Concise Review

Facts and Fallacies of the Fluoride Controversy: A Contemporary Perspective

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ABSTRACT

Fluoride is a natural element recognized for its dental benefits. Fluoride prevents caries due to its antimicrobial activity, enhancing enamel resistance and promoting remineralization After decades of fluoridation of municipal water supplies to reduce dental caries, an intense debate has resurfaced regarding water fluoridation as a public health strategy to combat caries. This renewed discourse occurs against the backdrop of extensive data that clearly demonstrate the vital role of fluoride in caries prevention. Indeed, the Centres for Disease Control and Prevention has stated water fluoridation as one of the top ten public health interventions in the twentieth century. The FDI World Dental Federation also advocates systemic fluoride use as a cost-effective caries prevention strategy, and supports its inclusion in public health policies through a number of policy directives. This debate in the US has intensified as a Court concluded that water fluoridation poses unreasonable risks such as reduction of the intelligence quotient (IQ) in children. Additionally, recent statements from the leadership of the US Health and Human Services agency suggest that water fluoridation may cause more harm than good leading some states, like Utah, to revoke fluoridation mandates This article aims to provide a contemporary perspective on fluoride by revisiting its benefits, controversies, and potential risks. It highlights the dual role of fluoride in both individual oral care and public health and underscores the necessity for safe, equitable, and effective delivery strategies tailored to the needs of diverse populations, balancing its preventive advantages with potential health concerns. The review culminates with a summary of policy statements from the FDI World Dental Federation regarding the promotion of oral health through both systemic and topical fluoridation.

Introduction

Oral health is fundamental to overall well-being, influencing essential functions such as communication, facial expressions, sensory perception (taste and smell), touch, mastication, swallowing, and the ability to express emotions without craniofacial discomfort or pain.[1] Indeed in a very recent report, entitled 'Global Report on Oral Health', the World Health Organization (WHO) highlighted the urgent need to incorporate oral health within the broader framework of non-communicable diseases (NCDs).[2] Another study has identified untreated dental caries in permanent teeth as the most prevalent oral disease, affecting approximately 2.5 billion people

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worldwide and showing an age-standardized prevalence of 34.1%. In primary teeth, untreated caries impacted 573 million children, corresponding to a 7.8% age-standardized prevalence.[3] By 2017, estimates indicated that around 3.5 billion individuals (95% uncertainty interval [95% UI]: 3.2-3.7 billion) suffered from oral diseases, with 2.3 billion people experiencing untreated caries in permanent teeth and 532 million children affected by caries in primary teeth.[4] As a result, dental caries remains among the most widespread yet frequently neglected NCDs, particularly affecting children and adolescents, many of whom require urgent dental care.[5,6]

Caries prevention can be achieved through both community-based and individual interventions. Effective strategies focus on biofilm management, modulation of oral microorganisms, and promoting a low-sugar diet to mitigate caries risk and prevent lesion progression[7] alongside the topical or systemic delivery of fluroides. The latter, in particular plays a critical role and has a number of delivery modes, each addressing specific needs to promote oral health effectively (Figure 1). Topical fluoride is applied directly to the tooth surface and includes self-applied methods, such as fluoride-containing toothpaste, mouth rinses, and gels, as well as professionally administered techniques such as fluoride varnishes, solutions, gels, and dental materials.[8] Topical methods in particular enhance enamel remineralization of teeth that are already erupted within the oral ecosystem. On the other hand, systemic fluoride is ingested and incorporated into developing teeth and bodily fluids like saliva, providing long-term protection. Moreover, for children with developing permanent dentition, there is no alternative to systemic fluoridation as it provides lifelong benefits by incorporating fluoride into the developing enamel prior to eruption, ensuring long-term resistance to acid attacks.

Common systemic fluoride delivery systems include community water fluoridation, school water programs, fluoride supplements, fluoridated salt, and milk fluoridation. In addition, water-added foods and beverages, teas, floss, and mouthwashes complement the supply of community water fluoridation. Together, these methods play a pivotal role in comprehensive caries prevention strategies, tailored to suit individual and community needs.[9]

Community water fluoridation, in particular, has been practiced since 1945 and is considered an effective and efficient way to deliver fluoride on a large scale to communities.[9] Its effect in reducing caries levels in these communities, compared to those with very low fluoride content, has been conclusively demonstrated in many international studies. Indeed, the Centres for Disease Control and Prevention (CDC) declared in 1991 water fluoridation 1 of the ten great public health achievements of the twentieth century.[10] It has been estimated that in 2014, more than 370 million people in over 27 countries received the benefits of water fluoridation.[11] Due to such overwhelming evidence, the FDI World Dental Federation, the largest non-governmental organization representing millions of dentists worldwide, has been a strong advocate for the inclusion of systemic as well as topical fluoride in public health policies for decades, emphasizing its role in preventing dental caries and improving global oral health.[11]

Fluoride, depending on its level of ingestion has both beneficial and harmful systemic effects on humans. Due to some of the potential adverse effects due to excess fluoride intake there has been a vociferous anti-fluoride movement in many regions of the world, canvassing against the introduction of this element into water and as food additives.[12] This issue has resurfaced recently in the USA when, on September 24, 2024, a California District Court ruled in the case of Food & Water Watch Inc. v. the US Environmental Protection Agency (EPA). The decision stated that if the EPA denies a US resident's petition of concern, that resident is entitled to judicial review regarding whether the chemical poses an unreasonable risk, regardless of the EPA's stance and interpretation of the data. In this particular case, the judge also ruled that community water fluoridation presents a risk of reduced IQ in children.[13] This, along with the newly confirmed views of the leadership of the Health and Human Services secretariat that water fluoridation may lead to more harm than good, has rekindled the debate over water and food fluoridation.[14]

The aim of this article is to provide a contemporary perspective on fluoride by revisiting its benefits, controversies, and potential risks. By examining the scientific evidence and clinical practices surrounding fluoride use, this review seeks

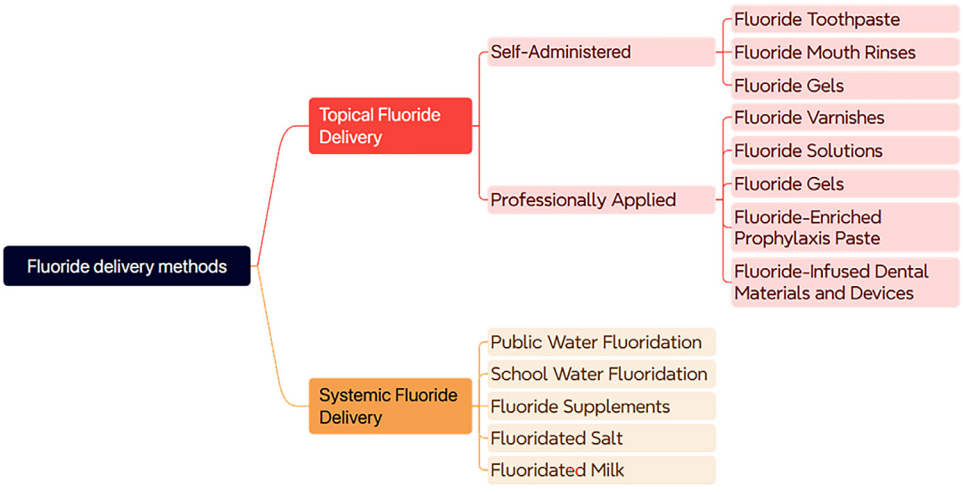

Fig. 1 – Current methods of fluoride delivery to the public.

to enlighten dental professionals and the general public on the appropriate and safe application of fluoride in dentistry.

Mechanism of fluoride action

Fluoride is widely recognized as an essential element in the prevention and management of dental caries due to its unique properties that target both bacterial activity and tooth mineral dynamics.[15] Its anticariogenic and antimicrobial effects have been extensively studied, establishing fluoride as a cornerstone of modern preventive dentistry. Fluoride works by interacting with the oral environment in multiple ways, influencing bacterial metabolism and enhancing tooth resistance to acid dissolution.[16-19]

The antimicrobial action of fluoride primarily stems from its ability to acidify the bacterial cytoplasm.[20,21] When fluoride ions (F^-) combine with hydrogen ions (H^+) to form hydrogen fluoride (HF), the HF molecule penetrates bacterial cells. Once inside the cellular cytoplasm, HF dissociates, releasing H^+ and F^- ions that disrupt the pH balance, and inhibit its enzymatic processes. However, this earlier concept appears to be an over-simplification as recent evidence suggests that fluoride exerts stress on bacterial cell membranes through *Fluc* family fluoride channels, that are specific to fluoride ions.[22,23] Thus, higher fluoride concentrations can inhibit bacterial growth, lowering the pH and increasing extracellular H^+ also facilitate greater cellular uptake allowing for bacterial inhibition at lower extracellular fluoride levels.

Due to increased intracellular fluoride content enzymes such as ATPase, which regulates energy production, and enolase, crucial for glycolysis, are inhibited by fluoride, preventing the bacteria from efficiently metabolizing sugars. This not only reduces acid production but also impairs bacterial growth, reproduction, and biofilm formation.[24]

Fluoride also reduces the production of extracellular polysaccharides by bacteria, which helps disrupt biofilm integrity and reduces bacterial adhesion to tooth surfaces.[25] Furthermore, it mitigates the production of vital bacterial enzymes such as immunoglobulin A protease that breaks down the host defences further highlights its multifaceted action against cariogenic biofilms. Moreover, the ability of fluorides to concentrate within dental plaque ensures that their protective effects are localized to areas at high risk of demineralization.[26,27]

Beyond its effects on microbes, fluoride has a profound impact on the dynamics of tooth mineralization and demineralization. It enhances the remineralization process by fostering the deposition of calcium and phosphate ions into demineralized areas of enamel.[28] This process is further strengthened by the formation of fluorine-containing apatites, e.g. fluorapatite and hydroxyfluorapatite, that are more resistant to acid attacks and demineralization than hydroxyapatite, the natural mineral in tooth enamel. Fluorine-containing apatites have unique structures that make enamel less soluble in acidic milieus, providing long-term protection against caries.

Epidemiological and laboratory evidence supports the notion that fluoride's predominant effects are topical and post-eruptive, emphasizing its importance throughout life, not just during childhood. When used consistently and appropriately, fluoride is most effective in small, sustained concentrations within dental plaque and saliva. This allows it to continuously interact with the oral environment, maintaining a balance that favors remineralization over demineralization. Contrary to earlier assumptions, fluoride is highly beneficial for adults, especially for individuals with demineralized enamel, as the uptake of fluoride is greater in compromised areas than in sound enamel.[29]

In addition to its individual benefits, fluoride contributes to public health as an integral part of community caries prevention programs, such as water fluoridation, which ensures equitable access to its protective effects irrespective of affordability of topical applications. This dual role of fluoride—targeting both individual oral hygiene practices and broader public health initiatives—underscores its significance in controlling dental caries and improving oral health outcomes globally.[30] However, its effectiveness depends on regular exposure in optimal concentrations, making its integration into daily oral care routines and public health policies essential. The foregoing mechanisms of action of fluoride are illustrated in Figure 2.

Water fluoridation

Fluoride is a naturally present element in freshwater, with its concentration varying widely from 0.01 ppm (ppm, parts per million parts of water; 1.0 ppm = 1.0 mg/L) to as high as 100 ppm, depending on the geographic location and water source.[27] In the 1930s, researchers observed that populations consuming water with naturally elevated fluoride levels had a lower incidence of dental caries. This discovery led to the recognition of fluoride as a protective agent against tooth decay.[12] Based on this finding, water fluoridation—the controlled adjustment of fluoride levels in public water supplies—was introduced as a preventive public health measure in Grand Rapids, Michigan, USA in 1945.[31] Indeed, CDC named fluoridation of drinking water as one of ten great public health interventions of the 20th century because of the dramatic decline in cavities since community water fluoridation since 1945.[32] This method effectively delivers fluoride to large populations without requiring individual effort, making it an equitable and practical strategy for reducing dental caries.[27]

As stated above, more than 370 million people in over 27 countries worldwide had access to fluoridated water in 2012, either through natural sources or by controlled adjustments to reach optimal fluoride levels. A number of jurisdictions in the United States, Brazil, Australia, Canada, Spain, Argentina, South Korea, and New Zealand, have implemented water fluoridation programs[33] have public municipal water fluoridation programs. However, only Singapore[34] and Hong Kong[35] are having fluoridation (at ~ 0.5ppm F using disodium hexafluorosilicate (Na_2SiF_6) and hexafluorosilicic acid (H_2SiF_6) following BS:EN 12173 and 12174 standards, respectively) that covers virtually 100% of the population.

CDC has reaffirmed that community water fluoridation is a cornerstone strategy for the prevention of caries in the U.S, as it is a practical, cost-effective, and equitable way for communities to improve their residents' oral health regardless of age, education, or income.[35] It is notable, however, that CDC

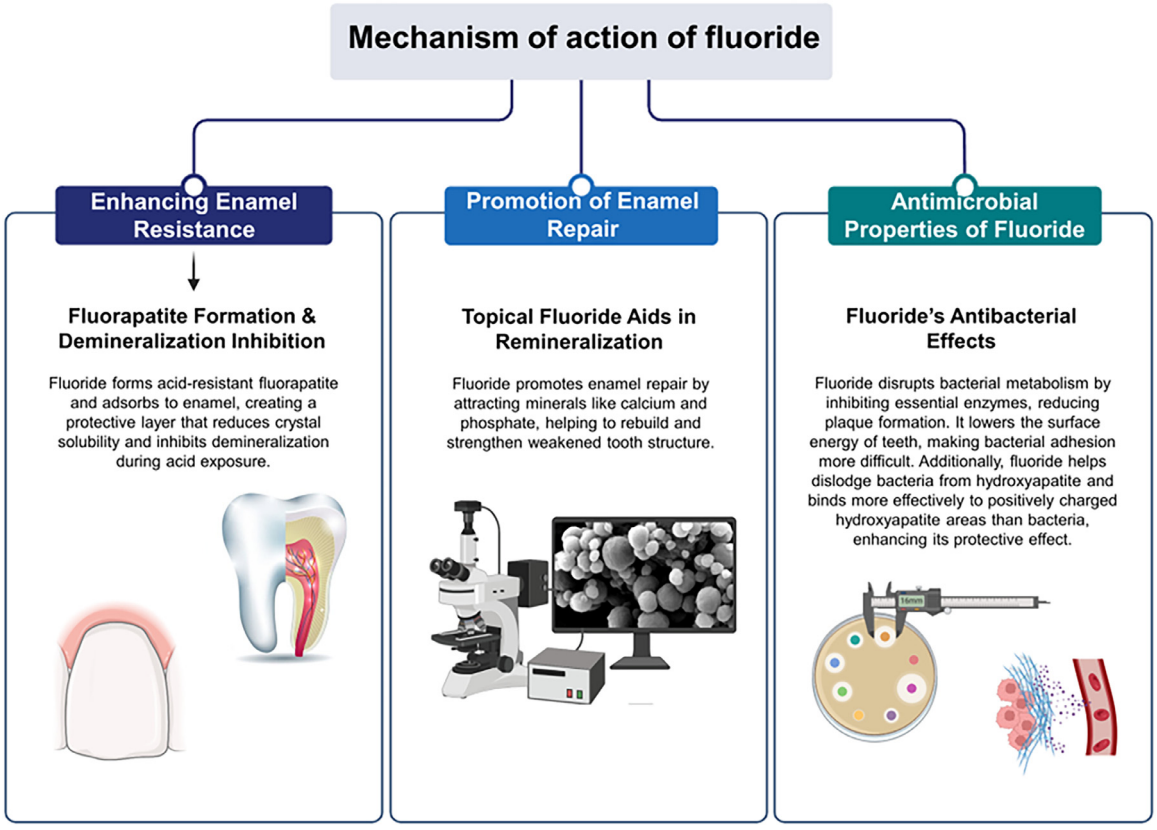

Fig. 2 – Flowchart showing the key mechanisms of the anti-caries action of fluorides.

does not mandate community water fluoridation and the U.S. Public Health Service (USPHS) recommended fluoride levels of 0.7 mg/L (0.7 ppm; equal to 3 drops of water in a 55-gallon barrel) are not an enforceable standard[36] and the US Environmental Protection Agency's (EPA's) enforceable and non-enforceable standards for fluoride in drinking water are 4.0 mg/L and 2.0 mg/L,[37] respectively, and the World Health Organization's (WHO's) drinking water quality guideline for fluoride is 1.5 mg/L.[36]

Over the past 7 decades, extensive research has consistently demonstrated the effectiveness of fluoride in caries prevention. Studies conducted before 1990 across 23 countries reported caries reductions of 40-50% in primary teeth and 50-60% in permanent teeth.[32] Other reviews also confirm a decline in caries prevalence, with reductions ranging from 30-59% in primary teeth and 40-49% in permanent teeth.[34]

In addition, multiple studies have shown the deleterious effect of stopping community water fluoridation on the prevalence of dental caries. More recent studies form Alaska[38] and Canada[39] have shown that communities that sopped water fluoridation show significant increase in childhood caries when compared with similar cities that did not. A 2024 study from Israel reported a 2-fold increase in dental treatments for children within 5 years after municipal water fluoridation was banned in 2014.[40]

While water fluoridation has significant benefits, excessive ingestion of fluoride during tooth development, particularly during the transition and early-maturation stages of enamel formation, can lead to dental fluorosis.[41] Dental fluorosis manifests as dental abnormalities, including discoloration (mottling of teeth), pitting, and enamel deterioration. Rarely individuals with severe dental fluorosis may experience tooth sensitivity.[42]

Dental fluorosis is usually seen where fluoridated water and fluoride-containing dental products are widely used. [41] Between 1999 and 2004, approximately 41% of American adolescents aged 12-15 exhibited some degree of dental fluorosis.[43] Overall, while dental fluorosis can have aesthetic and psychosocial implications, its direct health effects are minimal. However dental fluorosis is more pronounced in some regions of Africa with naturally high fluoride concentrations in drinking water and soil.[44]

Finally, in this context, it is noteworthy that only a small fraction of the global population—less than 10%—has access to fluoridated water, as implementing such programs is challenging in regions with complex water supply infrastructures or geographical limitations.[45,46] Despite these constraints, water fluoridation continues to be a cornerstone of caries prevention and remains a vital strategy for enhancing oral health worldwide.

Milk fluoridation

Milk, due to its rich nutritional content, plays a crucial role in human nutrition from infancy to old age. The concept of utilizing milk as a medium for fluoride delivery was first investigated in the early 1950s in Switzerland, the United States, and

Japan.[46] Since 1986, the World Health Organization (WHO) has actively promoted milk fluoridation through its International Programme for Milk Fluoridation, aiming to evaluate its effectiveness as a community-based approach for preventing dental caries.[46]

At present, approximately 15 countries implement milk fluoridation programs, supported by both the WHO and the Food and Agriculture Organization (FAO), with fluoridated milk primarily distributed to children in schools and kindergartens. Research has confirmed that fluoride in milk is bioavailable and can serve as an effective method for fluoride supplementation. Systematic reviews on milk fluoridation have documented a significant reduction in dental caries among children who regularly consume fluoridated milk. While earlier studies consistently demonstrated its benefits,[47] a broader review encompassing 18 studies from 12 different countries yielded mixed findings, with only 9 studies indicating benefits for primary teeth and 12 for permanent teeth.[48] Another study conducted in Bulgaria has further reinforced the protective effects of daily fluoridated milk intake in schools, showing a notable reduction in caries compared to non-fluoridated milk.[49] Overall, milk fluoridation has proven most effective when introduced early in childhood—before 4 years of age and around the eruption of the first permanent molars—providing preventive benefits for both primary and permanent dentition. However, the available data indicate that only over 1.5 million children worldwide participate in fluoridated milk programs[45] and community water fluoridation is a much more effective way to deliver fluorides to this demographic entity.

Children are generally recommended to intake up to 200 mL of fluoridated milk daily for approximately 200 days annually, ensuring a fluoride intake of 0.50-0.85 mg per child.[47] This dosage is carefully regulated based on factors such as age and existing fluoride exposure, minimizing the risk of adverse effects. However, milk fluoridation is regarded as less effective than water fluoridation because fluoride tends to form insoluble compounds in milk, which can diminish its absorption in the body.[46]

The economic and practical feasibility of milk fluoridation programs are noteworthy. The process of adding fluoride to milk is straightforward, and the cost difference between fluoridated and non-fluoridated milk is negligible. On average, these programs cost about 2-3 USD per child annually, as demonstrated by successful implementations in countries like Chile, Thailand, and the United Kingdom.[48] Despite its limitations, milk fluoridation remains a cost-effective and accessible strategy to improve oral health in communities lacking access to water fluoridation.

Salt fluoridation

As mentioned, in many regions worldwide, access to water fluoridation remains restricted due to political, geographical, financial, and technical challenges, including decentralized water supplies and inadequate infrastructure. To overcome these barriers, Switzerland introduced fluoridated salt in 1955, drawing inspiration from the success of iodized salt in preventing goitre.[9] This approach gained widespread acceptance following favourable results from community trials, and endorsements from organizations such as the WHO and the FDI International Dental Federation.

Subsequent approval of sodium and potassium fluorides as food additives by the European Union has added further weight to this notion.[50] In 1980-1982, fluoride addition to table salt was officially authorized for human consumption, providing an alternative to water fluoridation.[51] Fluoridated salt is distributed through various channels, including domestic salt for household use, meals served in schools and large kitchens, and even in baked goods such as bread. This approach delivers fluoride in a manner that exerts both systemic and topical effects, making it a viable option in regions where water fluoridation is impractical.[46]

Fluoridated toothpastes

Studies have shown that regular use of fluoride toothpaste can significantly reduce the risk of cavities. For children, whose teeth are still developing, fluoride plays a critical role in forming strong, healthy enamel. The CDC has reported that community water fluoridation and fluoride toothpaste have contributed to a dramatic decline in dental caries over the past few decades.[9]

A Cochrane review of numerous trials found that children aged 5 to 16 years who used a fluoridated toothpaste had fewer decayed, missing and filled (DMF) permanent teeth after 3 years (regardless of whether their drinking water was fluoridated or not). Twice a day fluoridated toothpaste use was shown to increase the benefit. The reviewers could not reach any conclusion on the risk that using fluoride toothpastes could mottle teeth (fluorosis), an effect of chronic ingestion of excessive amounts of fluoride when children are young.[52] Even though toothpaste manufacturers claim to have the same concentration of fluoride, the actual bioavailability of fluoride from these products tends to be lower. This discrepancy arises from the formulation of the toothpastes and the different fluoride compounds used (e.g. NaF, NaMFP and Olafur) which affect the solubility of fluoride ions.[53]

Combination of multiple fluoride sources

Utilizing multiple self-administered topical fluoride products alongside water fluoridation provides greater protection against dental caries than relying on a single method. A dose-response relationship exists, meaning that consistent exposure to multiple low-concentration fluoride sources enhances the overall effectiveness of caries prevention. This approach is particularly beneficial for individuals at high risk of developing caries.[54]

However, concerns have been raised regarding the concurrent use of fluoridated salt and fluoride toothpaste. Nevertheless, research suggests that this combination has not resulted in excessive levels of enamel fluorosis. Mild cases of dental fluorosis have been observed in children who consumed both fluoride tablets and fluoridated salt, but these are infrequent.[55] The risk of fluorosis is primarily linked to excessive fluoride intake during the stages of tooth development, particularly from the late secretion phase to early enamel

maturation. In contrast, for adults, the simultaneous use of topical fluoride products and fluoridated water does not present a fluorosis risk, as their teeth are already fully developed.

To minimize the risk of fluorosis in children, supervision during the use of topical fluoride products is important. The risk associated with children swallowing fluoride toothpaste arises mainly when large amounts are ingested consistently, particularly during the critical phases of tooth development. Using small, age-appropriate quantities under adult supervision generally poses no harm. Clearly frequent ingestion of excessive toothpaste can contribute to dental fluorosis.[42]

Thus, it is important for caregivers to supervise brushing and ensure that children use only a small, pea-sized amount. While small doses are generally safe, the regular swallowing of excessive amounts during the developmental stages of teeth increases the risk of fluorosis. Therefore, careful monitoring and appropriate use of fluoride are essential to maximize its caries-preventive benefits while minimizing risks.[56] Indeed, international efforts have been made to assess and enhance the fluoride availability in toothpastes.[52]

While topical fluoride is highly effective in preventing dental caries through its post-eruptive actions, it is important to recognize that systemic fluoride plays a crucial role in children during tooth development. Being incorporated into the enamel structure prior to eruption, systemic fluoride enhances long-term resistance to acid attacks.[57] Therefore, for children with developing dentition, systemic fluoridation offers a foundational, lifelong benefit that complements the effects of topical fluoride.

Potential adverse effects of fluoride

Fluoride is considered an essential nutrient, and its consistent use within recommended levels is safe and does not result in harmful physiological effects in humans.[58] However, like all chemicals, fluoride has safe ingestion thresholds, and exceeding these limits can lead to adverse effects.[59] Excessive fluoride exposure is associated with conditions such as skeletal and dental fluorosis, as well as systemic issues, including gastrointestinal, neurological, and urinary complications.[60] The majority of fluoride toxicity cases—over 80%—occur in children under the age of 6, primarily due to accidental ingestion of fluoride-containing products such as toothpaste or mouthwash. In contrast, fluoride toxicity is rare among adults, particularly in developed nations.[61]

In general, adverse effects of fluoride can be categorized into 2 types, acute or chronic. Acute toxicity occurs when large quantities of fluoride are accidentally ingested, leading to immediate and severe reactions. On the other hand chronic toxicity results from long-term exposure to elevated levels of fluoride, often observed in endemic regions where groundwater contains high concentrations of the chemical (Figure 3). These are further discussed below.

Acute toxicity

Acute fluoride toxicity occurs when a large amount of fluoride is ingested within a short period. While fatal fluoride overdoses, which are extremely rare, occur after a single dose of 5-10 mg/kg body weight. Finally, lethal doses typically range from 70-140 mg/kg body weight of fluoride.[62] Inhalation of fluoride can cause severe respiratory tract irritation, leading to symptoms such as coughing and choking.[63] Direct exposure to liquid or vapor fluoride may result in skin burns and, if it comes into contact with the eyes, can cause permanent visual damage.[64]

Acute fluoride poisoning often presents with nonspecific gastrointestinal symptoms, including nausea, vomiting, diarrhea, and abdominal pain. In severe instances, complications may escalate to renal and cardiac dysfunction, coma, or even death.[65] For children, toxic symptoms can emerge with fluoride ingestion as low as 8.4 mg/kg.[66]

Upon ingestion, fluoride interacts with gastric acid to produce hydrofluoric acid, a highly corrosive substance that triggers symptoms like nausea, vomiting, diarrhea, excessive salivation, and abdominal pain. In severe cases, this may progress to hemorrhagic gastroenteritis.[59] Critical

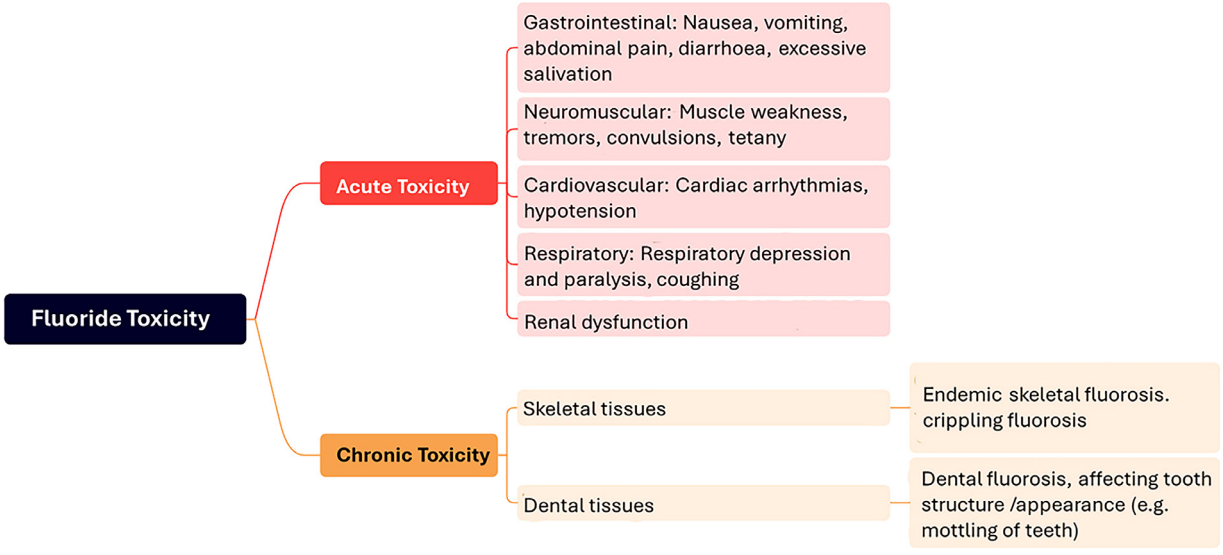

Fig. 3 – Variants of Fluoride toxicity.

complications include hypocalcemia, which can lead to cardiac arrhythmias, heightened reflex responses, and tetanic muscle contractions. Without prompt medical intervention, respiratory paralysis may develop, which can be fatal.[67] It should be noted however that these are extremely rare events.

Chronic toxicity

Chronic fluoride toxicity occurs from long-term ingestion of fluoride in amounts exceeding therapeutic levels, leading to dental fluorosis, skeletal fluorosis, and systemic effects like weight loss, malaise, and anaemia[64] and even effects on the reproductive systems.[68]

As mentioned above, dental fluorosis is a systemic disturbance of tooth development caused by excessive fluoride intake during enamel formation, particularly within the first 6 to 8 years of life. It does not occur in fully erupted teeth and is endemic in areas with high natural fluoride levels in water. Mild fluorosis may enhance resistance to decay due to the increased fluoride content in enamel. On the contrary, severe fluorosis can lead to uneven surfaces and enamel damage, increasing susceptibility to decay.[69]

Safe daily fluoride intake is 0.05 to 0.07 mg /kg/day. Exceeding this threshold increases the risk of fluorosis.[70] Factors influencing plasma fluoride levels include total fluoride intake, the type of intake, renal function, bone metabolism rates, and metabolic activity. Fluorosis can cause subsurface porosity and hypo- and hypermineralized bands within enamel, with severe porosity often affecting the outer enamel layer.[71,72]

Clinically, fluorosis is most visible in the permanent dentition, though primary teeth may also be affected due to fluoride transfer through the placenta or due to shorter enamel formation periods in primary teeth.[73] Fluorosis commonly affects the premolars, second molars, and upper incisors, with visible effects typically appearing on the incisal or occlusal 2-thirds of enamel.[74]

Mild fluorosis manifests as white opacities, while severe forms lead to enamel hypoplasia, pitting, fractures, and discoloration ranging from yellow to dark brown.[71] In severe cases, extensive enamel loss and structural damage may result, affecting normal tooth morphology.[75]

Endemic Skeletal Fluorosis: Endemic skeletal fluorosis is a chronic bone and joint disease resulting from long-term daily ingestion of fluoride at doses exceeding 8 ppm.[76] This condition leads to progressive bone density increase, calcification of ligaments, joint stiffness, and restricted movement. Advanced stages, known as “crippling fluorosis,” cause deformities and fixation of the spine and chest in an inspiratory position.[71]

Learning and Memory Deficit: One of the more important concerns regarding chronic toxicity of fluorides is the contention that the long-term ingestion of fluorides either via the community water supply and/or other sources is likely to affect the learning and memory (IQ) of children.

In light of this, the NTP (National Toxicology Program) of the US recently conducted a comprehensive meta-analysis of 74 studies from multiple countries including Canada, China, India, Iran, Pakistan, and Mexico, but not the US.[77] The cohorts evaluated in these studies comprised infants, and children who received total fluoride exposure amounts higher than 1.5 mg fluoride/L of drinking water. A number of animal studies were also included in the evaluation. The review concluded that ‘experimental animal studies and human mechanistic evidence do not provide clarity on the association between fluoride exposure and cognitive or neurodevelopmental human health effects. Human mechanistic studies are too heterogeneous and limited in number to make any determination on biological plausibility.[77] The authors of also concluded that data were of‘ ‘low quality‘ and there is uncertainty in the dose-response association between fluoride exposure and children’s IQ when fluoride exposure was estimated by drinking water alone at concentrations less than 1.5 mg/L.[78]

Growing opposition to fluoridation

Concerns over fluoride toxicity and related risks have sparked ongoing debates about fluoridation, prompting some countries to implement measures to limit fluoride exposure and intake. Key claims related to this topic, as proposed by various authorities along with counterpoints, are highlighted below.

1. **Claim: Water fluoridation leads to uncontrollable fluoride intake:** Once water is fluoridated, it becomes challenging to regulate fluoride intake since individuals consume varying amounts of water depending on their activity levels and health conditions. For example, manual labourers, diabetics, and athletes tend to drink more water, increasing their risk of excessive fluoride intake.[79] This inconsistency affects people regardless of age, health status, or specific therapeutic needs, as children receive the same fluoride concentration as adults, and patients with conditions such as kidney disease are exposed to similar levels as healthy individuals.

   Counterpoint: Public health recommendations in the US and other regions (e.g., 0.7 mg/mL or ppm) include a wide safety margin far below that which leads to any signs of toxicity. Hence even with variation in water intake by individuals, toxicity thresholds are not reached.
2. **Claim: Contamination of water with toxins occurs during fluoride addition.** Fluoridated water raises concerns about contamination with toxic chemicals like arsenic. While some countries, such as New Zealand, mandate suppliers to provide detailed certificates of analysis for water additives, this is not universally enforced, increasing the potential for contamination.[80] Additionally, animal and human studies suggest that fluoride exposure may have neurotoxic,[81] nephrotoxic,[82] and thyroid-disrupting effects.[83]

   Counterpoint: Fluoride additives for water treatment are strictly regulated and monitored for purity and safety. Contamination risks are non-existent in countries with strong public health infrastructure. To date, after over 7 decades of water fluoridation, no studies indicate a history of such events.
3. **Claim: Dental fluorosis and mottling.** Excessive fluoride intake It can cause dental fluorosis, with severity ranging from mild to severe. The CDC’s 2024 report highlighted a high prevalence of fluorosis among children in some regions.[40]

Counterpoint: Dental fluorosis has been observed in both fluoridated and non-fluoridated regions, such as in New Zealand's[84] although, this trend is inconsistent worldwide. Mild fluorosis is typically cosmetic and often undetectable. Severe forms are rare and usually linked to excessive fluoride from multiple sources during early childhood. Usually, such endemic widespread fluorosis (e.g. mottling of teeth) is seen when the local water supply has naturally high levels of fluoride.

4. **Claim: Monitoring of fluoride.** Poor Monitoring and oversight of fluoridation in some jurisdictions may lead to unwanted side effects.

   Counterpoint: This is an issue of regulatory enforcement, not fluoride itself. Proper policy and oversight can mitigate this risk without dismissing the value of fluoridation.
5. **Claim: Availability of alternative Sources of Fluoride.** Fluoride is now present in numerous sources beyond water,

Table 1 – Misconceptions on fluoridation and evidence-based counterpoints and clarifications.

Misconception or Concern	Claim	Evidence-Based Clarification
Uncontrollable Fluoride Intake	Fluoride intake varies depending on water consumption, making it difficult to control.	Public health recommendations (e.g., 0.7 ppm) include a wide safety margin. Even with variation in water intake, toxicity thresholds are not reached.[41]
Risk of Water Contamination	Fluoridated water may contain harmful contaminants like arsenic.	Fluoride additives for water treatment are regulated and monitored for purity and safety. Contamination risks are rare in countries with strong public health infrastructure.[41]
Lack of Monitoring in Some Countries	Some nations do not enforce certification of fluoride additives.	This is an issue of regulatory enforcement, not fluoride itself. Proper policy and oversight can mitigate this risk without dismissing the value of fluoridation.[77]
Dental Fluorosis	Excess fluoride causes cosmetic or structural damage to enamel.	Mild fluorosis is typically cosmetic and often undetectable. Severe forms are rare and usually linked to excessive fluoride from multiple sources during early childhood.
Adverse Health Effects	Fluoride may cause neurotoxic, kidney, or thyroid effects.	Such effects have only been observed with chronic exposure to high levels (well above 1.5-2 ppm). No harm is associated with fluoride levels used in community water (0.7 ppm).[40]
Alternative Sources of Fluoride available	Fluoride is already present in food, beverages, and dental products.	Multiple sources improve dental protection. Total intake from all sources in most populations remains within the recommended safe range.[27,46] Fluoridation provides a simple, cost-effective way to reduce cavities across entire populations, especially in communities with limited dental care access
Topical Benefit Over Systemic Use	Fluoride is more effective topically than systemically.	Topical fluoride is important, but systemic exposure during tooth development and the equitable delivery through water remain vital for population-level prevention.[41] Being incorporated into the enamel structure prior to eruption, systemic fluoride enhances long-term resistance to acid attacks.[45]
Tooth Decay in Low-Income Countries	Fluoridation hasn't eliminated caries in disadvantaged regions.	Various studies have shown that fluoridation reduces overall caries risk in low income populations.[41] Fluoridation is a preventive tool, not a cure-all.[27]
Lack of RCT Evidence	Fluoridation lacks support from RCTs.	Ethical and logistical barriers limit RCTs in public health. However, decades of high-quality observational and cohort studies provide strong evidence for effectiveness.[57]
"Unapproved Drug" Claim	The U.S. FDA classifies fluoride as an unapproved drug.	This label applies to specific supplements, not to water fluoridation. Major bodies like the CDC, WHO, American Dental Association (ADA), and FDI endorse community fluoridation as safe and effective.[41]
Professional Opposition	Thousands of professionals oppose water fluoridation.	A small minority oppose it, while over 100 national and global health organizations support fluoridation based on solid scientific evidence.[14]

including foods like tea,[85] mechanically deboned meat, and pesticide residues[83] as well as in non-ingested products like fluoride-based dental items. Research increasingly supports that fluoride's primary benefit is topical rather than systemic.[57] Therefore, applying fluoride directly to teeth via toothpaste is more effective and safer than systemic ingestion.[79]

Counterpoint: It is true that multiple sources of fluorides are available but these are not accessible to the whole populace due to reasons of access, poverty and/or ignorance.

Additionally, for children with developing permanent dentition, there is no alternative to systemic fluoridation as it provides lifelong benefits by incorporating fluoride into the enamel structure prior to eruption, whereas topical fluorides do not reach systemic circulation. Finally, the toxic dose of fluoride is significantly high, ensuring that the total intake from all sources in most populations remains within the recommended safe range.

6. **Claim: Miscellaneous**. Tooth decay remains a prevalent issue in many fluoridated low-income countries, where poor oral hygiene and lack of access to dental care are the main contributors to the problem.[79] The York Review commissioned by the British Government found that none of the available fluoridation studies met the highest quality (Grade A) classification.[86] By 2012, over 4000 professionals had signed a memorandum advocating for the end of water fluoridation worldwide.[87]

   Counterpoint: Fluoridation reduces caries risk, but oral hygiene, sugar intake, and dental care access also play key roles. Fluoridation is a preventive tool, not a cure-all. More recent comprehensive meta-analyses of numerous studies, conducted over several decades, clearly indicate that fluoride exposures that far exceed the World Health Organization Guidelines for Drinking-water Quality of 1.5 mg/L are needed for adverse side effects mentioned above including lower IQ levels of children.[78]

A summary of misconceptions and concerns about fluoridation with Evidence-Based Clarifications is given in Table 1.

As for the public and professional opposition to water fluoridation, several major governmental and non-governmental bodies such as the CDC, WHO, American Dental Association (ADA), and FDI World Dental Federation fully endorse community fluoridation as safe and effective.

Two recent public polls in the USA have found that the largest share of Americans support fluoridation, with 48% and 40% of respondents wanting to keep fluorides in public water supplies, and a minority, 28% and 26%, respectively supporting its withdrawal.[88]

Finally, we provide below a summary of 5 policy statements on fluoridation and oral health promulgated by the FDI from 2009 onwards.

FDI policy statements on fluorides: promoting oral health through water fluoridation

Over the past few decades the FDI World Dental Federation has addressed the issues of both topical and systemic fluoridation, including water fluoridation, on multiple occasions.[11,89,90]

The organization has categorically stated fluoridation as an effective measure for preventing dental caries. Some of the key points from their policy statements are summarised below:

- *Systemic Fluoridation*: FDI endorses community water fluoridation as a safe and effective public health measure that significantly reduces dental caries in populations.
- *Topical Fluoridation*: The organization advocates for the use of topical fluorides, such as fluoride toothpaste and professional applications, as they are effective in reducing the incidence of dental caries.
- *Safety and Efficacy*: FDI emphasizes that both topical and systemic forms of fluoridation are safe when used correctly as they have been extensively studied for their benefits in oral health.
- *Public Health Policy*: The federation encourages governments and health authorities to implement and maintain fluoridation programs based on the strength of overwhelming evidence-based scientific evidence and public health needs.

The foregoing should be read in conjunction with a number of other policy statements on fluorides in the Fluoride archives of the FDI World Dental Federation.

Conclusions

Fluoride has played a pivotal role in the prevention and management of dental caries through its well-established mechanisms of action, including enamel remineralization, inhibition of demineralization, and antimicrobial properties. Various fluoride delivery methods, such as water, milk, and salt fluoridation, and toothpastes have demonstrated significant public health benefits, particularly in reducing caries prevalence. However, concerns regarding fluoride toxicity, excessive intake, and potential systemic effects have fuelled ongoing debates on its widespread use. While controlled exposure to fluoride is essential for maximizing its dental benefits, unregulated consumption poses rare risks such as dental and skeletal fluorosis.

The controversy surrounding fluoride highlights the need for evidence-based public health policies that prioritize safety, efficacy, and equitable access to fluoride. Given that fluoride's primary benefits are topical, strategies emphasizing the use of fluoride toothpaste and professionally applied treatments clearly offer supplementary alternatives or adjunctive modalities to water fluoridation. However, for children with developing permanent dentition, there is no substitute for systemic fluoridation as it provides lifelong benefits by incorporating fluoride into the enamel structure whereas topical fluorides do not reach systemic circulation. Further high-quality research, including randomized controlled trials, is necessary to assess long-term outcomes and refine fluoride recommendations. The review highlights the dual role of fluoride in both individual oral care and public health and underscores the necessity for safe, equitable, and effective fluoride delivery strategies tailored to the needs of diverse populations, balancing its preventive advantages

with potential health concerns. Indeed, the need for water fluoridation and its global adoption has become all the more imperative considering that the burden of oral disease including dental caries has remained largely unchanged and at a high level over the past 30 years.[91,92]

Availability of data and material

All the data available have been included in the manuscript.

Author contributions

Nozimjon Tuygunov and **Lakshman Samaranayake**: Conception; Data curation; investigation; methodology; formal analysis; software; writing – original draft; writing – review and editing. **James Tsoi:** formal analysis; investigation; methodology; software; writing – original draft; writing – review and editing. **Thantrira Porntaveetus:** Investigation; resources; software; writing – review and editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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