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# Fluoride in Agriculture: From Sources and Soil Mobility to Crop Toxicity, Food-Chain Exposure, and Risk Mitigation—A Critical Review (2016– 2026)

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**Abstract**

Fluoride is ubiquitous in agricultural environments, yet researchers often misclassify agricultural risk by treating total concentrations in soil, water, fertilizers, and plant tissues as interchangeable exposure indicators. This critical review synthesizes evidence published from 2016 to September 2026 across the water–soil–plant–food continuum and addresses a decision-oriented question: under which combinations of source intensity, geochemistry, crop biology, and management does fluoride become agronomically damaging or relevant to food and feed safety? The review integrates geogenic inputs, phosphate fertilizers, industrial deposition, and irrigation with evidence on soil sorption, mineral precipitation, speciation, root and foliar uptake, physiological injury, transfer to edible tissues, dietary exposure, co-contaminant interactions, and remediation. Across the literature, pH, calcium availability, aluminum and iron phases, clay mineralogy, bicarbonate and sodium chemistry, and exposure duration repeatedly decouple total fluorine inventory from mobile or plant-available fluoride. Plant response is likewise non-universal: species and cultivars differ in uptake, transport, fluoride-export capacity, antioxidant defense, and yield sensitivity. Tea and selected food crops can represent important exposure pathways, whereas field evidence for many proposed amendments remains less mature than laboratory evidence. A hierarchical management strategy is therefore proposed: prevent new loading, diagnose the dominant mobility mechanism, reduce fluoride mobility with mechanism-compatible interventions, select crops or cultivars when necessary, measure fluoride in edible tissues rather than relying on soil totals, and verify performance through multi-season field studies. Priority research needs are standardized bioavailability metrics, matched monitoring of water–soil–crop compartments, realistic co-contaminant assessment, and field validation that includes agronomic performance, durability, and cost.

**Keywords:** fluoride; agriculture; soil bioavailability; crop toxicity; food-chain exposure; remediation

**Highlights**

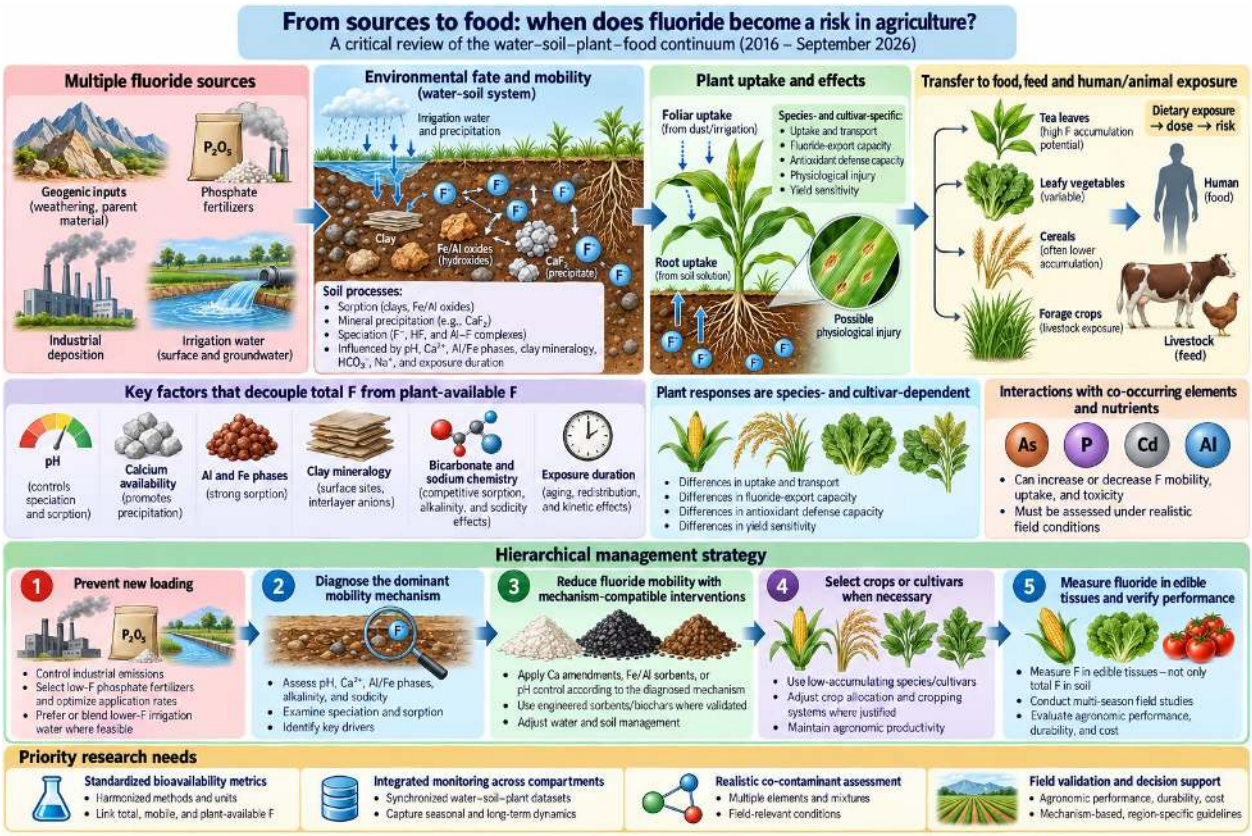
- Fluoride risk in agriculture is governed more by mobility and transfer to edible tissues than by total soil fluoride alone.
- Soil pH, Ca–Al–Fe chemistry, irrigation-water composition, and loading history jointly control fluoride bioavailability.

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- Plant responses are strongly species-, cultivar-, dose-, and co-contaminant-dependent, limiting universal toxicity thresholds.
- Mitigation should prioritize source control and field-validated immobilization, followed by crop selection and exposure verification.

## Graphical abstract




## 1. Introduction

Fluoride occurs naturally in minerals, groundwater, atmospheric emissions, and soils, and it also enters agricultural systems through anthropogenic activities. In cropping regions, relevant inputs include phosphate fertilizers, industrial emissions, irrigation with fluoride-bearing water, deposition of dust or process residues, and redistribution of fluoride already stored in soil. Agricultural exposure is therefore not a single-medium problem but a coupled water–soil–plant–food problem in which identical nominal concentrations can produce very different outcomes depending on geochemical conditions, exposure history, and biological sensitivity. Throughout this review, “total fluorine” is used for bulk elemental inventory

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when studies report total F, whereas “fluoride” refers to the ionic or operationally available forms discussed in mobility, uptake, and exposure studies.

The central analytical difficulty is that total fluoride is a poor stand-alone proxy for agronomic or dietary risk. Long-term fertilizer application can increase soil fluorine inventories, but the fraction that remains mobile or plant-available depends on pH, calcium activity, aluminum and iron (hydr)oxides, clay mineralogy, dissolved organic matter, ionic strength, and residence time. Conversely, alkaline water enriched in sodium and bicarbonate can sustain fluoride mobility even where total soil concentrations are not exceptional. Recent work has therefore shifted attention toward fluoride fractions, transfer factors, edible-tissue concentrations, and matched monitoring of water, soil, and crops rather than reliance on a single total-concentration metric (Gray, 2018; Huang et al., 2023; Li et al., 2023; Moirana et al., 2021; Singh et al., 2018; Singh et al., 2022; M. Wang et al., 2023).

Plant response adds a second layer of nonlinearity. Fluoride can enter through roots and, under atmospheric exposure, through foliage; reported effects include marginal leaf injury, impairment of photosynthesis and respiration, disruption of calcium–phosphorus homeostasis, oxidative stress, altered antioxidant and glyoxalase systems, and changes in growth or reproductive performance. Genotype, developmental stage, co-exposure, nutrient status, dose, and duration strongly modify these responses (Ahmad et al., 2022; Banerjee & Roychoudhury, 2019; Banerjee, Roychoudhury, et al., 2019; Banerjee et al., 2021; Fina et al., 2016; Ijaz et al., 2026; Mondal, 2017; Pelc et al., 2020; G. Singh et al., 2023; Tausta et al., 2021). Tea is a particularly important case because Camellia sinensis can accumulate fluoride and beverage preparation creates a direct pathway from plant tissue to human intake (Cai et al., 2016; Das et al., 2017; Jayasingha et al., 2025; Pattaravisitsate et al., 2021; Pavlovič et al., 2023; Peng et al., 2016; Peng, Xu, Ren, et al., 2021; Penteado et al., 2026).

This review critically evaluates literature published from 2016 to September 2026 with four objectives: (i) to distinguish source intensity from bioavailable fluoride; (ii) to connect soil geochemistry with plant uptake and agronomic effects; (iii) to link crop transfer with food-chain exposure without conflating hazard and risk; and (iv) to assess whether mitigation strategies have progressed from laboratory proof-of-concept to durable field

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management. The review is organized around causal links and decision points rather than as a catalog of fluoride occurrence.

## 2. Review Scope, Evidence Handling, and Critical-Assessment Framework

### 2.1 Evidence boundaries and organizing questions

The evidence base covers January 2016 through September 2026 and includes field surveys, controlled plant experiments, soil sorption and fractionation studies, mechanistic plant research, food and feed exposure assessments, remediation studies, and recent critical or systematic reviews. Publications were retained when they directly informed at least one transition in the source–soil/water–plant–food chain or the performance of a mitigation option. Earlier foundational chemistry is discussed only where necessary to interpret the 2016–2026 evidence. The present article retains one previous review by the author as contextual background and expands the evidence window while applying a more explicit bioavailability-to-decision framework (Pereira, 2026).

Relation to the author's previous review. Pereira (2026) provides contextual coverage of agricultural fluoride sources, soil mobility, plant uptake, and health implications. The present manuscript advances beyond that topic survey through an expanded literature window, the formal evidence-appraisal dimensions in Section 2.3, compartment-resolved loading and exposure calculations, the risk archetypes in Section 9.1, and the FARC decision checklist in Section 9.2. Detailed disclosure of any textual or illustrative reuse should follow a document-level comparison with the earlier publication.

Novelty and relationship to contemporary reviews. Farooqi et al. (2026) comprehensively synthesize fluoride contamination across the water–soil–plant continuum, including geochemical mobility, crop toxicity, dietary transfer, and remediation. The present review does not claim novelty for those established pathways. Its distinct contribution is a decision-traceability architecture—the author-developed Fluoride Agricultural Risk Chain (FARC)—which distinguishes source loading, mobile fluoride, crop-specific response, edible or feed-relevant tissue, intake, intervention, and verification as separate evidentiary transitions. Four conceptual risk archetypes, an endpoint hierarchy, and explicit durability requirements operationalize this architecture. These archetypes and FARC are diagnostic

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syntheses, not empirically calibrated classifiers or validated predictive risk models (Farooqi et al., 2026).

Five questions structure the synthesis: What loads fluoride into an agricultural system? Which geochemical controls convert that loading into mobile or plant-available fluoride? Which crop traits determine uptake, translocation, and injury? When does plant accumulation become a food- or feed-exposure problem? Which interventions reduce risk without creating unacceptable agronomic, environmental, or economic trade-offs? This structure deliberately separates soil contamination, crop toxicity, and human or animal exposure rather than treating them as interchangeable endpoints.

### 2.2 Literature selection and evidence handling

This article was prepared as a critical narrative review rather than as a formal systematic review or meta-analysis. We included evidence that provided direct measurements, mechanistic interpretation, or management-relevant findings on fluoride loading, mobility or bioavailability, crop uptake or toxicity, edible-tissue transfer, dietary or feed exposure, or mitigation. Field surveys and matched water–soil–crop datasets were used to establish environmental relevance; controlled experiments were used to resolve mechanisms and dose responses; and reviews were used to identify broader patterns and unresolved questions. Evidence from unrealistic exposure conditions or from endpoints that were exclusively biochemical was interpreted cautiously when extrapolating to field performance or food safety.

Search transparency and limitations. The manuscript covers publications dated January 2016–September 2026. Representative, reproducible topic queries for supplementary screening include (fluoride OR fluorine) AND (agriculture OR crop OR soil) AND (bioavailability OR speciation OR mobility); (fluoride AND (irrigation OR phosphate fertilizer OR atmospheric deposition) AND loading); (fluoride AND (plant uptake OR phytotoxicity OR edible tissue OR tea)); and (fluoride AND (risk assessment OR dietary exposure OR remediation OR immobilization)). These are transparent illustrative search strings, not a retrospectively authenticated log of searches undertaken during the original review. The exact original search platforms, execution dates, language restrictions, citation-

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chaining history, and duplicate-removal counts cannot be reconstructed reliably from the retained manuscript alone; no PRISMA flow or undocumented search counts are claimed. The original search records should be supplied by the author if available. Primary measurements should be cited for individual numerical values where possible, and reviews used primarily for synthesis and contextual comparisons.

### 2.3 Critical appraisal and weighting of evidence

Evidence was compared qualitatively across four dimensions: environmental realism, endpoint relevance, causal resolution, and durability. For management questions, greater weight was assigned to mature-crop yield, edible-tissue fluoride, matched environmental measurements, and multi-season field performance than to isolated short-term biochemical responses. Mechanistic laboratory studies remain essential for explaining pathways, but they were not treated as direct evidence of field efficacy. Remediation evidence was considered strongest when it addressed persistence, crop response, nutrient interactions, secondary residues, and practical feasibility. This qualitative weighting makes the critical logic of the review explicit without implying a numerical quality score.

The four appraisal dimensions constitute an author-developed qualitative critical-appraisal framework; they have not been independently validated as a formal risk-of-bias instrument, quantitative evidence-grading scheme, or reproducible numerical score.

Table 1 summarizes the critical-evaluation framework used throughout this review and defines the evidence required to move from detection of fluoride to a defensible management decision.

**Table 1. Critical-evaluation framework for fluoride in agricultural systems.**

| Decision layer | Core variable | Preferred evidence | Common interpretive error |
|---|---|---|---|
| **Source** | Annual or cumulative F loading | Fertilizer/water/deposition mass balance | Equating presence of a source with plant risk |
| **Soil/water** | Mobile or bioavailable F | Fractionation, pore-water F, pH, Ca, Al/Fe, $HCO_3^-$, ionic strength | Using total soil F as the sole exposure metric |
| **Plant** | Uptake, translocation, injury, yield | Root/leaf/grain data, physiology, genotype response | Generalizing from one species or hydroponic dose |
| **Food/feed** | Edible-tissue F and | Commodity concentration | Treating tissue |

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| Decision layer | Core variable | Preferred evidence | Common interpretive error |
|---|---|---|---|
| | intake | + consumption + age/body mass | concentration alone as health risk |
| **Mitigation** | Durable reduction in exposure | Multi-season field performance + soil fertility + cost | Assuming short-term adsorption equals long-term remediation |

The framework separates hazard identification from exposure and management relevance. This distinction becomes especially important when comparing pot experiments, field observations, and dietary-risk studies, because the measured endpoints and exposure geometries differ substantially.

Figure 1 presents the causal framework used to integrate the literature from source loading to risk control.

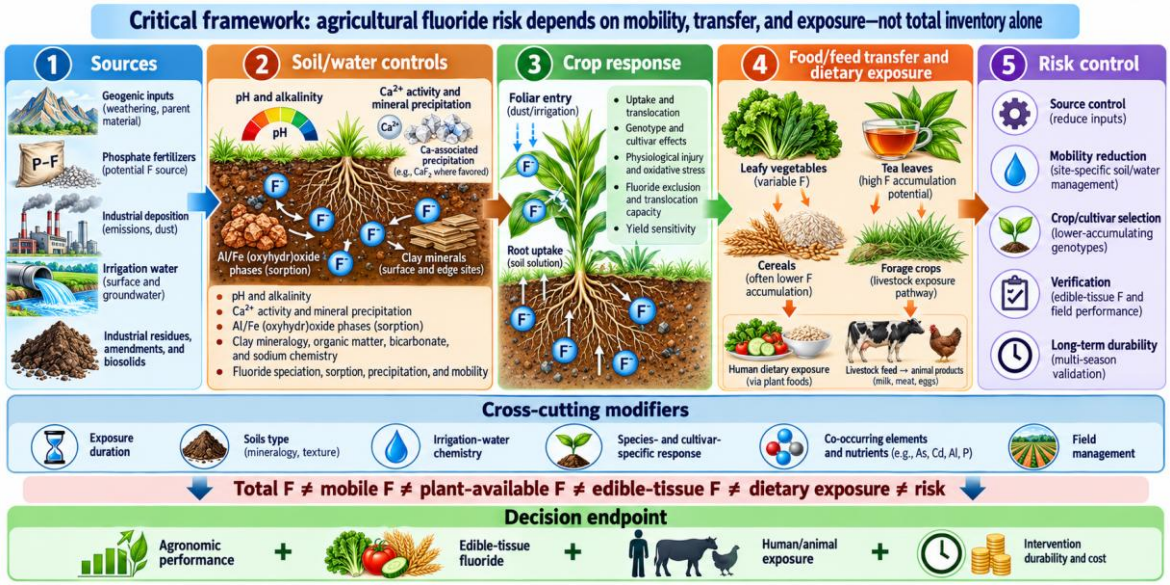



**Figure 1. Causal framework linking fluoride sources, geochemical controls, crop response, food-chain exposure, and management decisions.**

*Note.* Original conceptual synthesis by the author based on the literature reviewed in this article.

The framework emphasizes that each arrow is conditional rather than automatic. A large fluoride inventory does not necessarily imply high plant transfer, and a measurable plant concentration does not by itself imply unacceptable dietary risk; the relevant modifiers must be measured at each transition.

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## 3. Sources, Loading Pathways, and Accumulation in Agricultural Systems

### 3.1 Geogenic sources and irrigation-water loading

Fluoride-rich minerals, prolonged water–rock interaction, evaporation, and groundwater geochemistry can generate irrigation water with elevated fluoride, particularly in arid and semi-arid settings. Groundwater studies show that residence time, host-rock composition, alkalinity, mineral–microbe interactions, and competing ions can influence fluoride release and persistence (Keesari et al., 2021; Kumar et al., 2018; Nakaya et al., 2023; Wei et al., 2024; Y. Yang et al., 2026; Zhang et al., 2026). For agriculture, the relevant quantity is not only irrigation-water concentration but cumulative loading over seasons, because repeated irrigation can build a soil reservoir while simultaneously modifying alkalinity and salinity.

This loading pathway is often underestimated because irrigation is evaluated as a water-quality issue rather than as a soil mass-balance input. In long-lived orchards, tea gardens, or continuously irrigated cereal systems, even moderate concentrations can become relevant if the annual water volume is large and removal in harvested biomass or drainage is small. Consequently, monitoring should report irrigation volume, fluoride concentration, drainage conditions, and soil fluoride fractions together, rather than reporting water concentration alone.

For a specified accounting period, the irrigation-derived area-normalized fluorine loading can be calculated as $L_{F,irr} = (C_{F,water} \times V_{irr})/A$, where $C_{F,water}$ is dissolved fluoride expressed as mg F $L^{-1}$, $V_{irr}$ is irrigation water volume (L $yr^{-1}$), and A is irrigated area (ha). Conversion from mg to kg gives $L_{F,irr}$ (kg F $ha^{-1}$ $yr^{-1}$) = $C_{F,water} \times V_{irr} /(10^6 \times A)$. For fertilizer, $L_{F,fert}$ (kg F $ha^{-1}$ $yr^{-1}$) = $(C_{F,fert} \times M_{fert})/A$ when $C_{F,fert}$ is a mass fraction in kg F per kg product, $M_{fert}$ is applied product mass (kg $yr^{-1}$), and A is area (ha). These are gross input fluxes, not predictions of retained soil inventory or plant uptake; net balance additionally considers drainage, erosion, crop export, and other inputs and outputs. Multiyear cumulative input is the sum of annual loads with units and reporting bases harmonized.

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### 3.2 Phosphate fertilizers, industrial emissions, and secondary sources

Phosphate fertilizers are a recurring anthropogenic source because fluorine is naturally associated with phosphate rock and can remain in commercial products. Measurements of commercial fertilizers and studies of long-term fertilized soils confirm that repeated application can increase soil fluorine inventories (Gray, 2018; Huang et al., 2023; Li et al., 2023; Ramteke et al., 2018). Industrial activities add a different exposure geometry: gaseous and particulate fluoride can affect vegetation directly through foliar uptake while also depositing fluoride to soil. Evidence from aluminum and phosphate-industry settings demonstrates that emission control can materially alter plant exposure (Gomes et al., 2021; He et al., 2021; Louback et al., 2016; Silva & Ferraz-Almeida, 2023).

The source term is heterogeneous in both chemical form and point of entry. Fertilizer-derived fluoride is introduced mainly to soil; irrigation-derived fluoride enters in dissolved form; and atmospheric fluoride can bypass soil controls through direct foliar uptake. Process residues and phosphogypsum can add localized solid-phase inputs. A credible source inventory must therefore distinguish pathways and chemical forms, because a mitigation strategy designed for one pathway may be ineffective for another (Cui et al., 2021; Hogen et al., 2024; W. Yang et al., 2026).

Table 2 compares the principal fluoride-loading pathways and the measurements needed to determine whether each source is likely to control crop exposure.

**Table 2. Principal fluoride sources in agriculture, exposure geometry, and priority monitoring variables.**

| Source/pathway | Primary entry | Key controls | Priority monitoring |
|---|---|---|---|
| **Fluoride-bearing groundwater** | Dissolved F via irrigation | pH, $HCO_3^-$, Ca, Na, irrigation volume, drainage | Water F + seasonal irrigation load + soil solution/fractions |
| **Phosphate fertilizer** | Solid/dissolved F to topsoil | F content, application rate, soil sorption, cumulative history | Product F + kg F $ha^{-1}$ $yr^{-1}$ + depth profiles |
| **Industrial deposition** | Foliar + soil deposition | Emission rate, distance, wind, canopy properties | Air/deposition + leaf F + spatial gradients |
| **Phosphogypsum/process residues** | Localized soil input | Mineralogy, weathering, leaching | Total and leachable F + pore water |
| **Natural parent material** | Diffuse soil/groundwater | Mineralogy, weathering, residence | Mineralogy + groundwater chemistry |

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| Source/pathway | Primary entry | Key controls | Priority monitoring |
|---|---|---|---|
| | source | time | + soil fractions |

Source characterization should therefore be expressed as a flux or cumulative load wherever possible. Concentration-only comparisons can obscure the difference between a short episodic exposure and decades of repeated fertilizer or irrigation input.

## 4. Soil Geochemistry: Why Total Fluorine Does Not Equal Bioavailable Fluoride

### 4.1 Sorption, precipitation, and pH dependence

Fluoride retention in soil reflects competition among adsorption, mineral precipitation, complexation, and leaching. Aluminum and iron phases can provide strong sorption sites, whereas calcium can reduce dissolved fluoride through association or precipitation under appropriate conditions. Clay minerals and organic matter modify surface charge, pore-water chemistry, and the abundance of reactive sites. These mechanisms explain why soils with similar total fluorine inventories can exhibit markedly different plant-available fluoride fractions (Huang, Chen, et al., 2025; Iriel et al., 2018; Padhi & Tokunaga, 2018; Wehr et al., 2023; Yi et al., 2017).

pH is especially consequential because it affects mineral solubility, surface protonation, aluminum speciation, hydroxyl competition, and fluoride complexation. In many alkaline systems, sorption weakens and sodium–bicarbonate chemistry can favor mobility. Nevertheless, pH should not be interpreted in isolation: a shift that weakens one retention mechanism may simultaneously modify calcium availability, aluminum speciation, or competing-ion behavior. Mechanistic interpretation therefore requires multiparameter chemistry rather than a simple pH–fluoride correlation (Feng et al., 2025; Huang, Chen, et al., 2025; Jha et al., 2023; Shi et al., 2023; Wei et al., 2024).

### 4.2 Fractionation, land use, and chronic accumulation

Fractionation studies in tea soils and broader agricultural settings show that fluoride pools differ in lability and crop relevance. Long-term phosphate fertilization, land-use change, and crop management can alter not only the total inventory but also the distribution of fluoride among operationally defined fractions (Huang, Gao, et al., 2025; Huang et al., 2023; Moirana et al., 2021; M. Wang et al., 2023; Yi et al., 2017). This distinction is critical

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because an intervention may reduce dissolved fluoride without lowering the total inventory, or may transfer fluoride into a less labile pool that can remobilize if soil chemistry subsequently changes.

Terminology and analytical comparability. Total fluorine after complete digestion, water-extractable fluoride, pore-water fluoride, exchangeable or salt-extractable fluoride, and sequentially extracted fractions describe different analytical measurands. An ion-selective electrode quantifies fluoride activity under the specified measurement and buffering conditions and is not by itself a unique definition of plant bioavailability. Every study should identify the digestion or extraction reagents, soil-to-solution ratio, extraction time, solution handling, measured species, and mass basis. Operational fractions from distinct protocols must not be compared as though they were equivalent or uniformly plant-available.

Minimum fluoride QA/QC reporting should specify calibration range and checks, analytical technique (including ion-selective electrode or chromatographic method), ionic-strength adjustment and pH control, detection and quantification limits, sample blanks, duplicates, spike recovery or certified reference materials, and control of matrix effects involving Al, Fe, Ca, ionic strength, and complexation. Soil and crop concentrations should explicitly distinguish dry from fresh mass and report moisture content or conversion. Pore-water F, pH, Ca, Al/Fe phases or proxies, bicarbonate, Na, salinity, mineralogy, and organic matter should be jointly reported where mechanistic conclusions depend on them.

Predictive approaches are beginning to incorporate soil physicochemical properties, fluoride speciation, and machine-learning methods to estimate crop fluoride concentrations (Feng et al., 2025; Zhang et al., 2024). These models are promising because they move beyond a single soil concentration, but they remain sensitive to training-domain bias. Models developed in one region or crop system should not be transferred to another without external validation, particularly where irrigation chemistry, mineralogy, or cultivar differs.

For machine-learning applications, training and test records should be separated by field or location where possible; independent geographic and crop-system validation should accompany any claimed transferability. Reporting should include predictor definitions, missing-data treatment, calibration, prediction intervals or other uncertainty estimates, and

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comparisons against parsimonious geochemical or statistical baseline models. Random record-level partitions risk data leakage when measurements from the same site occur in both training and testing subsets.

Figure 2 summarizes the interacting soil controls that determine whether a fluoride inventory becomes mobile and available for crop uptake.

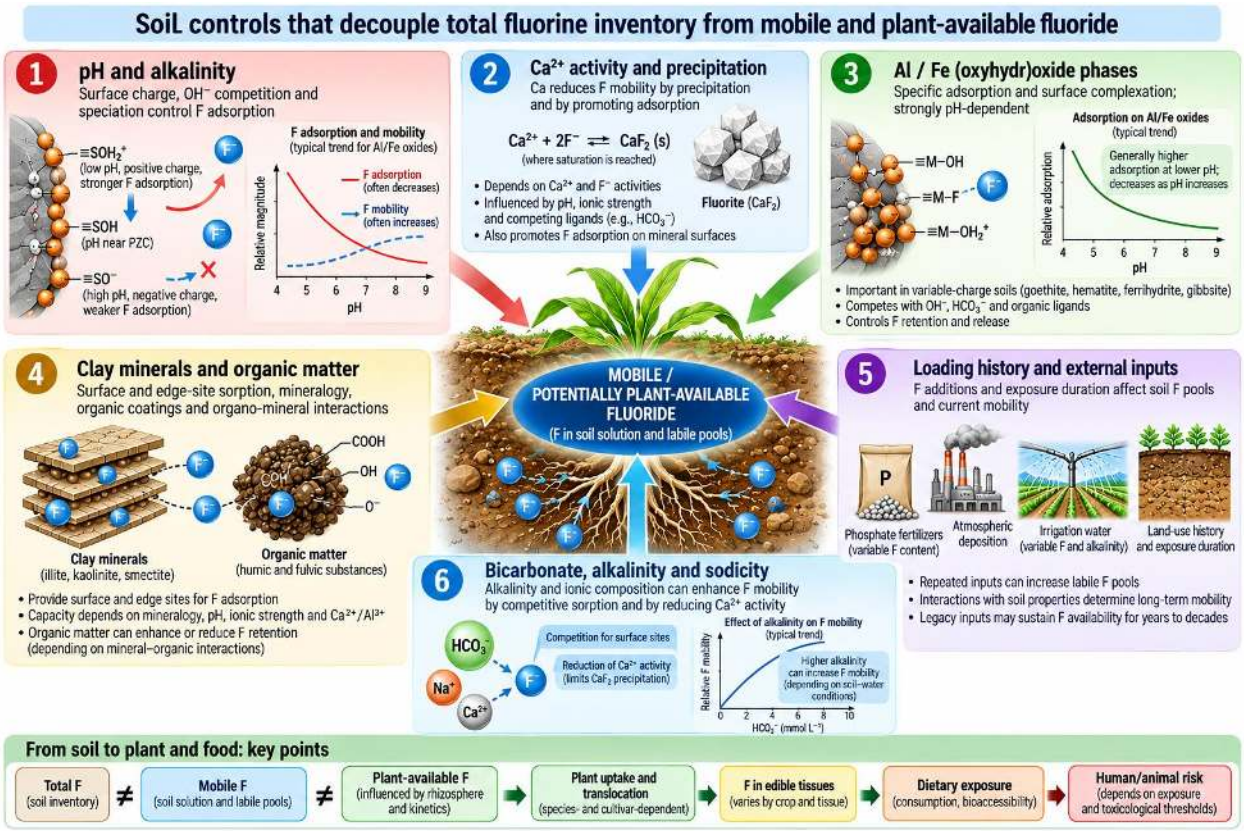



**Figure 2. Interacting geochemical controls on fluoride bioavailability in agricultural soils.**
*Note.* Original conceptual synthesis by the author based on soil sorption, fractionation, and field studies reviewed herein.

The main implication is that "soil fluoride" is not a single exposure variable. For management and risk assessment, pair total fluoride with a lability metric and the chemical variables that control that lability.

Table 3 translates the soil mechanisms into testable expectations that can guide field diagnosis and amendment selection.

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**Table 3. Mechanistic interpretation of soil variables controlling fluoride mobility and crop transfer.**

| Variable | Expected influence | Diagnostic value | Management implication |
|---|---|---|---|
| **pH/alkalinity** | Changes sorption, mineral equilibria, and $OH^-$ competition | High | Avoid generic liming assumptions; evaluate full chemistry |
| **Calcium activity** | Can reduce dissolved F through association/precipitation | High | Supports Ca-based immobilization where compatible |
| **Al/Fe (hydr)oxides** | Provide specific sorption sites; pH dependent | High | Useful for predicting retention and amendment response |
| **Na–$HCO_3$ / salinity** | Can maintain F mobility in alkaline waters/soils | High in irrigated systems | Treat water chemistry as part of soil risk |
| **Clay/organic matter** | Modifies sorption capacity and pore-water chemistry | Moderate–high | Site-specific amendment effectiveness |
| **Total soil F** | Inventory indicator, not direct bioavailability | Moderate alone | Use with fraction/solution measurements |

The decision value of Table 3 is practical: it indicates which measurements should precede remediation. Applying an adsorbent without diagnosing the dominant mobility mechanism can produce short-lived or ineffective treatment.

## 5. Plant Uptake, Transport, and Toxicity Mechanisms

### 5.1 Entry routes, transport, and genotype dependence

Plants encounter fluoride through roots and aerial tissues. Root uptake depends on fluoride activity in the rhizosphere, whereas foliar exposure can be important near industrial sources. Once inside the plant, transport and compartmentation vary among species and genotypes. Studies in rice and tea identify marked differences in uptake and translocation and support an important role for fluoride-export mechanisms such as FEX proteins (Banerjee & Roychoudhury, 2019; Banerjee & Roychoudhury, 2021a; Banerjee, Roychoudhury, et al., 2019; Banerjee et al., 2021; Peng, Xu, Ren, et al., 2021; Tausta et al., 2021; Wu et al., 2024; Zhang et al., 2016).

The existence of exporter-based tolerance is important because it helps explain why tissue concentration and visible injury do not always move in parallel. A genotype may restrict cytosolic fluoride, redistribute it among tissues, or tolerate a given concentration

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through stronger antioxidant or osmotic defenses. This is one reason universal plant-toxicity thresholds are difficult to defend across crops.

### 5.2 Physiological injury and biochemical defense

Controlled studies link fluoride exposure to reduced germination, leaf injury, lower biomass, impaired photosynthesis, altered respiratory metabolism, oxidative stress, and disrupted antioxidant systems. Wheat, rice, bean, maize, soybean, sorghum, lettuce, safflower, and turf species show quantitatively different responses (Ahmad et al., 2022; Almeida Rodrigues et al., 2022; Chahine et al., 2024; Fan et al., 2022; Fina et al., 2016; Ghassemi-Golezani & Farhangi-Abriz, 2019; Maressa Hungria de Lima e Silva et al., 2022; Mondal, 2017; Pelc et al., 2020; G. Singh et al., 2023). Such variation is not experimental noise; it is a biological determinant of field risk.

Mechanistic studies implicate oxidative stress, sugar metabolism, the tricarboxylic acid cycle, organic-acid production, calcium signaling, and ion-homeostasis pathways in plant responses to fluoride. Exogenous silicon, calcium, selenium, spermidine, and selected nanofertilization approaches have reduced injury in specific experimental systems (Banerjee & Roychoudhury, 2021b; Banerjee, Singh, et al., 2019; Niu et al., 2020; Pan et al., 2020; Singh & Roychoudhury, 2020; Singh et al., 2021). These results are mechanistically valuable, but they should not be interpreted as field-ready agronomic recommendations without dose optimization, residue assessment, and multi-season validation.

### 5.3 Co-contaminants and combined stress

Agricultural fluoride exposure frequently occurs in chemically complex settings. Arsenic, aluminum, lead, and other elements can modify fluoride uptake and toxicity, while essential elements may alter antioxidant defenses or ion homeostasis. Rice studies demonstrate that arsenic–fluoride co-exposure can change uptake, defense responses, and metabolic damage relative to single-contaminant exposure (Banerjee & Roychoudhury, 2022; Banerjee et al., 2020; Fan et al., 2022; Li et al., 2019; Meng et al., 2026; Shehzadi et al., 2026; Singh & Roychoudhury, 2023; Zhang et al., 2026). The practical consequence is that single-contaminant thresholds can understate or misstate risk in groundwater-fed systems where multiple contaminants share geochemical controls.

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Mixture effects should be described as synergistic, antagonistic, or additive only where factorial designs, response-surface analysis, or other statistically defensible interaction tests support the classification. A combined-treatment response differing from one single-contaminant treatment is not sufficient to demonstrate mechanistic synergy.

Figure 3 organizes the plant evidence as a mechanistic chain from fluoride entry to agronomic and food-safety outcomes.

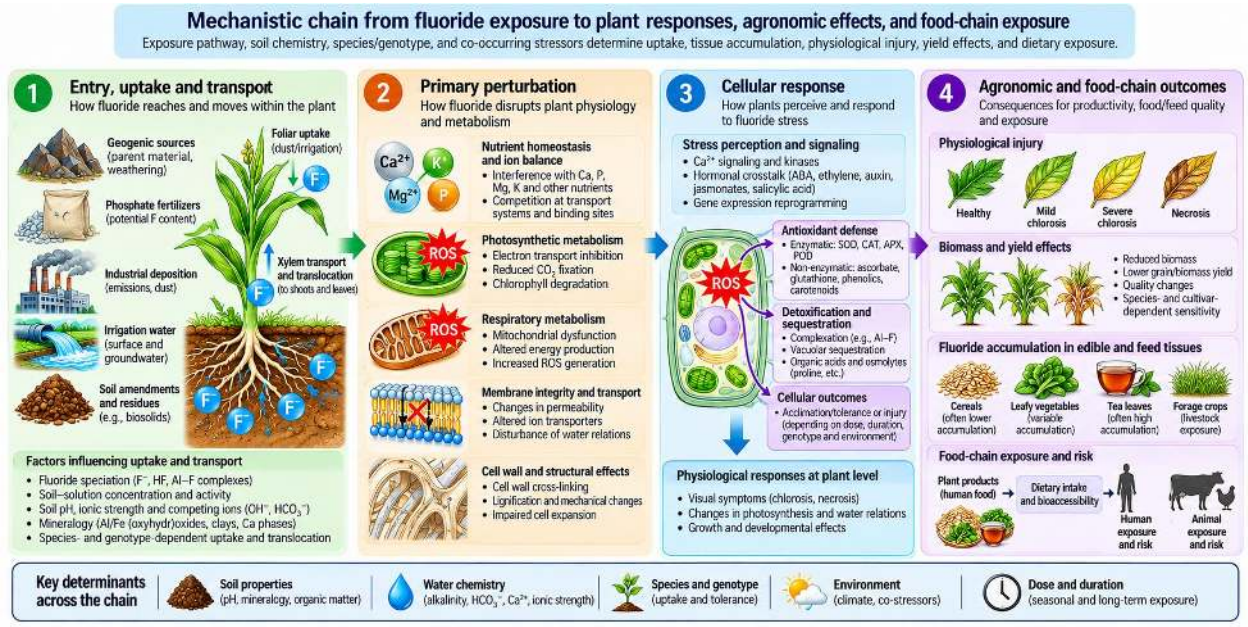



**Figure 3. Mechanistic chain linking fluoride entry, cellular perturbation, defense responses, and agronomic outcomes.**

*Note.* Original conceptual synthesis by the author based on crop-physiology and molecular studies reviewed herein.

Mechanistic endpoints are valuable only when connected to whole-plant performance. A change in an antioxidant enzyme is not equivalent to a yield effect, and visible injury is not equivalent to elevated edible-tissue fluoride.

Table 4 compares recurring plant-response endpoints and their interpretive strengths for a critical review.

**Table 4. Plant fluoride-response endpoints and their value for agronomic interpretation.**

| Endpoint | What it indicates | Strength | Main limitation |
|---|---|---|---|
| **Germination / seedling growth** | Early phytotoxicity | Useful screening | May not predict mature-crop yield |
| **Leaf injury/chlorosis / tip burn** | Visible tissue damage | Field-observable | Can be nonspecific |

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| Endpoint | What it indicates | Strength | Main limitation |
|---|---|---|---|
| **Photosynthesis/respiration** | Functional impairment | Mechanistic–agronomic bridge | Often short-duration experiments |
| **ROS / antioxidant enzymes** | Cellular stress and defense | Mechanistic depth | Not a direct yield or food-safety endpoint |
| **Biomass/grain yield** | Agronomic consequence | High practical relevance | Needs realistic field exposure |
| **Edible-tissue F** | Food/feed exposure potential | High exposure relevance | Must be paired with consumption data |

A stronger evidence hierarchy therefore places mature-crop yield and edible-tissue fluoride above isolated biochemical changes when the management question is agricultural safety. Biochemical endpoints remain essential for explaining why species and cultivars differ.

## 6. Crop Transfer, Food and Feed Pathways, and Exposure Hotspots

### 6.1 Food crops and edible-tissue transfer

A descriptive organ-specific transfer factor can be written as TF_organ,total = C_F,organ/C_F,soil,total and, where an operationally relevant fraction is available, TF_organ,mobile = C_F,organ/C_F,soil,mobile. Separate values should be reported for roots, shoots, grains, and leaves (TF_root, TF_shoot, TF_grain, and TF_leaf) with harmonized concentration units and dry/fresh mass conventions. A denominator based on total soil fluorine describes inventory-normalized transfer, not mechanistic bioavailability; an extractable denominator remains method-dependent and must not be presumed universally predictive.

Field and regional studies show that fluoride can enter rice, pulses, vegetables, and other foods when crops are grown in fluoride-affected soils or irrigated with contaminated water (Bhattacharya et al., 2017; De et al., 2021; Essebbahi et al., 2024; Gevera et al., 2022; Li et al., 2019; Rizzu et al., 2020). Transfer is heterogeneous among crop species and plant organs, so soil concentration alone cannot predict dietary exposure. Edible-tissue concentration should be treated as the key bridge between agricultural contamination and food safety.

Several studies also emphasize the importance of distinguishing total plant uptake from the concentration in the consumed fraction. High fluoride in roots or leaves may have

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limited dietary significance for a grain crop, whereas moderate accumulation in a directly consumed leaf can be more consequential. For feed crops, the relevant endpoint may instead be whole-shoot concentration and livestock intake.

### 6.2 Tea as a high-accumulation special case

Tea receives disproportionate attention because Camellia sinensis can accumulate fluoride and because infusion transfers a fraction of leaf fluoride into a beverage consumed repeatedly. Studies have addressed natural occurrence, soil fractions, uptake and transport, metabolic response, brewing conditions, and consumer exposure (Cai et al., 2016; Das et al., 2017; Jayasingha et al., 2025; Pattaravisitsate et al., 2021; Pavlovič et al., 2023; Peng et al., 2016; Peng, Xu, Ren, et al., 2021; Peng, Xu, Zhu, et al., 2021; Penteado et al., 2026; Satou et al., 2021; Wu et al., 2024; Yang et al., 2024). The tea literature illustrates the entire source-to-exposure chain: soil chemistry affects uptake, plant physiology affects accumulation, processing and brewing affect extraction, and consumption patterns determine dose.

For tea, analytical reports should distinguish dry-leaf concentration (mg $kg^{-1}$), brewed-infusion concentration (mg $L^{-1}$), leaf-to-water ratio, extraction temperature, brewing duration, and the consumed volume. Use infusion concentration directly in beverage intake calculations whenever it has been measured, rather than converting dry-leaf data without a validated brewing-transfer assumption.

The critical lesson from tea is methodological. Food-safety assessment should not stop at plant concentration. It should quantify the fraction actually transferred into the consumed product and combine that concentration with realistic consumption patterns and vulnerable age groups. This principle also applies to vegetables, grains, and feed.

Estimated daily intake can be expressed as $EDI = (C_F \times IR \times PF)/BW$, where $C_F$ is fluoride concentration of the unprocessed food (mg $kg^{-1}$), IR is food consumption (kg $day^{-1}$), PF is the dimensionless preparation/processing transfer factor, and BW is body mass (kg); EDI is then mg $kg^{-1}$ body mass $day^{-1}$. When $C_F$ is measured in the actual prepared food, PF = 1. For a prepared beverage, use the measured infusion concentration (mg $L^{-1}$) and intake in L $day^{-1}$. Combine population-specific food and drinking-water intakes using consistent units and time periods, and benchmark comparisons should distinguish safe intake levels, tolerable

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upper intake levels, and water-quality guidelines rather than treating them as interchangeable hazard-quotient denominators.

### 6.3 From concentration to dietary risk

Health-risk studies in fluoride-endemic regions have combined food concentrations with drinking-water exposure and consumption data, showing that multiple pathways, not a single commodity, can dominate total intake (Bhattacharya et al., 2017; De et al., 2021; Jaudenes et al., 2020; Mridha et al., 2021). Recent European reassessments likewise emphasize total oral exposure from food, water, salt, and ingested dental products, not food alone (EFSA Scientific Committee, 2025). This supports a cumulative-exposure perspective for agricultural risk assessment.

Table 5 distinguishes the measurements needed at each step of a food-chain exposure assessment and identifies where uncertainty most often enters.

**Table 5. Minimum evidence chain for translating agricultural fluoride contamination into dietary exposure.**

| Step | Required measurement | Preferred expression | Major uncertainty |
|---|---|---|---|
| **Source / soil** | Loading and bioavailable F | kg F $ha^{-1}$ $yr^{-1}$; solution/fraction F | Temporal variability |
| **Crop** | Edible-tissue F | mg $kg^{-1}$ fresh or dry weight, clearly stated | Species/cultivar and tissue basis |
| **Processing** | Retention or extraction | Fraction transferred after cooking/brewing | Preparation behavior |
| **Consumption** | Food/water intake | g or L $person^{-1}$ $day^{-1}$ by age group | Survey representativeness |
| **Dose** | Estimated daily intake | mg F $kg^{-1}$ bw $day^{-1}$ | Body mass and co-exposures |
| **Risk interpretation** | Comparison with health-based guidance | Age-specific, source-integrated | Different agencies/endpoints |

This chain makes clear why “high fluoride in soil” and “high health risk” are not equivalent statements. Each intermediate transfer step should be measured or explicitly modeled, with uncertainty carried forward.

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## 7. Human and Animal Health Relevance: Interpreting Agricultural Exposure

### 7.1 Fluorosis and health-based guidance

Chronic excessive fluoride intake is associated most clearly with dental and skeletal fluorosis. Drinking water remains a major exposure pathway in many endemic areas, but foods and beverages can add materially to total intake, particularly where crops are produced with high-fluoride water or where high-accumulating commodities are consumed frequently (Bhattacharya et al., 2017; EFSA Scientific Committee, 2025; Jayasingha et al., 2025; Long et al., 2026; Mridha et al., 2021; Penteado et al., 2026). The World Health Organization retains a guideline value of 1.5 mg $L^{-1}$ for fluoride in drinking water while emphasizing that total intake and local climatic and consumption conditions must be considered (World Health Organization [WHO], 2026). The 2026 guideline compilation therefore supports a risk-management interpretation rather than use of a single concentration target in isolation.

EFSA's 2025 reassessment updated safe and tolerable upper intake levels across age groups and concluded that current European exposure is generally below levels of concern for most groups. This context is useful but should not be extrapolated uncritically to fluoride-endemic agricultural regions, where drinking-water concentrations, tea consumption, irrigation-derived crop exposure, and body-size distributions may differ substantially (EFSA Scientific Committee, 2025).

The EFSA Scientific Committee (2025) established tolerable upper intake levels of 1.0 mg $day^{-1}$ for infants aged 0–12 months, 1.6 mg $day^{-1}$ for children aged 1–3 years, and 2.0 mg $day^{-1}$ for children aged 4–8 years. For individuals older than 8 years, including adults and pregnant women, EFSA derived a safe intake level of 3.3 mg $day^{-1}$, explicitly distinct from a conventional tolerable upper intake level. These values address aggregate oral intake; they do not establish agricultural-soil, crop, or irrigation-water limits. WHO (2026) retains 1.5 mg $L^{-1}$ as a guideline value for fluoride in drinking water, not an agronomic or food commodity threshold. Population exposures outside Europe require locally appropriate water and food-consumption scenarios (EFSA Scientific Committee, 2025; World Health Organization, 2026).

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### 7.2 Critical cautions in agricultural health-risk assessment

Three interpretive cautions are essential. First, exposure assessment should integrate water and food rather than summing incomparable studies. Second, concentration units and moisture bases must be harmonized before dietary calculations. Third, risk estimates are scenario-dependent: they reflect consumption, body mass, bioavailability assumptions, and reference values, not simply analytical concentration. Studies of foods, tea, and endemic-region crops provide useful screening, but their outputs are not universal risk coefficients (Das et al., 2017; De et al., 2021; Essebbahi et al., 2024; Gevera et al., 2022; Jaudenes et al., 2020; Jayasingha et al., 2025; Li et al., 2019; Pattaravisitsate et al., 2021; Pavlovič et al., 2023; Penteado et al., 2026).

For livestock, feed and water exposures should be evaluated together because animal products and animal health can create additional pathways of concern. Recent literature increasingly treats fluoride alongside co-contaminants and nutritional modifiers, which better reflects agricultural systems than single-element toxicology (Meng et al., 2026).

## 8. Mitigation and Remediation: From Mechanism to Field Durability

### 8.1 Source control first

The most robust intervention is to prevent additional loading. This includes selecting lower-fluoride fertilizer inputs where feasible, improving industrial fluoride capture, managing fluoride-rich irrigation water, and avoiding repeated application of high-fluoride residues. Studies on phosphate fertilizers show that commercial products contain fluoride and that processing can reduce it (Li et al., 2023; Ramteke et al., 2021; Ramteke et al., 2018). Emission-control evidence from fertilizer production further shows that source control can reduce downstream crop accumulation (Silva & Ferraz-Almeida, 2023).

### 8.2 Soil immobilization and sorbent-based approaches

For Ca-rich and hydroxyapatite amendments, field assessment should track available phosphorus and micronutrients, post-treatment soil pH, pore-water fluoride, edible-tissue fluoride, yield, and drainage effects. Biochar studies should also identify feedstock, pyrolysis temperature, ash and Ca/Al/Fe content, surface properties, pH, and applied dose. A durability

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comparison should report mobile fluoride and crop endpoints before and after defined wet–dry cycles, seasonal irrigation, repeated fertilization, and successive cropping cycles; fluoride immobilization must not be described as removal of the total fluorine inventory.

Where legacy soil fluoride is the principal problem, immobilization aims to reduce the dissolved or exchangeable fraction rather than remove the entire fluorine inventory. Nano-hydroxyapatite, bone-derived materials, seaweed-derived amendments, biochar, aluminum-humate systems, organic manures, and related sorbents have shown potential in experimental studies (Chen et al., 2024; Gan et al., 2021; Ghassemi-Golezani & Farhangi-Abriz, 2019; Huang et al., 2020; Imtiaz et al., 2024; Moirana et al., 2022, 2023; H. Wang et al., 2023). Calcium-based materials are mechanistically attractive because they can lower fluoride activity, but performance depends on pH, competing ions, amendment stability, and potential effects on phosphorus and micronutrient availability.

The strongest limitation of the remediation literature is scale. Many studies demonstrate short-term reductions in solution fluoride or plant uptake under controlled conditions; fewer establish persistence through wet–dry cycles, repeated fertilization, root activity, seasonal irrigation, and changing pH. A sorbent that initially binds fluoride may not remain effective if surface sites age, dissolve, or become saturated. Field durability, not maximum batch adsorption capacity, should therefore be the principal criterion for agronomic remediation.

### 8.3 Biological and crop-management strategies

Rhizofiltration, crop or cultivar selection, and nutrient-mediated stress mitigation represent complementary strategies (Banerjee & Roychoudhury, 2022; Kumar et al., 2021; Makete et al., 2022; Niu et al., 2020; Periasamy & Gopi, 2023; Sant'Anna-Santos et al., 2021; Singh & Roychoudhury, 2020). These approaches can be useful where source elimination is impractical, but they operate at different endpoints. Rhizofiltration treats water; tolerant cultivars protect yield; and physiological protectants may reduce injury without necessarily reducing fluoride in edible tissues. Consequently, “tolerance” should not be equated with “food safety.” A cultivar that maintains yield while accumulating fluoride could increase dietary transfer.

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Figure 4 converts the remediation literature into a risk-control hierarchy that prioritizes prevention and field verification over isolated laboratory removal efficiency.

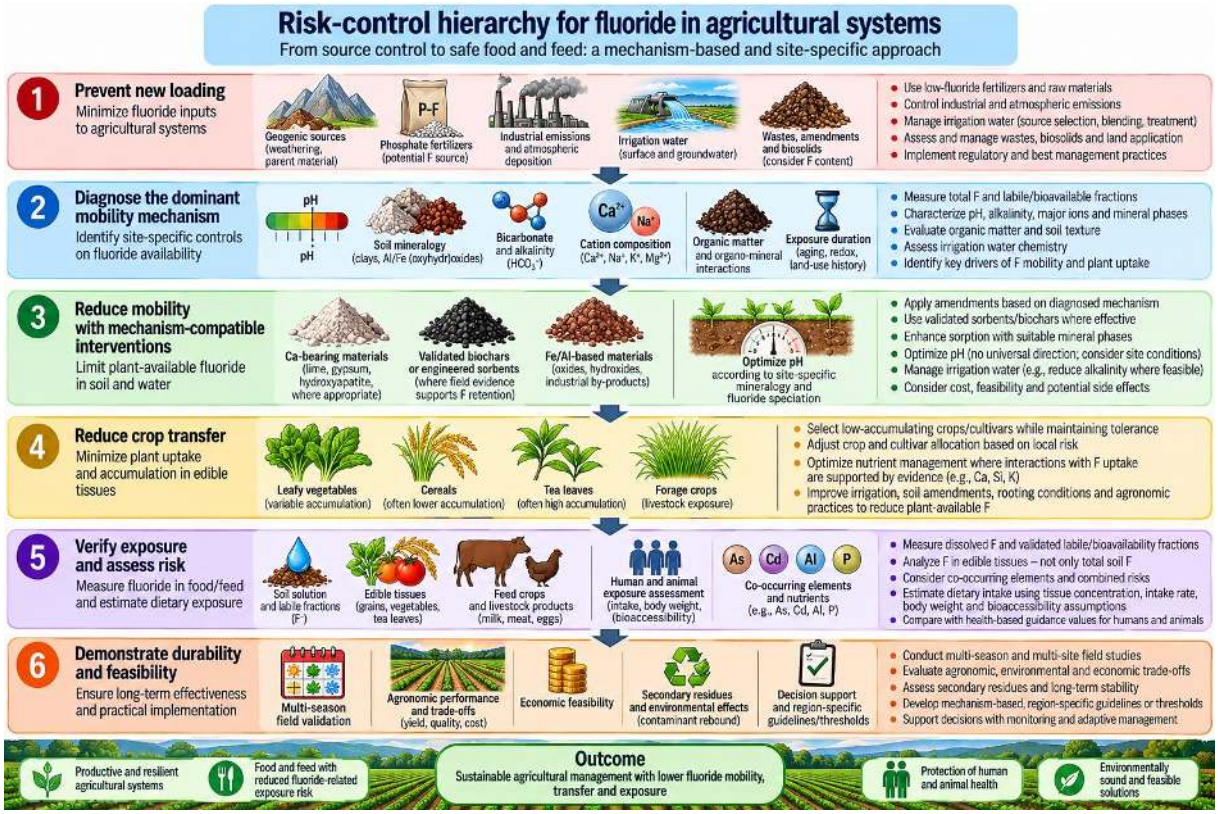



**Figure 4. Risk-control hierarchy for managing fluoride in agricultural systems.**

*Note.* Original decision framework by the author, synthesized from source-control, immobilization, crop-management, and risk-assessment studies reviewed herein.

The hierarchy is intentionally sequential. Lower tiers do not compensate for failure to control a dominant source, and successful laboratory immobilization is not considered a completed remedy until crop exposure and field durability are verified.

Table 6 compares major mitigation approaches by mechanism, endpoint, and principal evidence gap.

**Table 6. Critical comparison of fluoride mitigation strategies for agricultural systems.**

| Strategy | Primary mechanism | Best endpoint | Main evidence gap |
|---|---|---|---|
| **Source substitution/control** | Prevents new F loading | Reduced annual mass input | Cost and supply-chain feasibility |
| **Water treatment/rhizofiltration** | Removes F before irrigation | Irrigation-water F | Residuals and treatment capacity |
| **Ca/hydroxyapatite amendments** | Immobilization / precipitation / sorption | Lower pore-water and crop F | Long-term stability; P interactions |
| **Biochar/organic** | Sorption + chemistry | Lower bioavailable F | Feedstock variability; |

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| Strategy | Primary mechanism | Best endpoint | Main evidence gap |
|---|---|---|---|
| **amendments** | modification | / improved soil function | durability |
| **Crop/cultivar selection** | Avoidance/tolerance/low transfer | Yield + edible-tissue F | Multi-location validation |
| **Nutrient protectants** | Strengthen physiological defense | Reduced injury | May not reduce edible-tissue F |

No single option is universally preferable. Selection should follow a site diagnosis that identifies the dominant source, mobility controls, crop endpoint, and acceptable residual risk.

## 9. Critical Synthesis: A Decision Framework for Agricultural Fluoride Risk

### 9.1 Four risk archetypes

The four Types I–IV are interpretive risk archetypes constructed to guide evidence collection and intervention choice. They are not numerical classes supported by calibrated boundaries, validated probabilities, or a field-tested classification algorithm. Assignment should remain provisional wherever pore-water, crop-organ, intake, or multi-season monitoring data are missing.

The literature can be synthesized into four practical archetypes. Type I systems have high total soil fluoride but low mobility and low crop transfer; aggressive remediation may be unnecessary if edible-tissue concentrations remain low. Type II systems have moderate soil inventories but high mobility caused by alkaline or sodium–bicarbonate chemistry; these systems may present greater crop-transfer risk than total fluoride suggests. Type III systems are dominated by foliar industrial exposure, where soil amendments alone cannot solve the problem. Type IV systems combine fluoride with arsenic, metals, or salinity, requiring multi-contaminant rather than fluoride-only management (Cui et al., 2021; He et al., 2021; Li et al., 2019; Meng et al., 2026; Singh et al., 2018; Singh et al., 2022; Zhang et al., 2026).

These archetypes reveal why generic threshold-based management often fails. The same measured soil concentration can belong to different risk classes depending on water chemistry, source geometry, crop, and edible-tissue transfer. A robust management decision should therefore be based on a chain of evidence rather than on a single exceedance value.

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### 9.2 Proposed Fluoride Agricultural Risk Chain (FARC)

FARC is an author-developed diagnostic and reporting structure, not a validated toxicity predictor or a risk-score calculator. Each link requires independently appropriate evidence; the absence of a crop or consumption measurement should be reported as an evidence gap rather than treated as a zero-risk result. Its utility should be prospectively evaluated in diverse crops, climates, and soil geochemical settings before any numerical decision thresholds are proposed.

A conceptual decision structure—termed here the Fluoride Agricultural Risk Chain (FARC)—is proposed. Step 1 quantifies source loading. Step 2 characterizes mobility using soil-solution or fraction data together with pH, Ca, Al/Fe, and irrigation-water chemistry. Step 3 measures crop-specific transfer and agronomic response. Step 4 quantifies fluoride in the edible or feed-relevant fraction. Step 5 integrates realistic food, water, or feed intake. Step 6 selects an intervention matched to the dominant control point, and Step 7 verifies performance over multiple seasons. FARC is not a new toxicity model and does not establish universal numerical thresholds; it is a minimum evidence sequence intended to prevent premature conclusions and to make decision logic traceable.

Table 7 operationalizes the proposed FARC sequence as a decision checklist for field studies and agricultural management.

**Table 7. Proposed Fluoride Agricultural Risk Chain (FARC) for field diagnosis and management.**

| FARC step | Question | Minimum evidence | Interpretive criterion |
|---|---|---|---|
| **1. Source** | Where is F entering? | Water/fertilizer/deposition/residue inventory | Dominant annual/cumulative load identified |
| **2. Mobility** | Is F chemically available? | Solution/fraction F + pH + Ca + Al/Fe + $HCO_3^-$ | Mobile fraction elevated relative to site context or increasing over time |
| **3. Crop response** | Does the crop take up F or lose performance? | Tissue profile + yield/physiology | Crop-specific uptake or injury |
| **4. Edible fraction** | Does F reach consumed tissue? | Edible-tissue concentration | Edible-tissue transfer confirmed on a clearly defined mass basis |
| **5. Exposure** | Is intake potentially | Food + water intake by group | Integrated exposure is relevant to the selected |

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| FARC step | Question | Minimum evidence | Interpretive criterion |
|---|---|---|---|
| | relevant? | | health-based guidance |
| **6. Intervention** | What control point is most efficient? | Mechanism-matched option | Intervention targets the dominant source, mobility, or crop-transfer pathway |
| **7. Verification** | Does control persist? | Multi-season field monitoring | Stable reduction persists without unacceptable agronomic penalty |

The principal value of FARC is traceability: each management statement can be linked to a measured transition in the source–soil–plant–food chain, while missing transitions remain visible. For example, if total soil fluorine is known but edible-tissue fluoride has not been measured, a food-safety conclusion remains premature. The framework is therefore best used as a diagnostic checklist and reporting structure rather than as a validated predictive model.

## 10. Research Gaps and Priorities for 2027 and Beyond

### 10.1 Standardize bioavailable-fluoride metrics

The largest cross-study limitation is the inconsistent relationship among total fluorine, operationally defined soil fractions, pore-water fluoride, and plant uptake. Studies use different extractants, units, moisture bases, exposure durations, and crop tissues, which restricts cross-study comparison and meta-analysis. Future work should report total fluorine alongside at least one mobility or lability metric, complete water chemistry, and a clearly defined plant compartment (Huang, Chen, et al., 2025; Wehr et al., 2023; Yi et al., 2017).

### 10.2 Move from pot studies to multi-season field validation

The remediation literature is rich in candidate materials but comparatively poor in long-duration field evidence. Multi-season trials should measure not only fluoride immobilization but also crop yield, phosphorus and micronutrient availability, soil biological function, amendment aging, secondary residues, and cost. The same requirement applies to nutrient protectants and tolerant cultivars: success should include edible-tissue fluoride, not only visual injury or biomass (Chen et al., 2024; Gan et al., 2021; Imtiaz et al., 2024; Makete et al., 2022; Moirana et al., 2022, 2023; Periasamy & Gopi, 2023; H. Wang et al., 2023).

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### 10.3 Integrate co-contaminants and realistic exposure scenarios

Fluoride commonly co-occurs with arsenic, aluminum, salinity, or other stressors, but most agronomic experiments remain single-contaminant studies. Future designs should use environmentally realistic mixtures and should distinguish additive, antagonistic, and synergistic responses. Risk assessments should combine drinking water and food, account for processing or brewing, and report age-specific exposure scenarios (Banerjee et al., 2020; Fan et al., 2022; Li et al., 2019; Meng et al., 2026; Shehzadi et al., 2026; Singh & Roychoudhury, 2023; Zhang et al., 2026).

### 10.4 Improve prediction without losing mechanistic interpretability

Machine-learning approaches can help predict crop fluoride from soil chemistry and landscape variables, but model accuracy alone is insufficient. Models should preserve mechanistic variables, report external validation, and provide uncertainty intervals. Hybrid models that combine geochemical constraints with statistical prediction are likely to be more transferable than purely empirical algorithms (Feng et al., 2025; Zhang et al., 2024).

### 10.5 Establish reporting standards for critical reviews and primary studies

Reporting should also identify spatial/temporal sampling design, analytical reference materials and recoveries, detection/quantification limits, fertilizer F content and application rates, annual irrigation volumes, independent field validation of predictive models, mixture-interaction statistical tests, and pre/post-intervention soil fertility and crop endpoints. Any conversion between operationally measured soluble fluoride and inferred bioavailability should be declared explicitly.

A minimum reporting standard should include fluoride source and analytical method, units and dry/fresh-weight basis, soil pH and extractant, calcium and major-ion chemistry where relevant, crop cultivar and growth stage, tissue analyzed, exposure duration, and uncertainty. Without these fields, apparent contradictions among studies may reflect methodology rather than true biological differences.

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## 11. Conclusions

Fluoride in agriculture is best understood as a transfer problem rather than as a concentration problem. Agricultural risk emerges when a fluoride source generates a mobile fraction under site-specific soil and water chemistry, that fraction reaches a susceptible or accumulating crop, fluoride enters the edible or feed-relevant tissue, and exposure becomes relevant to human or animal health. Breaking any link in this chain can reduce risk.

The evidence reviewed here shows that total soil fluorine, although useful as an inventory measure, is insufficient for agronomic or food-safety decisions. pH, calcium, aluminum and iron phases, bicarbonate and sodium chemistry, loading history, plant genotype, exposure duration, and co-contaminants materially alter mobility and biological response. The most defensible management sequence is therefore to prevent further loading, diagnose the dominant mobility mechanism, apply mechanism-compatible source treatment or immobilization, select crops when needed, measure fluoride in consumed tissues, and verify performance under field conditions over multiple seasons.

Future advances are likely to depend less on identifying additional fluoride hotspots and more on standardizing bioavailability metrics, linking matched water–soil–crop measurements, testing realistic contaminant mixtures, and demonstrating that mitigation remains effective, agronomically acceptable, and economically practical beyond short-term laboratory conditions.

## Declarations

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### Conflict of Interest

The author declares no conflict of interest.

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## Data Availability

No new experimental datasets were generated. All quantitative values discussed in the review are traceable to the cited literature.

## Author Contributions

The author performed conceptualization, critical analysis, literature synthesis, visualization, and manuscript preparation.

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