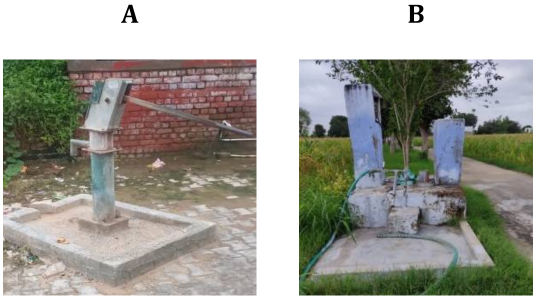

Figure 2: Most prevalent groundwater source: (A) Handpump (B) Tubewell

Impact on air quality

Fluorine naturally occurs in the atmosphere through volcanic activity, ocean spray, and soil dust. However, industrial operations, including phosphate fertilizer production, aluminum smelting, and brick and ceramic manufacturing, release harmful fluoride pollutants into the environment. Since fluoride is a naturally occurring element in both coal and brick raw materials, the development sector, particularly the brick-baking business, depends on the burning of lignite coal in kilns, which is the primary source of fluoride contamination [57]. A comprehensive study in Beijing from 1995 to 1998 revealed alarming fluoride levels in ambient aerosols, averaging 0.61 $\mu g/m^3$ with concentrations soaring to 1.61 $\mu g/m^3$ in winter – 20 times higher than summer levels. Comparatively, this exceeds the yearly average fluoride concentration in Chongqing, Sichuan Province, a region notorious for fluoride pollution [58]. Prolonged exposure to minimal HF amounts in air, as low as 0.3$\mu g/m^3$, can cause noticeable harm [59]. Because of the industrial production of phosphate fertilizers, aluminum, coal ash from burning coal, and volcanic activity, fluorides are widely dispersed throughout the environment. Nevertheless, air exposure only makes for a very small percentage of total fluoride exposure.

Fluorides exist in two atmospheric forms: gases and particulates. Notably, sulfur hexafluoride can persist in the atmosphere for 500 to several thousand years, while small fluoride-bound particles can linger for days (World Health Organization, 2002). Rain absorption of hydrogen fluoride gas creates aqueous hydrofluoric acid, which eventually settles on land through precipitation [60]. Despite recent regulatory efforts and improved emission filters, environmental fluoride release remains a concern. Global airborne fluoride concentrations vary significantly, ranging from 0.04 to 1.2 ppb in the US, but reaching alarming levels of 2.14 ppb in underdeveloped nations like China [61]. Fluoride levels in streams adjacent to aluminium smelters can exceed the natural background limit of 0.05 mg/L by more than a factor of ten. Fluorine emitted into the atmosphere through anthropogenic activities exhibits high reactivity and readily undergoes hydrolysis to produce hydrogen fluoride [62].

IMPACT ON HUMAN HEALTH

The association between fluoride and human health was first recognized in the late 19th century. While fluoride is essential for teeth and bone development in small quantities, excessive consumption has dire consequences [53]. Prevention is the sole remedy for fluorosis, as there is no cure. The severity of fluoride's impact on human health depends on the dose and lifetime exposure to high levels. Notably, occupational fluorosis was initially identified in 1930 [7]. Research has revealed alarming effects even at low fluoride concentrations. For instance, studies have shown that children with iodine deficiencies who consume water fluoridated at just 0.9 ppm are prone to intellectual deficiencies [63]. This emphasises the importance of careful fluoride management to prevent long-term health issues. Table (4) illustrates the effects of fluoridating water on human health dependent on fluoride consumption.

Table 4: Health effects of Fluoride contaminated water.

S. No	F^- Concentration (mg/l)	Health outcomes/effects
1	Less than 0.5	Intellectual deficiencies
2	0.5–1.5	Optimum dental health affected, early childhood caries (ECC)
3	1.5–4.0	Dental fluorosis, Stiffness, and rigidity of joints
4	4.0–10	Skeletal and dental fluorosis, Muscle weakness, Tingling sensations in limbs
5	More than 10.0	Crippling fluorosis, Osteosclerosis, reduces intelligence quotient

Research on menarcheal age suggests a potential link between fluoride exposure and earlier onset of menstruation, although findings are inconclusive. Children globally are disproportionately vulnerable to fluoride exposure compared to adults. Notably, fluorosis disproportionately affects economically disadvantaged communities, with higher prevalence and severity rates observed in these groups [64]. Male laborers are also more susceptible, particularly those consuming nicotine, betel nuts, and alcohol, which exacerbate fluorosis severity and prevalence. In contrast, citrus fruit consumption and optimal nutritional status correlate with lower fluorosis rates [65]. Figure (3) illustrates the detrimental health consequences of consuming water contaminated with high fluoride levels. Regrettably, fluorosis remains a chronic condition without an Ayurvedic treatment [66]. Given the risks, health risk assessments are crucial, enabling estimation of potential hazards confronting water consumers.

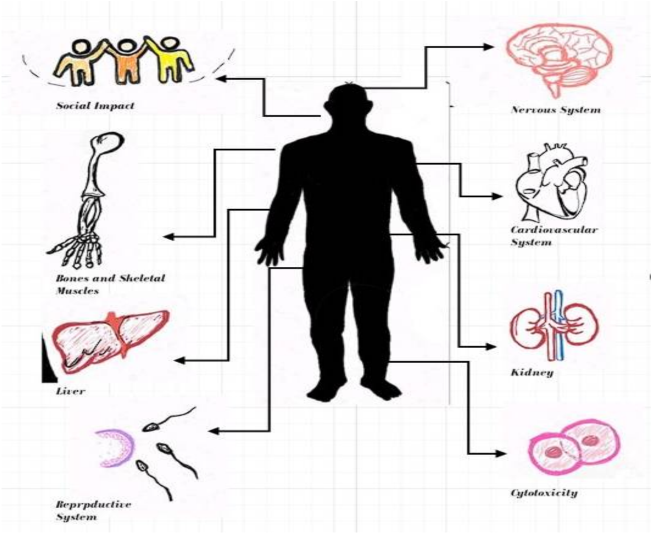

Figure 3: Chart illustrating impact and organs affected by Fluoride poisoning

Social Impact

Physical appearance significantly influences social interactions, particularly in public settings where individuals manage impressions. However, anxiety surrounding tooth color, especially when smiling, can hinder effective impression management. Industrial fluoride contamination costs ranchers and livestock owner's monetary resources in addition to causing a variety of physical abnormalities in animals. Research reveals alarming consequences of fluoride exposure in areas with high levels in drinking water. Studies have established a strong link between fluoride exposure and school dropout rates. Moreover, women afflicted with dental and skeletal fluorosis often face inadequate treatment, leading to further social issues, including divorce [67]. Severe fluorosis can relegate individuals to the "sick role," prompting withdrawal from social interactions, a phenomenon sociologists' term "retreatism" [68]. This isolation is exacerbated in regions like India's Manbhum-Singhbhum Plateau, where Ghosh *et al*., [69] found a direct correlation between elevated fluoride levels and increased social isolation.

Impact on Teeth

Access to proper dental care is crucial for overall health, and understanding fluoride's role is vital to mitigating its harmful effects on vulnerable populations, including children and the elderly. The pioneering work of Fredrick McKay (1925) revealed the link between consumable water, fluoride concentration, and the formation of dental fluorosis, characterized by permanent stains on tooth enamel. Dental fluorosis typically affects individuals who ingest elevated fluoride levels during tooth development, between six and eight years old [70]. However, fluoride also has profound benefits, strengthening enamel against acidic substances and accelerating mineral accumulation, thereby delaying deterioration [71]. Of the total fluoride that the body consumes, the bones or teeth retain the most of it (almost 80–90% in newborns and 60% in adults), with the remainder being eliminated through urine [11].

Fluoride is a ubiquitous ingredient in mouthwashes, toothpaste, and dental procedures. Children without access to fluoridated water often receive prescribed fluoride supplements. Moreover, fluoride combats tooth decay by dissolving in solution, altering tooth mineral saturation properties, promoting re-mineralization, and inhibiting de-mineralization (Figure 4) [72]. At higher concentrations, fluoride even prevents bacterial carbohydrate breakdown, a critical factor in cariogenesis [72].

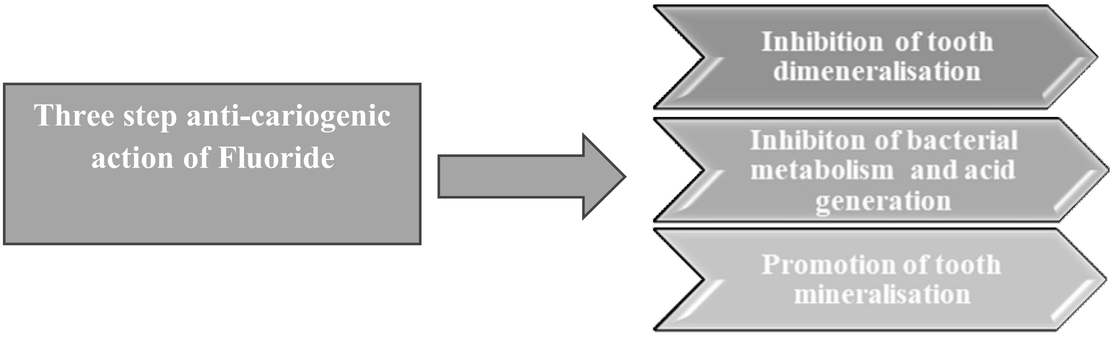

Fig 4: The flow chart outlining how fluoride exerts its anti-cariogenic actions.

Prolonged consumption of fluoride-contaminated water has dire consequences for dental health, leading to teeth hardening and increased fragility. As dental fluorosis progresses, teeth become coarse and exhibit chalky white patches, often accompanied by yellow to dark brown discolorations [73]. The severity of this condition is commonly assessed using the Dean index for the first time in 1922 [74], a widely accepted and established benchmark (Table 5). This index delineates the various stages of dental fluorosis, providing a crucial framework for evaluating the extent of damage and guiding treatment.

Prolonged exposure to excessive fluoride can lead to structural degradation of teeth, manifesting as pitting or chipping due to enhanced porosity [70]. Notably, optimal fluoride intake has been shown to prevent dental cavities without causing orthodontic discoloration [76]. However, excessive fluoride exposure disrupts amelogenesis and dentinogenesis, distorting the crystalline arrangement and leading to fluorosis [77]. The severity of fluorosis is directly correlated with fluoride concentrations in drinking water, ranging from dental fluorosis (1.5-4.0 mg Fluoride/L) to crippling fluorosis (>10 mg Fluoride/L) [2]. Alarmingly, unregulated use of dental products and excessive fluoride in water remains a primary cause of fluoride poisoning, emphasizing the need for stringent regulations and mindful consumption.

Table 5: Dental fluorosis is categorized using Dean's index.

Fluorosis Numerical Scale Indicator	The Degree of Dental Fluorosis	Visible Effects
1-2	Normal to questionable	dazzling surface with a variety of cream and white hues. Fleck deviations or isolated white patches begin to occur with increased fluoride intake.
3-5	Mild to moderate	Tiny areas devoid of brown marks that amount to 25% of the surface. Up to 50% of the changes occur when consumption is increased. Even though lesions and black patches cover much of the tooth's surface, the shape typically does not change. (Figure 5)
6-7	Severe	The frequency, depth, and extent of cavities are all higher. Extensive lesions ranging in shade from brown to almost black indicate visible hypoplasia. (Figure 5)

Mild Dental Fluorosis **Severe Dental Fluorosis**

Fig 5 Pictures showing dental fluorosis

Impact on bones and skeletal muscles

Skeletal fluorosis is a debilitating health condition characterized by excessive fluoride accumulation in bones and skeletal muscles, leading to elevated bone density and increased mass, Prolonged exposure to fluoride levels exceeding 4 mg/L triggers this harmful process [70]. The condition manifests through a range of distressing symptoms, including abdominal pain, joint calcification, ligament and tendon hardening, stiffness, joint discomfort, and restricted movement [78]. While relatively rare in Western nations, skeletal fluorosis is endemic in regions with extremely high fluoride exposure, such as parts of Asia, particularly India. In these areas, geological factors and cultural practices contribute to alarming fluoride levels, with mean water fluoride concentrations reaching 4 mg/L [72]. The widespread consumption of highly fluoridated beverages further exacerbates the problem, making skeletal fluorosis a pressing health concern.

Severe skeletal fluorosis can lead to a debilitating condition known as "poker back," characterized by progressively stiffening bones (Figure 7). This crippling disease has far-reaching consequences, frequently resulting in bone fractures and severely impairing daily activities in rural communities [79]. Moreover, skeletal fluorosis poses significant risks for women during childbirth. The severity of the condition is multifaceted, influenced by various factors including fluoride concentration, duration and frequency of exposure, age, sex, nutrition, water chemistry, physical function, genetic predisposition, environmental factors, and individual tolerance to fluoride. These interconnected factors contribute to the complexity of skeletal fluorosis, underscoring the need for comprehensive understanding and targeted interventions to mitigate its devastating effects.

Fig 7: Poker back a consequence of fluoride

The devastating consequences of prolonged fluoride exposure culminate in skeletal fluorosis, a debilitating condition characterized by limited joint mobility and progressive deterioration. As the disease advances, individuals typically suffer from invalidism, crippling disabilities, and striking skeletal deformities, including kyphosis (hunchback) (Figure 8) and genu varum (bow legs or outward bending of the legs at the knee) [80]. Skeletal fluorosis, typically affecting over 20% of individuals exposed to excessive fluoride, manifests through debilitating symptoms including knock-knees, back pain, numbness and tingling in extremities, and joint pain in both upper and lower limbs [81]. Severe cases may lead to spinal cord compression due to vertebral osteosclerosis, a potentially crippling consequence [24]. Paradoxically, fluoride also exhibits beneficial effects. By enhancing bone density and reducing fracture risk, fluoride ions can promote bone health [82]. This dual nature of fluoride has led to its occasional use as an osteoporosis treatment, highlighting the need for nuanced understanding of its effects.

Fig 8: The picture showing women suffering from skeletal fluorosis.

Cytotoxicity

Cell structural changes and damage to nucleosome DNA have been linked to high fluoride exposure [83]. The lowest dose of fluoride documented to trigger chromosomal mutation in mammalian cells was around 170 times higher than the amount ordinarily found in human cells [84]. Findings have demonstrated that exposure to high concentrations of fluoride can alter the expression of apoptotic genes in peripheral blood mononuclear cells (PBMCs) in populations of people in Mexico [85]. Fluoride exposure's route of action has been seen in vitro in a variety of cell types and in vivo in soft tissues such as the liver, kidney, brain, lung, and testes in both humans and animals residing in endemic fluorosis locations, by inhibiting metalloproteins, disrupting organelles, changing pH, and causing electrolyte imbalance, fluoride appears to cause oxidative stress, cell cycle arrest, and death at the cellular level [63].

As fluoride penetrates cells, it mostly affects the mitochondria, which results in a malfunction of calcium control, a reduction in the activity of mitochondrial enzymes, a weakening of protein production, damage to the respiratory chain, excessive fission, and disruption of fusion. Reactive oxygen species accumulate and intracellular ATP levels decrease as a result of these consequences [86]. The research conducted by Seshadri *et al.*, [87] revealed that fluoride varnish has a concentration-dependent cytotoxic impact on human gingival fibroblasts (hGFs). As the dosage of fluoride grew, the cell viability dropped.

Nervous system

Fluoride exposure has profound consequences on cognitive function, particularly in developing brains. Research reveals that increased fluoride levels trigger lipid peroxidation, inhibit crucial brain enzymes, and disrupt neurotransmitters, myelin, and neurons, ultimately impairing brain function [88]. The neurological impact of fluoride is further evidenced by symptoms such as nausea, vomiting, and diarrhea, indicating nervous system damage [78]. Recent studies warn that fluoride exposure during pregnancy and lactation may have neurotoxic consequences, causing mitochondrial damage and disrupting biogenesis [89]. High fluoride intake has been linked to neurological conditions, paralysis, and impaired cell migration in developing neurons [90]. The effects on children's cognitive development are alarming, with reduced cognitive quotient and growth hormone production [91]. Fluoride also disrupts the Central Nervous System's energy requirements [92]. The Environmental Protection Agency (EPA) has designated fluoride as a developmental neurotoxin, highlighting its potential for harm [93]. Fluoride in drinking water was linked to changes in cardiac autonomic function and decreased visual acuity in infants, which further supports the mounting evidence of fluoride's developmental neurotoxicity [94].

Cardiovascular system

Research reveals a disturbing link between fluoride exposure and cardiovascular dysfunction. Excessive fluoride levels can trigger hyper- and hypocalcemia, disrupting the delicate balance of calcium essential for nerve function and cardiac health [53]. Fluoride's affinity for serum calcium can lead to hypocalcemia, compromising cardiac contractility and potentially causing circulatory collapse. Studies have shown that fluoride contamination, particularly from coal combustion, significantly elevates both diastolic and systolic blood pressure in adults [95]. Moreover, exposure to fluoride pollution increases the risk of underweight, hypothyroidism, diabetes mellitus, irregular cardiac rhythms, diminished myocardial function, and obesity [96]. Prolonged exposure to high levels of fluoride in drinking water may raise the prevalence of stroke.

Liver and Kidney

Chronic fluoride ingestion through food accelerates the progression of chronic kidney disease (CKD), with devastating consequences [97]. Moreover, excessive fluoride consumption increases the risk of urinary tract infections, colorectal cancer, and kidney cancer, posing a significant threat to public health [7]. A landmark investigation by the National Research Council (NRC) [98] exposed the alarming effects of fluoride on human health. The study revealed that the kidneys concentrate fluoride from plasma up to 50 times in urine, rendering renal tissues disproportionately vulnerable to fluoride toxicity compared to other soft tissues. Montanez-Rodriguez *et al.*, [99] experimented to evaluated harmful impact of fluoride on adult renal health. The results demonstrated that fluoride was transferred to the amniotic fluid and foetus, resulting in lower weight, more significant foetal restriction, and reduced creatinine, osmolarity, and amniotic fluid volume. Fluorine exposure during pregnancy changes kidney development and promotes early maturity of tubular segments. Ramadhan *et al.*, [100] revealed that 30 days of treatment of NaF in potable water produced liver damage and a modification in the glycemic index in adult male rats. A considerable rise in blood glucose levels and a decline in blood insulin levels were identified at the end of the studies in the handled (NaF) group when compared to the placebo. Histopathological alterations in the NaF treatment group were detected in hepatic and pancreatic tissue evidenced by widespread degeneration and necrosis of hepatocytes. The onset of excessive fluoride exposure can cause elevated oxidative stress, which might result in cell death, when hepatic problems occur, the detrimental effects include mitochondrial malfunction, DNA damage, autophagy, and apoptosis and there have been reports of cell cycle stoppage, and abnormalities in urinary concentrations in renal tissues [101].

Reproductive system

Skeletal fluorosis has profound implications for reproductive health. Research reveals that male patients afflicted with this condition experience significant declines in testosterone levels [102, 103]. Furthermore, studies have consistently shown alarming trends in reproductive hormones, including dwindling birthrates, estrogen, and follicle-stimulating hormone levels [7]. Recent investigations have expanded our understanding of fluoride's far-reaching effects, demonstrating disruptions in thyroid hormones and other vital endocrine processes [25]. These changes can have devastating consequences for fertility. High fluoride exposure has been irrefutably linked to decreased fertility in both men and women. Specifically, women with elevated fluoride levels suffer from irregular menstrual cycles and reduced fertility [104]. Dong *et al.*, [105] concluded that fluorosis induces female reproductive disruption, resulting in diminished fertility, without a well-defined pathophysiology. To elucidate the mechanism, Sprague-Dawley female rats were chosen by them and were provided with drinking water containing low, moderate, and high sodium fluoride. Treatment with NaF dramatically reduced steroid hormone levels and lowered the pregnancy rate. NaF is determined to limit hormone secretion and estradiol (E2) release from the ovary, thereby diminishing the rate of pregnancy. It induced reproductive failure in female rats by modulating the production of reproductive hormones, FSH and LH. Masnaoui *et al.*, [106] in Settat province, Morocco, examined the correlation between elevated plasma fluoride concentrations, oxidative stress, and pregnancy problems, including abortion, intrauterine foetal demise, preterm delivery, and preeclampsia. Furthermore, a significant association existed between plasma fluoride concentrations, antioxidant activity, and problems during pregnancy. It was concluded that the presence of high plasma fluoride levels might contribute to an upsurge in pregnancy complications, via the oxidative stress pathway.

Impact on animals, aquatic life, and birds

As early as 1000 CE, Icelandic literature referenced a debilitating condition known as "gaddur," which afflicted animals [7]. This ailment was attributed to fluoride exposure, likely stemming from volcanic eruptions. Herbivores, both domestic and feral, are particularly vulnerable to environmental fluoride contamination due to their non-selective grazing habits, which can lead to the ingestion of polluted feed, water, and forage. Gupta *et al*., [107] uncovered a disturbing link between high-fluoride drinking water and reduced birth rates. Their study revealed alarming reproductive damage in male rats exposed to 2-6 ppm sodium fluoride in their drinking water for six months, leading to testicular dysfunction and impaired fertility. Zhao *et al*., [108], evaluated the metabolic pathways impacted by fluoride exposure in rats. The causes of fluoride-induced damage to many organs may encompass oxidative stress, inflammation, mitochondrial impairment, and disruptions in fatty acid, amino acid, and energy metabolism.

Wild canids, such as foxes and raccoon dogs, serve as valuable sentinels for fluoride-related environmental contamination [109]. A comprehensive study by Choubisa [110] investigated fluorosis in various domestic animals, including donkeys (*Equus asinus*), cattle (*Bos taurus*), buffaloes (*Bubalus bubalis*), camels (*Camelus dromedarius*), and horses (*Equus caballus*). The research uncovered alarming evidence of fluoride-induced damage, with 42.8% of examined animals displaying severe symptoms, notably periosteal exostoses, debilitating hoof abnormalities, intermittent lameness, leg and tendon rigidity, and pronounced muscle atrophy in the shoulders and hindquarters. Consumption of fluoride has devastating consequences for cattle, leading to impaired milk production, debilitating lameness, and lethargy, ultimately compromising their wellbeing, productivity, and overall health [111]. Modasiya *et al*., [112] discovered alarming rates of fluorotic dental mottling in calves and cows, with 41.7% (10/24) and 37.3% (28/75) exhibiting noticeable bilateral stains on their front teeth, ranging from pale to dark yellow. Conversely, research by Choubisa [110] highlights the essential role of fluoride in animal health, as low-fluoride diets can impede growth and reproductive performance. Ghosh *et al*., [68] exposed the dire consequences of fluoride-contaminated drinking water on horse health, manifesting as tooth fluorosis, debilitating skin allergies, and bone stiffness eerily similar to arthritis. This toxic legacy now threatens domesticated animals, as widespread borewell and hand pump use has led livestock owners to unknowingly feed contaminated water to their animals. The outcome is catastrophic: exposed animals succumb to frailty, emaciation, lameness, and disability, leaving them perpetually vulnerable to chronic health issues [80].

Aging cattle exhibited a disturbing escalation in tooth mottling severity. The environmental toxin inflames chronic fluoride poisoning, leading to devastating declines in appetite, reproductive performance, and productivity, and ultimately threatening the financial viability of the dairy sector [113]. Anjum *et al*., [114] probed the impact of elevated fluoride levels on liver and kidney enzymes in domestic hens. In a four-week study, four groups received weekly NaF doses of 0, 10, 20, and 30 µg/g per body weight. Researchers assessed liver function via alkaline phosphatase (ALP), aspartate aminotransferase (AST), alanine aminotransferase (ALT), and bilirubin levels, and used uric acid as a renal function indicator. The findings were alarming: fluoride exposure significantly elevated all measured parameters ($p<0.05$), revealing severe kidney and liver dysfunction in exposed birds

The relentless deterioration of water quality, fuelled by escalating pollution, threatens the very foundation of aquatic life and the entire food chain. Fluoride contamination poses a significant risk to aquatic animals, particularly freshwater invertebrates and fish, such as adult *Salmon* migrating upstream, which are disproportionately vulnerable to fluoride toxicity [115]. Studies have consistently highlighted the devastating impact of fluoride exposure on aquatic life. For instance, research on *Heteropneustis fossilis* (Bloch) revealed stunted growth [116], while investigations on *Puntius ticto* in Lake Nainital, India, exposed a link between aquatic fluoride levels and variations in fish weight and length [117]. Similarly, sublethal fluoride exposure compromised the protein composition, glycogen, and lipid content in *Labeo rohita*'s kidney, gills, and liver muscle [118]. High fluoride concentrations also triggered cytotoxicity, hindering cell division and development in fish [119]. Notably, fluoride accumulation in fish ranged from 121 to 452 mg L^{-1}, predominantly affecting *Nandus* and *Catla* species [120]. Alonso and Camargo [121] investigated the immediate and long-term effects of fluoride toxicity on the aquatic snail *Potamopyrgus antipodarum.* Their study revealed that elevated fluoride concentrations significantly altered behavioural activity and severely impaired reproductive success, with the highest concentration causing a pronounced decline in embryonic shell development. These findings raise concerns about fluoride-induced apoptosis in aquatic animals, underscoring the grave health risks associated with consuming fluoride-exposed fish.

Despite the potential risks, remarkably little is known about the fluoride levels harmful to wild bird species. However, research offers glimpses into the impact of fluoride on avian health. Hou *et al.*, [122] demonstrated the adverse effects of sub chronic NaF exposure on chicken hearts. Prolonged exposure to NaF resulted in cardiac tissue damage and endoplasmic reticulum (ER) dilation, primarily associated with heightened inflammatory responses and apoptosis triggered by ER stress (ERS) and heat shock proteins (HSPs). Notably, they observed a compelling phenomenon: the chicken heart has the ability to prevent the toxic consequences of sub chronic NaF exposure from progressing to more severe necroptosis via adaptive modifications in HSPs. Interestingly, research on the emperor penguin (*Aptenodytes forsteri*), an Antarctica-endemic species, reveals remarkable resilience to fluoride-related skeletal disorders, including osteoporosis, osteopetrosis, and hyperostosis [109]. This adaptation enables these birds to thrive despite elevated fluoride concentrations.

Impact on Plants

Despite its natural occurrence, fluorine is not an essential nutrient for plant growth and development [123]. Nevertheless, fluorine can infiltrate plants through various pathways, including soil absorption, water uptake, and atmospheric deposition. Prolonged exposure to excessive fluoride levels leads to cumulative toxicity in plant tissues, causing devastating consequences for vegetation. Notably, fluorine's scarcity in nature belies its potential harm, as plants do not require it for energy production or metabolic processes. The use of fluoride-contaminated groundwater for irrigation exacerbates agricultural productivity loss, inflicting additional damage on crops. A strong positive correlation has been established between fluoride accumulation in plant tissues and soil concentration [124]. Notably, this toxic ion can infiltrate plant cells through stomatal uptake; compromising plant health [125]. Fluoride-contaminated soil in southern Tunisia, a country in Africa, where Gabes identified as the most polluted site. Fluorine concentrations in the aerial parts of *Atractilys serratuloides*, a gypsum-tolerant plant species prevalent near superphosphate factories in Tunisia, reached approximately 300 ppm in Gabes. Earlier reproductive events, including flowering and fructification, were observed at the cost of diminished vegetative shoot growth of this species at the polluted sites, particularly during the summer season [126].

Fluoride accumulation causes structural and ultrastructural damage to leaf tissues and cells. Excessive fluoride exposure disrupts photosynthesis by reducing chlorophyll formation, degrading chloroplasts, and inhibiting the Hills reaction [127]. This results in impaired plant growth, characterized by decreased total chlorophyll, chlorophyll-a, and chlorophyll-b concentrations, reduced carotenoids and photosynthetic capacity, impaired root and shoot growth, decreased seedling health and mineral status, particularly calcium content [128]. Consistent with these findings, research in semi-arid zones has also shown that Fluoride contaminated soil leads to similar adverse effects on plant health [129]. Furthermore, excessive Fluoride levels have been linked to additional harmful consequences, including leaf tip burn, chlorosis, leaf necrosis, leaf spots, and decreased grain yield [130, 131] (Figure 9).

Fluoride poisoning may also have an impact on flowers, such as tulips, gladioli, and lilies [132]. In tomato, mung, and bell pepper plants exposed to fluoride at a dosage of 20–100 ppm, the NPP dropped by 6.46–62.24%, 10.27–53.61%, and 6.64–56.72%, respectively [133]. It is therefore known that fluoride toxicity in soil may have a severe impact on NPP in several crops at both very low and very high concentrations [124]. It has also been shown that fluoride inhibits calcium transport, which is essential for germination [134]. Long-term high fluoride tea consumption can lead to chronic fluoride intoxication [135]. Mondal and George [136] stated the highest drop in root biomass was 82.5% at a fluoride dosage of 95 mg NaF kg^{-1} soil, and shoot length rapidly declined as the fluoride concentration increased. Even though fluoride contamination severely reduces plant production, little is known about how plants respond in terms of morphology, mineralogy, and metabolic profile [128].

Figure 9: Fluoride-infested *Dracaena trifasciata* leaves showing leaf tip burn

Impact on quality of soil and microbial activity in soil

More than 90% of soil-bound fluoride is irreversibly bound to soil particles, rendering it insoluble [137]. Elevated fluoride levels in soil have devastating consequences, such as disrupted microbial activity, impaired soil ecology, and soil pollution, compromised plant survival. Fluoride in soil exists in five forms: water-soluble, exchangeable, organically bound, ferromanganese oxide-bound, and residual. Notably, the residual state accounts for approximately 98% of total fluoride, severely impairing soil health [138]. Unchecked industrial and agricultural emissions have led to fluoride over-enrichment in soil, hindering plant growth and posing significant human health risks.

The presence of fluoride in soil significantly impairs the functioning of soil microbial populations. Fluoride's broad-spectrum enzyme inhibition, affecting phosphoglucomutase, enolase, F-ATPase, sulfatase, catalase, and other enzymes, confers potent antibacterial properties [139]. Notably, fluorine's interaction with magnesium in bacterial enolase likely hinders glucose transport into bacterial cells, disrupting cellular metabolism [140]. Kumari *et al.*, [141] through their studies concluded that soil microorganisms play a vital role in nutrient mineralization and reutilization, alterations in microbial communities can precipitate cascading effects on ecosystem health, minerals like apatite, fluorspar, topaz, and mica break down, and fluoride ions are naturally released into the soil. When crops, vegetables, and fruits are irrigated with water stained with fluoride, it spreads to them. Since this bioaccumulation adds extra fluoride to the food chain in addition to the route through drinking water, it raises the danger of fluoride poisoning for the population that is already at risk.

CONCLUSION

Fluoride contamination has reached catastrophic levels, pervading every aspect of our planet's air, water, and soil through natural and human-induced sources. Natural sources, including volcanic rocks, geothermal waters, and mineral deposits, contribute to the fluoride menace, but human activities vastly exacerbate the issue through industrial emissions from aluminium, steel, and cement production, agricultural pesticides and fertilizers, sewage and wastewater discharge, fluoride-based medications, and contaminated groundwater from landfills. The combined impact of these sources has catastrophic consequences, endangering the health of our ecosystem and the very foundations of life on Earth. This pervasive pollution poses a pressing global threat, imperilling the health of plants, animals, and humans. Fluorosis, a debilitating condition triggered by excessive fluoride exposure, has attained alarming proportions worldwide. Groundwater contamination is a critical concern, with far-reaching consequences for human, animal, and environmental health. Fluoride exposure carries severe health risks, including chronic bone and joint pain, neurological damage, kidney, and hormonal disruption disproportionately affecting indigenous communities. Meanwhile, plants wither with stunted growth and leaf damage, soils degrade with altered pH and microbial disruption, and animals suffer skeletal fluorosis, dental problems, and reproductive issues. The economic and social fallout is equally devastating: widespread poverty, school dropouts, social isolation, and barriers to remarriage. Vulnerable populations in Asia remain largely uninformed of these dangers, exacerbated by inadequate regulation. To combat this crisis, thorough evaluations are crucial for informing health and financial policies, particularly in impoverished regions. Proactive measures, scientific research, and effective mitigation strategies are essential to minimize financial burdens and safeguard public health. Challenges persist due to unclear water rights, costly remediation technologies, communication breakdowns, and inadequate medical facilities. Moreover, public unawareness of climate change's intensifying effects on fluoride contamination adds complexity. To address this pressing issue, comprehensive monitoring and mitigation strategies are imperative to ensure access to safe drinking water, protect public health, and enhance the quality of life for affected communities.

COMPETING INTERESTS

The authors have declared that no competing interests exist.

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