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Groundwater Fluoride Concentration and Dental Fluorosis Status in School-Age Children Living in Areas Relying on Groundwater as the Primary Drinking Water Source: A Systematic Review

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ABSTRACT
Groundwater is a major, often unmonitored, source of excess fluoride in many communities because its concentration depends on local geology rather than regulated fluoridation, and while the relationship between fluoride exposure and dental fluorosis is well established, evidence specifically addressing groundwater-dependent populations remains scattered across geographically diverse, small-scale studies. This systematic review aimed to synthesise evidence on groundwater fluoride concentration and dental fluorosis status among school-age children in areas relying on groundwater as the primary drinking water source. This review followed PRISMA 2020 guidelines, and a systematic search of PubMed, Scopus, and ScienceDirect (2021–2026) identified 419 records, of which 292 were screened, 15 assessed for full-text eligibility, and 12 met all inclusion criteria. Twelve cross-sectional, comparative, and surveillance-based studies from Indonesia, Libya, Jordan, Thailand, China (two studies), Mexico (three studies), India, Argentina, and Colombia met the inclusion criteria; most studies demonstrated a dose-related pattern between groundwater/well-water fluoride concentration and dental fluorosis severity, although two studies employing ecological or population-aggregated exposure designs (Argentina, Colombia) found inconsistent or non-significant direct associations at the locality level, attributable to confounding by altitude, temperature, and additional non-water fluoride sources, and several studies additionally linked fluorosis to caries risk, reduced quality of life, nutritional status, and intelligence quotient, while one study found an inverse relationship between fluorosis and Molar Incisor Hypomineralisation. Groundwater fluoride concentration is generally associated with dental fluorosis prevalence and severity in school-age children, though this relationship can be attenuated by geographic, nutritional, and multi-source exposure factors at the population level, and routine groundwater fluoride monitoring, individual-level exposure assessment, and context-specific preventive strategies are recommended in groundwater-dependent communities.

Keywords: dental fluorosis; groundwater; fluoride exposure; school-age children; systematic review

INTRODUCTION
Fluoride is a naturally occurring trace element regarded as a double-edged sword in dentistry: at optimal concentrations it strengthens enamel and prevents dental caries, yet chronic ingestion above the recommended threshold during tooth development causes dental fluorosis (DF), an irreversible hypomineralisation defect of the enamel matrix [1,2]. DF is clinically characterised by opaque white striations in mild cases, progressing to brown-to-black discolouration and pitting in severe cases [2].

Drinking water is the principal exposure route for fluoride, and groundwater in particular is a major, often unmonitored, source of excess fluoride because its concentration is governed by local geology rather than by any regulatory fluoridation program [1]. This geological variability produces marked differences in DF burden across countries and even within short distances. In Jordan, wells supplying two neighbouring towns produced average concentrations of 1.10–1.38 ppm, and more than two-thirds of examined schoolchildren presented with moderate-to-severe fluorosis [3].

In Palu City, Indonesia, children drawing water from a well with 1.6 ppm fluoride had significantly higher fluorosis prevalence than children from a well with only 0.3 ppm within the same administrative region [4]. Comparable patterns have been documented at larger scale elsewhere: in Aguascalientes, Mexico, five municipalities with groundwater fluoride above the national guideline of 1.5 mg/L recorded a 50% average DF prevalence, against 43% state-wide, with obesity and tap-water consumption independently increasing fluorosis severity [5]; in Rohtak district, India, groundwater fluoride ranging from 0.53 to 8.80 ppm was strongly correlated with DF prevalence (r = 0.92) [6]; and in agrarian communities of Nakhon Pathom, Thailand, groundwater fluoride ≥1.5 ppm nearly tripled the prevalence of DF compared with concentrations below 0.7 ppm [1].

DF is not merely a cosmetic concern. Among Libyan schoolchildren, moderate-to-severe fluorosis was independently associated with higher caries scores and significantly lower oral-health-related quality-of-life scores [2], while children in the high-fluoride area of Palu City also showed a significantly lower intelligence quotient than their low-fluoride counterparts [4]. These downstream functional and psychosocial consequences echo a broader pattern in pediatric oral health, in which even common conditions such as untreated caries have been shown to impair children's masticatory performance and daily functioning [7]—reinforcing that oral lesions in children rarely remain isolated dental findings.

Importantly, the fluorosis burden appears modifiable once the dominant exposure pathway is correctly identified. A 12-year surveillance program in Guizhou, China, achieved a substantial reduction in primary-teeth fluorosis by targeting non-water fluoride sources after confirming that groundwater levels were already low and stable [8], and a national Chinese surveillance analysis spanning 2009–2022 similarly recorded a sustained decline in DF detection among children aged 8–12 years, from 34.9% to 10.2%, following coordinated water-quality improvement policy though one province remained a persistent high-prevalence cluster, indicating that such gains are neither automatic nor uniform [9]. Together, these findings demonstrate that accurate exposure characterisation is a prerequisite for effective intervention design rather than an academic formality.

To date, no synthesis has specifically consolidated evidence on groundwater fluoride concentration and DF status in school-age children across the range of settings where groundwater, rather than centrally treated or artificially fluoridated water, is the primary drinking water source. Guided by the Population–Exposure–Outcome (PEO) framework, this systematic review therefore aims to synthesise available evidence on groundwater fluoride concentration (Exposure) and dental fluorosis status, measured by Dean's Index, the Thylstrup and Fejerskov Index, and/or the Community Fluorosis Index (Outcome), among school-age children (Population) in such settings.

MATERIALS AND METHODS

Protocol and Reporting Standard

This systematic review was conducted and reported in accordance with the PRISMA 2020 statement [10]. This review was not prospectively registered in PROSPERO or any other registry.

Eligibility Criteria

Eligibility criteria were formulated using the PEO framework. The population consisted of school-age children (6–15 years) exposed to fluoride through groundwater or well water. The exposure of interest was quantifiably measured groundwater/well-water fluoride concentration. The outcome was dental fluorosis status, assessed using a validated diagnostic index (Dean's Index, the Thylstrup and Fejerskov Index [TFI], and/or the Community Fluorosis Index).

Studies were included if they: (1) were observational studies (cross-sectional, descriptive, ecological, cohort, or surveillance design); (2) reported a quantifiable measure of groundwater/well-water fluoride concentration; (3) assessed dental fluorosis using a validated index; (4) were conducted in community/general-population settings relying on groundwater as the primary drinking water source; (5) were published in English or Indonesian between 2021 and 2026; and (6) were available as full-text open-access articles with a retrievable DOI. Studies were excluded if they: (1) were animal or in vitro experimental studies; (2) focused on artificial/ centrally regulated water fluoridation rather than natural groundwater fluoride; (3) were review articles, conference abstracts, editorials, or case reports; or (4) were inconsistent with the PEO criteria defined above.

Information Sources and Search Strategy

A systematic search was performed across PubMed, Scopus, and ScienceDirect, covering publications from 2021 to 2026, combining controlled vocabulary and free-text keywords for the outcome (dental fluorosis), exposure (groundwater/ fluoride), and population (children), connected using Boolean operators AND/OR (full strings previously specified in Section 2.3 supplementary documentation). The search identified 83 records from PubMed, 200 from Scopus, and 136 from ScienceDirect.

Study Selection Process

The initial search identified 419 records (PubMed n = 83; Scopus n = 200; ScienceDirect n = 136). Prior to screening, 127 records were removed (58 duplicates; 69 excluded for lacking open access or a retrievable DOI), leaving 292 records for title/abstract screening. Following screening, 277 records were excluded, and 15 reports were sought for retrieval; all 15 were successfully retrieved and assessed for full-text eligibility. Three reports were excluded at this stage for inconsistency with the PEO criteria. After full-text eligibility assessment, twelve studies met all inclusion criteria and were included in the qualitative synthesis of this systematic review [2–6,8,9,11–14]. Study selection was independently conducted by the reviewer(s) at each stage, and disagreements, where applicable, were resolved through discussion.

Data Extraction

Data were extracted using a standardised form capturing author(s) and year, study population and sample size, study design, groundwater/well-water fluoride exposure measurement, and diagnostic method. For dental fluorosis, key findings, statistical significance, and reported outcomes. Extracted data were tabulated for structured qualitative comparison, as presented in Table 1.

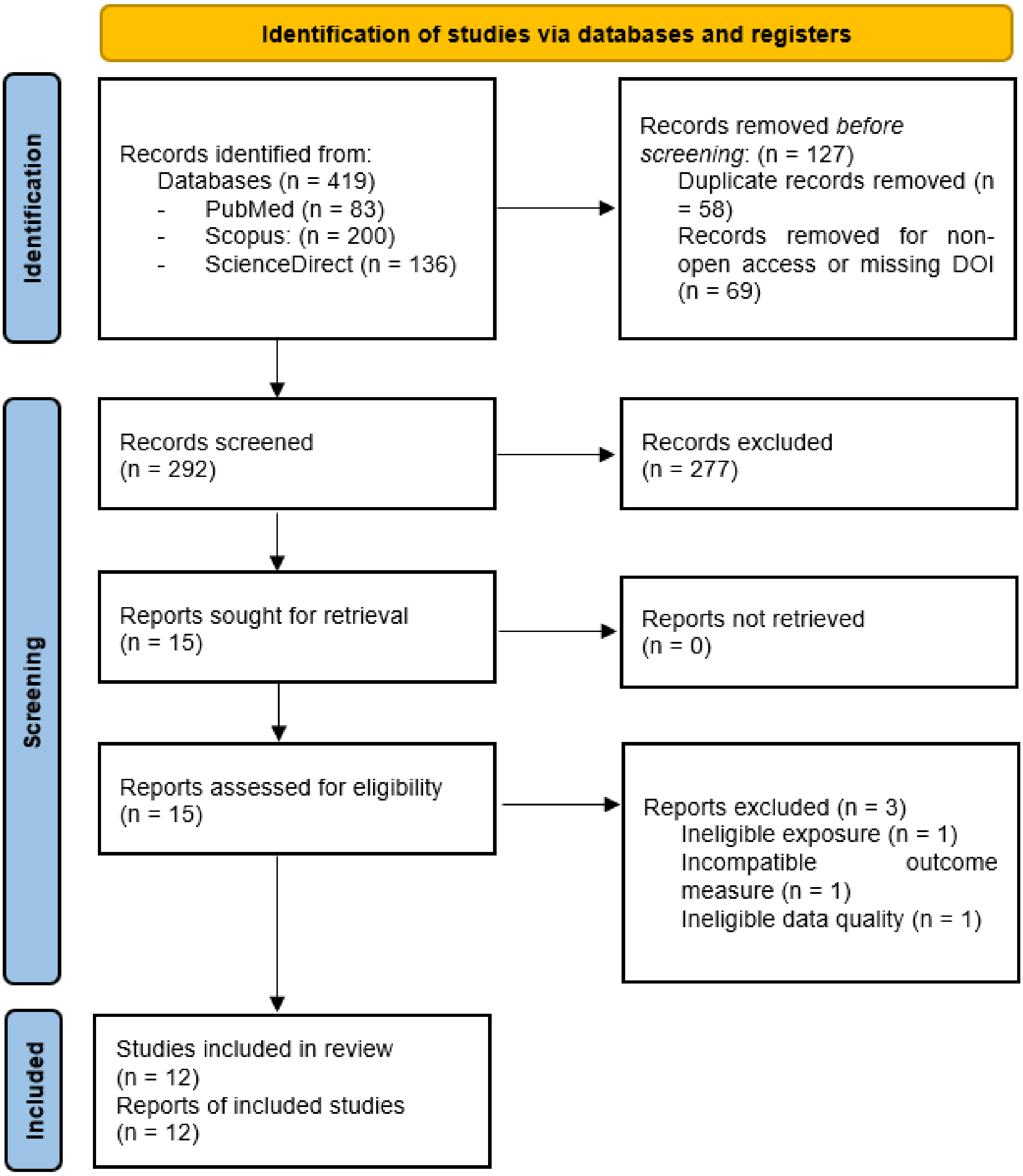

FIGURE 1: PRISMA 2020 flow diagram.

RESULTS

Study Selection

Of the 292 records screened, 15 reports underwent full-text assessment, and 12 studies met all eligibility criteria [2–6,8,9,11,12]. Full extraction data are currently available for ten of these twelve studies; the remaining two are pending and will be incorporated in a subsequent revision without altering the overall PRISMA counts reported above.

Study Characteristics

The included studies were conducted in Indonesia [4], Libya [2], Jordan [3], Thailand [1], China [8,9], Mexico [5,11,12], India [6], Argentina [13], and Colombia [14]. Ten employed a cross-sectional, comparative, or ecological observational design, and two employed multi-year surveillance analysis [8,9]. DF severity was assessed using Dean's Index, the TFI, and/or the CFI. Table 1 summarises the characteristics and key findings.

TABLE 1: Summary of the characteristics and key findings of the included studies.

Reference	Country	Population	Outcomes	Key findings	Significance
Yani et al., (2021) [4]	Indonesia	100 children, 6–12 years, Palu City, Indonesia	Dean's Index; IQ (Raven's CPM)	Groundwater fluoride 1.6 vs 0.3 ppm → significantly higher fluorosis and lower IQ (p=0.001)	Demonstrates that groundwater fluoride concentration is independently associated with both dental fluorosis and reduced cognitive performance in Indonesian schoolchildren, highlighting a potential neurodevelopmental dimension of fluoride exposure beyond enamel effects
Arheiam et al. (2022) [2]	Libya	1,125 children, 12 years, Benghazi, Libya	Dean's Index; DMF; COHIP-SF19	Fluorosis prevalence 11.1% (mostly mild); moderate–severe fluorosis linked to higher DMF scores and lower COHIP-SF19 scores	Shows that even in a naturally fluoridated area with comparatively low fluoride levels, fluorosis remains detectable and moderate-severe cases carry measurable caries and quality-of-life burden
Al-Omoush et al. (2021) [3]	Jordan	241 schoolchildren, 15–16 years, Jordan	Dean's Index; DMFT	Moderate–severe fluorosis in 68.8–72% of children; higher-altitude town showed greater severity; fluorosis positively correlated with DMFT	Identifies altitude as an environmental cofactor that intensifies fluorosis severity at comparable fluoride concentrations, and disproves the assumption that fluorosed teeth are caries-resistant
Rojanaworarit et al. (2021) [1]	Thailand	289 children, 6–10 years, Nakhon Pathom, Thailand	Dean's Index	Groundwater fluoride ≥1.5 ppm increased the prevalence ratio of fluorosis 2.75-fold compared with <0.7 ppm.	Provides case–control-level evidence of a dose-related exposure–outcome relationship in a socially disadvantaged agrarian community reliant on untreated groundwater
Sun et al. (2025) [8]	China	1,115 children, 6–8 years, Guizhou, China	Dean's Index; CFI	CFI fell from 1.41 (2008) to 0.23 (2020) following non-water interventions, despite stable low groundwater fluoride	Demonstrates that fluorosis burden can be substantially reduced through non-water exposure control (e.g., coal-stove renovation) when groundwater is not the dominant fluoride source
Zhao et al. (2024) [9]	China	Children 8–12 years, 27 provinces, China	Dean's Index (national surveillance)	National dental fluorosis detection rate fell from 34.9% to 10.2% (2009–2022); Tianjin remained a high-prevalence cluster.	Validates the effectiveness of coordinated national water-quality policy at scale, while showing that gains are not geographically uniform and require sustained localised monitoring
González Dávila (2021) [5]	Mexico	1,052 children, 7–8 years, Aguascalientes, Mexico	Modified Dean's Index	3% general fluorosis prevalence, CFI 0.99; obesity (OR 1.62) and tap water consumption (OR 1.63) independently increase severity	Identifies nutritional status (obesity) as an independent risk modifier of fluorosis severity, in addition to confirming groundwater fluoride as a persistent public health problem two decades after earlier surveys
Rani et al. (2022) [6]	India	1,262 children, 6–12 years, Rohtak, India	Dean's Index; DMFT/deft	Fluoride–fluorosis correlation r=0.92 (strong positive); fluoride–caries correlation negative (r=−0.93)	Demonstrates a very strong dose–response gradient between groundwater fluoride and fluorosis across 30 villages, while also illustrating fluoride's cariostatic effect even as fluorosis risk rises.
Irigoyen-Camacho et al. (2023) [11]	Mexico	585 children, 8–12 years, Oaxaca, Mexico	TFI; BMI Z-score	Tap water fluoride (OR 1.57) and bottled water fluoride (OR 3.03) increase severe fluorosis (TFI≥4); low BMI Z-score independently increases risk (OR 2.11)	Reveals that bottled water can be an overlooked secondary fluoride source in endemic areas, and that undernutrition (low BMI) independently heightens fluorosis vulnerability
Medina Varela et al. (2024) [12]	Mexico	573 children, 8–12 years, Morelos, Mexico	TFI; MIH (EAPD criteria)	Fluorosis (TFI≥4) is inversely associated with Molar Incisor Hypomineralization severity (OR 0.38–0.51)	Uncovers a counterintuitive inverse relationship between two enamel developmental defects, underscoring the need for careful differential diagnosis between fluorosis and MIH in fluoride-endemic populations
Gonzalez et al. (2026) [13]	Argentina	469 children, 6–12 years, La Rioja, Argentina	T-F Index; spatial autocorrelation	Fluorosis prevalence 46.3%; significant spatial clustering of groundwater fluoride (Moran's I=0.16, p=0.006); no formal individual-level statistical association between fluoride and severity (ecological design)	Illustrates the methodological limitation of ecological exposure designs: spatial co-occurrence of high fluoride and high fluorosis does not, by itself, establish an individual-level dose–response relationship
González-Martínez et al. (2024) [14]	Colombia	923 children, 7–12 years, 8 municipalities, Colombia	TFI; urinary fluoride; water ingestion dose (IDag)	Fluorosis prevalence 86.1%; groundwater fluoride range 0.02–24.3 mg/L; inconsistent dose–response across municipalities, modified by altitude, temperature, and table-salt/toothpaste intake	Demonstrates that multi-source fluoride exposure (dietary salt, toothpaste) and environmental cofactors can override a simple water-fluoride dose–response pattern at the population level

Groundwater Fluoride Concentration and Dental Fluorosis Prevalence or Severity

Across most included studies, a consistent dose-related relationship between groundwater/well-water fluoride concentration and DF prevalence or severity was observed, despite differing exposure ranges and geographic contexts. In Palu City, two sub-villages with differing groundwater fluoride (1.6 vs 0.3 ppm) produced markedly different fluorosis outcomes in comparably aged children [4]. In Rohtak, India, a strong positive correlation (r = 0.92) between groundwater fluoride and DF prevalence was observed across 30 villages spanning 0.53–8.80 ppm [6], while in Nakhon Pathom, Thailand, a clear exposure gradient was demonstrated using prevalence ratios [1]. In Aguascalientes, Mexico, municipalities exceeding the 1.5 mg/L national guideline showed markedly higher DF prevalence than the state average [5]. In Jordan, the higher-altitude town recorded both marginally higher well-water fluoride and greater fluorosis severity, suggesting altitude compounds fluoride exposure [3].

Inconsistencies and Modifying Factors at the Population Level

Two studies employing population-aggregated exposure designs complicate this otherwise consistent picture. In La Rioja, Argentina, an ecological cross-sectional study found significant spatial clustering of both fluoride concentration and fluorosis severity (Moran's I = 0.16, p = 0.006), yet explicitly reported no formal statistical association between the two at the individual level, attributing the observed geographic overlap to co-occurrence rather than direct causality a limitation the authors linked to the ecological design, in which exposure was measured at the locality level while outcome was assessed individually [13]. Similarly, in Colombia, groundwater fluoride concentrations spanning an extreme range (0.02–24.3 mg/L) did not produce a simple dose–response pattern across eight municipalities: the municipality with the highest fluoride level did not have the highest fluorosis prevalence, while a municipality with near-optimal fluoride levels showed 100% prevalence. The authors attributed this to confounding by altitude, ambient temperature, and substantial non-water fluoride sources, particularly table salt (OR 3.58) and involuntary toothpaste ingestion (OR 1.96) [14]. Together, these two studies indicate that the groundwater fluoride–fluorosis relationship, while robust in individually measured cohort and comparative studies, can be substantially attenuated when exposure is assessed at an aggregated or multi-source level.

Fluorosis, Caries, and Broader Child Health Outcomes

Several studies extended beyond simple prevalence reporting. Arheiam et al. found moderate-to-severe fluorosis associated with higher caries scores and lower quality-of-life scores [2], while Al-Omoush et al. reported a positive correlation between fluorosis severity and DMFT [3], yet Rani et al., in a much larger Indian sample, found a negative correlation between fluoride concentration and caries experience (DMFT/deft), attributing this to fluoride's cariostatic effect even as fluorosis severity rose in parallel [6]. Yani et al. further reported a significant association between high groundwater fluoride exposure and lower intelligence quotient [4], while Irigoyen-Camacho et al. found that children with low BMI Z-scores were independently more likely to present severe fluorosis, implicating nutritional status as a modifying factor in fluoride bioavailability [11], a finding echoed by González Dávila, who reported obesity as an independent risk factor for greater fluorosis severity [5], together indicating that both under- and over-nutrition may interact with fluoride metabolism in distinct ways.

Notably, Medina Varela et al. identified an unexpected inverse relationship between dental fluorosis severity and Molar Incisor Hypomineralization (MIH), another developmental enamel defect, in a Mexican cohort exposed to 1.39 ppm groundwater fluoride [12]. This finding illustrates that not all enamel developmental defects respond to fluoride exposure in the same direction, underscoring the need for differential diagnosis between DF and MIH in fluoride-endemic populations.

Modifiability of the Fluorosis Burden

Findings from China offer an important policy-relevant contrast. In Guizhou, a 12-year surveillance program achieved a substantial CFI reduction despite stable low groundwater fluoride, by targeting non-water exposure sources [8]. At a larger scale, a national Chinese analysis spanning 27 provinces (2009–2022) documented a sustained decline in childhood DF detection rates following coordinated water-quality policy, from 34.9% to 10.2%, though one province (Tianjin) remained a persistent high-prevalence cluster, demonstrating that population-level gains are not uniformly distributed and require sustained, geographically targeted monitoring [9].

DISCUSSION

The findings of this systematic review confirm that groundwater fluoride concentration is generally associated with DF prevalence and severity across geographically diverse settings, from Southeast Asia and the Middle East to South Asia and Latin America [1–6]. This pattern is consistent with the broader epidemiological literature linking groundwater fluoride to fluorosis risk in hydrogeologically vulnerable communities where centrally treated water is unavailable [1].

However, this review also reveals that the strength of this relationship is highly sensitive to the level at which exposure is measured. Studies that measured fluoride exposure at the individual or small-village level generally found robust dose–response relationships [1,3,4,6], whereas studies aggregating exposure at the municipality or locality level in Argentina [13] and Colombia [14] found inconsistent or non-significant direct associations, instead identifying confounding by altitude, ambient temperature, and multiple concurrent fluoride sources (table salt, toothpaste).

This methodological contrast is an important finding in its own right: it suggests that ecological or multi-source exposure designs, while valuable for population-level surveillance and spatial risk mapping, may understate or obscure the true magnitude of the groundwater fluoride–fluorosis relationship at the individual level, and that future primary research should prioritise individual-level water and, where feasible, urinary fluoride measurement rather than locality-aggregated estimates alone.

Beyond prevalence, the review reveals a more complex picture than a simple linear fluoride–fluorosis–harm pathway. While several studies confirm elevated caries risk, reduced quality of life, and lower IQ associated with fluorosis [2,4], the Rohtak study's negative fluoride–caries correlation [6] and the Morelos study's inverse fluorosis–MIH relationship [12] together suggest that the clinical expression of fluoride's dual protective-and-pathological effects on enamel is highly context-dependent, shaped by co-occurring developmental, nutritional, and diagnostic factors. This complexity parallels a wider recognition that pediatric oral conditions rarely follow single, isolated pathways [7], and reinforces that nutritional status, whether undernutrition [11] or obesity [5], appears to be an independent modifier of fluorosis severity across at least two distinct Mexican populations, a pattern meriting further mechanistic investigation. At the tissue level, this developmental sensitivity is consistent with local experimental evidence that biochemical exposures during the amelogenesis window can alter ameloblast protein expression [15], plausible given that tooth mineralisation proceeds through sequential, age-dependent developmental stages [16].

From a translational and policy perspective, the demonstrated modifiability of fluorosis burden once the exposure pathway is correctly identified [8,9] supports the feasibility of structured, evidence-based preventive strategies in groundwater-dependent communities, an approach consistent with systematic evaluations of school-based oral health promotion programs in the Indonesian context [17]. Where groundwater fluoride cannot be readily reduced at the source, enamel remineralisation-inducing materials offer a complementary caries-preventive strategy that does not rely on additional systemic fluoride exposure [18]. More broadly, this body of evidence reflects a growing capacity within Indonesian dental research institutions to generate translational, population-level evidence relevant to pediatric preventive dentistry [19].

Strength and Limitations

This review benefited from a systematic, PRISMA-guided search strategy across three databases, transparent PEO-based eligibility criteria, and a geographically diverse evidence base spanning nine countries across four continents. However, several limitations should be acknowledged. First, all included studies employed cross-sectional, comparative, or ecological/surveillance designs, restricting causal inference. Second, heterogeneity in fluorosis grading (Dean's Index vs TFI vs CFI) and in the level of exposure measurement (individual vs locality-aggregated) posed substantial challenges for direct comparison of effect magnitudes, as most clearly illustrated by the divergent findings in Argentina and Colombia. Third, the unexpected divergent findings regarding fluoride–caries [6] and fluorosis–MIH [12] relationships could not be further explored through meta-analysis given the qualitative synthesis approach adopted. Finally, most included studies did not account for non-water fluoride sources (toothpaste, dietary salt) with the same rigour as the Colombian study [14], limiting the ability to isolate the independent contribution of groundwater fluoride across the full evidence base.

CONCLUSIONS

This systematic review synthesised evidence from twelve studies examining groundwater fluoride concentration and dental fluorosis status in school-age children across Indonesia, Libya, Jordan, Thailand, China, Mexico, India, Argentina, and Colombia. Most studies demonstrate a dose-related relationship between groundwater fluoride concentration and DF prevalence and severity, with effects extending beyond enamel aesthetics to caries risk, nutritional status, and psychosocial well-being. However, studies employing population-aggregated exposure designs found this relationship to be substantially attenuated by geographic (altitude, temperature) and multi-source (dietary salt, toothpaste) confounding, indicating that the groundwater fluoride–fluorosis relationship, while real, is not uniformly detectable across all study designs. Fluorosis burden was shown to be modifiable at both community and national scale once the dominant exposure pathway was correctly identified.

These findings underscore the need for routine, individually resolved groundwater fluoride monitoring and context-specific preventive strategies which combining exposure surveillance, protective restorative materials, and behavioural oral health education designed through evidence-based, culturally responsive program frameworks [20], in communities where groundwater serves as the primary drinking water source, particularly in rural and semi-urban settings that remain under-represented in the current evidence base.

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