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Fluoride toxicity in crop plants: Mechanisms, physiological responses and remediation strategies: A review

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Abstract
Fluoride (F^-) is a naturally occurring ion that is released by weathering of minerals, volcanic emissions, industrial activity, inputs of phosphate fertilisers and use of high-fluoride ground waters for irrigation. While low fluoride exposure may elicit neutral or stimulatory responses at times, excess fluoride is phytotoxic and a threat to crop productivity, food quality, and agricultural sustainability. Plants take in fluoride mainly through roots from contaminated soil or irrigation water and by foliage from atmospheric deposition. It is then transported in the transpiration stream and often accumulates in leaf margins and tips. The excess F can interfere with membrane function, mineral nutrition, photosynthesis, respiration, enzyme activity, cellular redox balance and reproductive development. The major effect of fluoride stress is the generation of excess reactive oxygen species, leading to lipid peroxidation, protein damage, pigment degradation and growth inhibition. Plants have several mechanisms to counteract fluoride exposure, including antioxidant defences, accumulation of osmolytes, reduction of uptake, storage in vacuoles and export of fluoride by fluoride exporter (FEX) transport proteins. However, the extent of damage differs among crop species, cultivars, developmental stages, soil properties and fluoride sources. This review summarises the current knowledge on sources of fluoride, uptake and transport, molecular mechanisms of toxicity, physiological and biochemical responses, food-chain implications, and mitigation practices. Effective remediation must combine source control, irrigation-water management, soil amendments, tolerant cultivars, beneficial microorganisms and judiciously selected phytoremediation strategies. Future research needs to consider field scale threshold values, crop specific food safety standards, genotype-based breeding and the long-term performance of remediation measures across soil and climate conditions.

Keywords: Fluoride, crop plants, oxidative stress, photosynthesis, FEX transporter, phytoremediation, soil amendment, food safety

Introduction

Fluoride is widely present in rocks, minerals in soil, groundwater, surface waters, atmospheric dust, industrial emissions, fertilisers and agro-industrial wastes. It can be increased in the environment by geogenic processes including weathering of fluoride-containing minerals, and by anthropogenic activities such as aluminium smelting, brick kilns, coal burning, phosphate fertiliser production and industrial discharge. Fluoride-rich groundwater irrigation in agricultural landscapes can be a persistent source of fluoride loading as repeated applications can increase the fluoride concentration in the crop root zone over time (Jha *et al*., 2022) [3].

Fluoride is not considered to be an essential plant nutrient for most higher plants. Some studies have reported neutral or apparently stimulatory effects on selected traits including seedling growth or respiration at very low concentrations. These responses are inconsistent and strongly depend on species, dose, exposure duration, and growth conditions. Fluoride is toxic at high concentrations and inhibits germination, root and shoot growth, biomass, reproduction and reduces yield (Gadi *et al*., 2012; Khandare *et al*., 2018) [2, 4].

Fluoride contamination is not only limited to loss in yield in terms of agricultural importance. Grains, vegetables, forages, and processed plant products can transmit crop-absorbed fluoride to the diets of humans and livestock. The accumulation of fluoride by vegetable and cereal crops varies considerably with the type of crop, the pathway of exposure, soil chemistry, irrigation source and local industrial deposition (Singh *et al*., 2023) [6]. Thus, fluoride pollution is a food safety as well as crop production concern.

Crop injury from fluoride is usually seen as chlorosis, necrosis, leaf tip burn, marginal scorching, reduced leaf area, stunted roots, delayed development, and poor grain or fruit filling. Visible symptoms may not appear until the physiological injury is already established. Before any external damage is visible, fluoride can disturb metabolic processes including photosynthetic electron transport, chlorophyll synthesis, ATP production, membrane transport, nutrient acquisition and antioxidant regulation (Khandare *et al*., 2018) [4].

This review discusses pathways of fluoride transfer to crops, uptake and internal distribution, mechanisms of plant injury, physiological and biochemical responses, detoxification systems, options for remediation and priorities for future research. Particular emphasis is placed on management practices that minimise fluoride exposure without impairing crop productivity and food quality.

Sources and Movement

Fluoride is a naturally-occurring and man-made substance. Fluoride occurs naturally at high concentrations in areas where ground water comes into contact with fluoride-bearing geological materials such as fluorite, apatite, mica, amphiboles and volcanic deposits. Geothermal activity and volcanic emissions may also release fluoride to air, soil and water. In dry and semi-arid regions, the evaporation and long residence time of groundwater may also concentrate

dissolved fluoride. Sources include burning of coal, production of aluminium, manufacture of ceramics and bricks, glass industries, processing of phosphates and fertiliser plants. Industrial emissions of atmospheric fluoride can be deposited on agricultural soils or directly on the leaf surface of crops. Exposure of foliage to fluoride is especially important in areas near emission sources, since fluoride can be absorbed by stomata or retained on the leaf surface before penetrating tissues (Weinstein & Davison, 2004) [13].

Fluoride can be added to agricultural soils via phosphate fertilisers because fluorine-containing minerals are present in phosphate rock. If such fertilisers continue to be used, they can add fluoride to the topsoil and under some conditions increase the exposure of plants. Ram *et al*. (2021) [10] reported that fluoride associated with fertiliser input may be retained in soils and cause fluoride stress in crops, particularly in areas with high natural fluoride levels. The availability of fluoride in soil depends on pH, calcium concentration, clay minerals, organic matter, aluminium and iron oxides, moisture and competing ions. Fluoride may complex with aluminium and other metals under acidic conditions, and be relatively mobile in alkaline and sodium-rich soils. Calcium may reduce fluoride bioavailability through the formation of sparingly soluble calcium fluoride. This means that the same total fluoride concentration can cause different responses in plants in different soils.

Fluoride can reach plants in two main ways

- **Root uptake:** Fluoride in soil solution or irrigation water is absorbed by roots and may be translocated via apoplastic and symplastic pathways.

- **Foliar uptake:** Stomatal and cuticular penetration (particularly under humid conditions) can allow gaseous hydrogen fluoride and soluble fluoride atoms to enter leaves.

Once in the plant, fluoride is mainly transported through the transpiration stream. It is often concentrated in mature leaves, and at leaf tips or margins, which are subject to high xylem flow and high evaporative water loss. Ram et al. (2021) [10] showed that fluoride is frequently deposited in the leaf tips and its concentrations are often much higher than in the basal tissues.

Uptake and Distribution

The uptake of fluoride is dependent on the chemical form of fluoride, pH of the root zone, membrane permeability, transpiration rate, plant species and nutrient status. Fluoride is usually present in water and soil solution as F-, but complexes with aluminium, calcium, magnesium and hydrogen may be formed under particular chemical conditions. Plants can take up fluoride by passive movement and through channels or transport systems that may not be fluoride specific.

Root uptake is influenced by soil fluoride availability, not total soil fluoride. High levels of calcium in soil may limit fluoride movement to roots, while acidic conditions, low availability of calcium, and some characteristics of irrigation water may increase fluoride exposure. Root architecture also affects uptake, as a larger and more active root surface may enhance contact with contaminated soil solution.

The absorbed fluoride may remain in the roots, move up to the shoots via xylem transport, or be deposited in the leaves. In many plant species a large proportion is retained in the roots, which may form a partial barrier to shoot translocation. But large translocation can occur under high exposure, especially when transpiration is vigorous. The crop species differed in their root to shoot transfer capacity, and their ability to limit the accumulation of fluoride in edible organs.

Of particular interest from a food-safety perspective are leafy vegetables, as the harvested tissue may receive atmospheric fluoride directly and may also accumulate fluoride transported from roots. Singh *et al*. (2023) [6] reported significant variations in the concentrations of fluoride in vegetable and cereal crops and stressed the need for local measurements due to large regional variations in the contamination pattern.

Age of crop also affects fluoride transport. Older leaves may have higher concentrations due to longer exposure times and sustained transpiration. This pattern helps to explain the high frequency of injuries at leaf margins, tips and older foliage.

Mechanisms of Toxicity

Fluoride toxicity reflects its high chemical reactivity and its ability to interfere with enzyme activity, membrane processes, metal-ion balance and cellular metabolism. The ion can bind metal cofactors, interfere with calcium signalling, inhibit enzymes that require magnesium or other cations, and affect membrane-associated transport systems. These effects all contribute to inhibit growth and development.

Enzyme Inhibition

Fluoride can inhibit a wide variety of enzymes by binding to metal centers or by changing the enzyme conformation. It can affect enzymes involved in carbohydrate metabolism, respiration, ATP production, protein synthesis, nucleic-acid metabolism and photosynthesis. A lot of metabolic reactions depend on enzymes, so even a mild inhibition could have ripple effects across the whole cellular process. Fluoride has been associated with inhibition of ATPases, including plasma-membrane H+-ATPases. These enzymes are important for the establishment of proton gradients involved in the uptake of nutrients, stomatal regulation, membrane potential and secondary transport. Thus, inhibition of ATPases may disturb ion homeostasis and reduce the energy available for active transport (Kumar *et al*., 2026) [7].

Fluoride may also inhibit ATP synthase, and disrupt energy metabolism. Reduced ATP availability limits biosynthesis, ion transport, phloem loading, stress repair and cell division. Plants exposed to fluoride are generally characterised by slower growth, decreased root elongation and lower biomass accumulation.

Membrane Damage

Fluoride stress mainly targets membrane integrity. Fluoride induced oxidative stress leads to lipid peroxidation which in turn damages membrane lipids and increases permeability. More membrane leakage can cause loss of ions, metabolites and cellular compartmentalisation. The membrane injury in fluoride stressed plants is usually shown by the increased electrolyte leakage and malondialdehyde accumulation.

Water uptake and nutrient transport can also be affected by membrane dysfunction. The cell membranes of damaged roots are less able to selectively absorb ions, leading to a deficit or imbalance of calcium, magnesium, potassium, phosphorus, iron, zinc and other essential elements. Such mineral disturbances may aggravate fluoride injury by impairing photosynthesis, antioxidant activity and cell-wall stability.

Calcium Disruption

Fluoride strongly interacts with calcium, which might lead to a reduction in free calcium and hamper calcium-dependent signalling. Calcium also plays a role in membrane stabilisation, cell wall formation, pollen germination, root development, and stress signalling. Therefore, the disruption of calcium homeostasis by fluoride can affect both vegetative and reproductive processes. The antagonistic relationship between fluoride and calcium also serves as a basis for remediation. Calcium amendments can bind fluoride in the soil as calcium fluoride, reducing its availability, and may help stabilise membranes and cell walls. Amendment performance, however, is a function of dose, soil pH, soil texture, existing calcium status, and irrigation chemistry.

Oxidative Stress

Oxidative stress is one of the most common consequences of fluoride exposure. Fluoride can promote formation of reactive oxygen species including superoxide radicals, hydrogen peroxide, hydroxyl radicals and singlet oxygen. Controlled levels of reactive oxygen species act as signalling molecules. However, under severe exposure to fluoride, their production exceeds antioxidant capacity and leads to oxidative damage.

Excess reactive oxygen species can oxidise proteins, degrade pigments, damage nucleic acids, affect membranes and impair organelle function. Chloroplasts, mitochondria and peroxisomes are particularly prone to damage as they are the major sites of redox activity. Fluoride exposure was shown to stimulate oxidative stress and induce antioxidant defence responses in Spirodela polyrhiza including changes in superoxide dismutase, catalase, ascorbate peroxidase, peroxidase and glutathione reductase activity (Rani *et al*. 2019) [11]

The extent of oxidative damage is dependent on the relative rate of production and detoxification of reactive oxygen species. Fluoride-tolerant genotypes usually possess higher antioxidant capacity, lower lipid peroxidation and better photosynthetic performance than sensitive genotypes under similar exposure.

Physiological Responses

Germination and Seedling Growth

Fluoride is very damaging to seed germination as the early development stage is dependent on rapid water uptake, enzyme activation, reserve mobilisation and cell division. Fluoride inhibits or retards germination by interference with hydrolytic enzymes, respiration, hormonal regulation, membrane integrity and embryonic growth. Fluoride-treated seeds often have a decreased germination percentage and a slower emergence.

Inhibition of the root is usually more marked in seedlings than inhibition of the shoot. The first tissues that come into contact with the fluoride-containing soil solution are the roots. Root length, root surface area, lateral root formation and root biomass may all be reduced. Less root growth reduces water and nutrient uptake, further exacerbating stress in the aerial tissues.

Gadi *et al*. (2012) [2] reported adverse effects of fluoride on germination, seedling growth and photosynthetic pigments in chickpea and barley. Responses vary in severity between species, dependent on uptake, internal distribution, metabolic sensitivity and capacity for stress-defence.

Photosynthesis and Pigments

The most damaging effects of fluoride are on photosynthesis. The major effects include reduced chlorophyll synthesis, chloroplast degradation, disruption of photosystem II activity, inhibition of the Hill reaction, altered stomatal function and decreased carbon assimilation. These changes reduce the leaf's ability to synthesise carbohydrates and support growth.

The loss of chlorophyll is a common visible and biochemical marker of injury by fluoride. Fluoride inhibited chlorophyll biosynthesis and increased pigment degradation. Chloroplast ultrastructure could be impaired, damage thylakoid membranes and decrease photochemical efficiency. Reduced chlorophyll and carotenoid content impair both light harvesting and photoprotection. Fluoride-induced stomatal closure may also decrease the entry of carbon dioxide into leaves and thus limit photosynthesis. In addition, ribulose-1,5-bisphosphate carboxylase/oxygenase and ATP synthase are inhibited, and this can lead to impaired carbon fixation and energy production. The number of active photosystem II reaction centers was reduced and primary photochemistry was impaired by fluoride, with maize being more inhibited than wheat under the conditions tested (O'Neill *et al*., 2020) [9].

A reduction in photosynthetic activity has wide ranging effects. Reduced carbohydrate production results in lower biomass accumulation, limited root growth, impaired reproductive development, and limited grain filling or fruit development. In prolonged stress carbon limitation may synergise with oxidative damage to accelerate leaf senescence.

Water Relations and Gas Exchange

Fluoride exposure can affect water relations by causing root injury, damaging membranes, altering stomatal regulation and reducing hydraulic conductivity. A reduced root system will absorb less water, and oxidative damage to membranes can reduce water retention in cells. The response of plants may be to close their stomata, which conserves water but limits the intake of carbon dioxide.

Reduced transpiration and stomatal conductance can be protective in the short term but expensive if prolonged. Lower gas exchange causes lower photosynthetic carbon gain and can lead to lower growth. The effects of fluoride on gas exchange are species and route of exposure dependent and influenced by humidity, nutrient supply and developmental stage.

Mineral Nutrition

Fluoride influences mineral nutrition through interference with root function, membrane transport, soil chemistry and ion competition. Deficiencies or imbalances in calcium, magnesium, potassium, phosphorus, iron, manganese, zinc and other nutrients have been noted under fluoride stress.

Nutritional disruption can exacerbate toxicity because these nutrients are involved in chlorophyll formation, enzyme activation, osmotic regulation and antioxidant defence. Calcium is particularly important as it may reduce the availability of fluoride in soils and decrease membrane damage. Magnesium deficiency can exacerbate loss of chlorophyll as magnesium is the central atom in the chlorophyll molecule. Iron deficiency may limit electron transport and chlorophyll synthesis and potassium imbalance may affect stomatal regulation and osmatic adjustment.

Therefore, nutrient management needs to be considered as part of fluoride risk management. Balanced fertilisation, specific calcium supplementation and soil testing can relieve secondary stress due to nutrient imbalance due to fluoride.

Reproduction and Yield

Fluoride toxicity influences flowering, pollen viability, pollen-tube growth, fertilisation, seed formation, grain filling and fruit development. Reproductive tissues may be especially vulnerable as successful reproduction requires rapid cell division, tightly controlled calcium gradients, high metabolic activity and adequate carbohydrate supply. Yield loss is due to total injury during development. Reduced emergence decreases plant population, impaired roots limit resource acquisition, damaged leaves reduce photosynthesis and reproductive disruption reduces the number or quality of harvestable organs. The ultimate effect can be a reduction in grain weight, a lower seed number, poor fruit set, a reduction in fodder quality or a reduction in marketability of vegetables due to leaf necrosis.

Biochemical and Molecular Responses

Fluoride-induced plant defence responses: different responses These include enzymatic antioxidants, non-enzymatic antioxidants, osmolytes, stress hormones, metal binding compounds, altered gene expression, and transport-mediated exclusion of fluoride.

Antioxidant Defense

The antioxidant system seems to be the key in fluoride tolerance. Superoxide dismutase converts superoxide radicals into hydrogen peroxide which is then removed by catalase, peroxidases, and ascorbate peroxidase. Glutathione reductase keeps glutathione in its reduced state and is an important part of the ascorbate–glutathione cycle.

The activity of the antioxidant enzymes is often enhanced in tolerant plants enough to limit oxidative damage. In sensitive plants, enzyme induction may be weak or transient or overridden by reactive oxygen species generation. Therefore, antioxidant capacity is often associated with fluoride tolerance, although enzyme responses may vary among species and exposure periods. Detoxification also involves non-enzymatic antioxidants such as ascorbate, glutathione, phenolics, flavonoids, tocopherols and carotenoids. These compounds can scavenge reactive oxygen species, thereby stabilising the membranes and protecting the proteins and nucleic acids.

Osmolytes and Stress Metabolites

Plants subjected to fluoride stress may accumulate compatible solutes such as proline, soluble sugars, glycine betaine and amino acids. These metabolites are involved in osmotic adjustment, stabilisation of proteins and membranes and buffering of the cellular redox status. However, a high proline or sugar concentration does not necessarily indicate a successful tolerance but can also be a sign of cellular damage and a disturbed metabolism.

Fluoride stress also impacts hormonal signalling. Abscisic acid can induce stomatal closure and the expression of stress-responsive genes. Salicylic acid, jasmonates, ethylene and auxin-related pathways can influence antioxidant defence, root growth and senescence. The outcome is dose-, tissue-, time- and co-stressor dependent.

Fluoride Export and Compartmentalization

One of the major molecular mechanisms of fluoride tolerance is the fluoride exporter protein, FEX. FEX transporters are used for cytosolic fluoride export and intracellular accumulation restriction. Ram *et al.* (2021) [10] showed that FEX is a major mechanism for fluoride tolerance in plants: plants without FEX are more sensitive to fluoride, and increased expression of AtFEX can improve tolerance.

Genome-wide studies have shown the existence of FEX-related genes in diverse plant species and their induction upon fluoride treatment. Fluoride exporter genes were identified from plant species and the fluoride-responsive expression of FEX genes in mung bean was reported by Mukherjee *et al.* (2021) [8]. The results indicate that fluoride transporters are promising targets for molecular breeding and genetic engineering.

Besides efflux, plants may also minimise fluoride toxicity by exclusion at the root surface, binding to cell walls, chelation and sequestration in less metabolically active compartments. Fluoride may be sequestered in vacuoles and thus reduce its concentration in the cytosol, where it would otherwise affect the activity of sensitive enzymes and organelles. The exact transport routes and the regulatory networks are not yet fully understood.

Crop Sensitivity and Food Safety

The sensitivity of the crops to fluoride varies greatly. Differences result from variations in root uptake, translocation, leaf retention, stomatal behaviour, antioxidant capacity, ion transport, and developmental timing. Variations in tolerance may be considerable even between genotypes of the same crop species.

Sensitive crops may show early chlorosis, necrosis, severe inhibition of root growth and rapid loss of yield. Tolerant crops may accumulate higher fluoride in roots, restrict its upward movement, sustain photosynthesis and possess a greater antioxidant defence. In addition to biomass and visible symptoms, screening programs should also evaluate fluoride accumulation in edible tissues.

A major concern of food safety exists when crops are irrigated with fluoride rich groundwater or grown near industrial sources of emissions. Fluoride can be moved from soil and air to vegetables and cereals and then into the food chain either by direct human consumption or by livestock feed. Fluoride accumulation occurs in both vegetables and cereals, and the local variability warrants a site-specific evaluation, according to Singh *et al*. (2023) [6].

Crop monitoring should distinguish total fluoride in soil, bioavailable fluoride in soil solution, fluoride in irrigation water, atmospheric deposition and fluoride in edible plant parts. The edible-tissue concentration is particularly

important because soil fluoride alone is not a good predictor of dietary exposure.

Remediation Strategies

Fluoride remediation should be based on the source of contamination, soil chemistry, water quality, crop type, and intended use of the harvested product. A successful strategy will usually involve a combination of prevention of further fluoride loading and measures that reduce bioavailable fluoride and increase crop tolerance.

Source Control

Source control is the most powerful option to manage. Industrial plants should be mandated to contain the fluoride emissions by proper capture, filtration and waste-management systems. The fluoride concentration of the irrigation water should be monitored and in the presence of alternatives, repeated use of highly contaminated sources should be avoided.

Where fluoride buildup is already a problem, phosphate fertilisers must be selected and managed carefully. Regular testing of soil and irrigation water can detect potential problems before they cause extensive crop damage.

Irrigation Management

Where groundwater has elevated fluoride farmers can reduce exposure by blending with low fluoride water, switching to safer sources, use treated water, improve drainage and adopt irrigation practices that reduce foliar wetting. Drip irrigation may reduce direct leaf exposure to fluoride compared to overhead irrigation, but root-zone fluoride loading must still be managed.

Water treatment technologies such as adsorption, ion exchange, membrane processes, precipitation and electrocoagulation are able to reduce fluoride in irrigation water. The feasibility is dependent on the size of the farm, the volume of water, the availability of energy, the infrastructure and the ability to dispose of waste. In many rural settings treatments at the community level may be more feasible than farm level treatment.

Soil Amendments

Calcium amendments, including lime, gypsum and calcium-rich materials can reduce fluoride availability via precipitation or adsorption. The success of these amendments depends on the soil pH and mineral constituents. Calcium management also can assist membrane stability and reduce physiological effects of fluoride.

Organic amendments such as compost, farmyard manure, biochar and humic substances may improve soil structure, water retention, cation exchange capacity, microbial activity and contaminant adsorption. Organic matter may either immobilise fluoride or change pH and ionic conditions in ways that affect mobility. Hence their effects on fluoride availability are context specific.

Biochar can offer adsorption sites and improve nutrient retention. However, its efficacy depends on feedstock, pyrolysis temperature, surface chemistry, rate of application, and soil pH. The amendment should be chosen according to local laboratory or field trials and not be assumed to be universally effective.

Nutrient and Biostimulant Management

A balanced supply of nutrients can reduce fluoride injury by enhancing root growth, chlorophyll synthesis, membrane integrity and antioxidant activity. Calcium, magnesium, potassium, silicon and phosphorus may be of particular importance to manage. Phosphorus should be used judiciously as some phosphate fertilisers may introduce fluoride.

Exogenous application of salicylic acid, glycine betaine, polyamines, melatonin and some nanoparticles have been reported to reduce fluoride induced oxidative damage in experimental systems. Khandare *et al*. (2020) [5] suggested that stress protectants may decrease fluoride accumulation or toxicity via antioxidant regulation, osmotic adjustment and altered membrane permeability. Field validation, dose optimisation, economic assessment and environmental safety evaluation are, however, still required before wide-scale adoption.

Beneficial Microorganisms

Plant growth-promoting rhizobacteria and mycorrhizal fungi may aid plants in dealing with fluoride by enhancing nutrient acquisition, altering rhizosphere chemistry, producing phytohormones, boosting antioxidant defences, and binding or immobilising fluoride. Some strains of microorganisms can adsorb fluoride on the surface of cells or produce exopolysaccharides which lower its bioavailability.

The potential of plant growth-promoting rhizobacteria to increase plant resistance level against fluoride toxicity was reported by Kumar *et al*. (2023) [6]. Microbial inoculants could be particularly helpful in the presence of organic amendments and balanced fertilisation. But microbial activity and survival depend on pH, moisture, temperature, native microbial competition and crop management so that microbial performance differs between soils.

Phytoremediation

Phytoremediation is the use of plants to remove, stabilise or filter out contaminants. In many situations, phytostabilization is a more realistic goal than complete phytoextraction of fluoride-contaminated soils, as fluoride may strongly bind to soil minerals and high-accumulating plants may create a contaminated biomass-disposal problem.

Some possible approaches are

- **Phytoextraction:** Use of fluoride accumulating plants which are bioavailable in removing fluoride from soil and safe disposal of the biomass.
- **Phytostabilization:** Establishment of tolerant vegetation that minimises erosion, dust generation and contaminant mobility.
- **Rhizofiltration:** Using plant roots or root-related materials to remove fluoride from polluted water.
- **Agroforestry and buffer planting:** Vegetative barriers to prevent the movement of fluoride-laden dust and protect sensitive crops against deposition from the atmosphere.

Phytoremediation should not be used without assessing the potential of harvested plant material to enter food or feed chains. Non-food plants could be better suited for contaminated sites. Phytoremediation may be slow and

effectiveness depends on bioavailability of fluoride, so long-term monitoring is important.

Tolerant Cultivars and Breeding

A practical and low-input option for fluoride tolerance is cultivar selection. Useful traits include low root uptake, translocation to edible tissues, strong antioxidant defences, maintenance of photosynthesis, efficient calcium homeostasis, and high expression or activity of fluoride-export systems.

FEX genes are promising targets for breeding and biotehnology. FEX-mediated efflux may also act to prevent toxic cytosolic fluoride accumulation and crop improvement programs could screen for favourable alleles, expression patterns, or regulatory variants. Ram *et al*. (2021) [10] demonstrated that increased expression of FEX can enhance fluoride tolerance, suggesting the potential value of this pathway.

But tolerance should not be measured only by visible growth. A productive cultivar accumulating fluoride in edible organs can still be a food-safety risk. Therefore, breeding objectives should include both productivity and low fluoride concentration in harvested tissues.

Research Priorities

The development of reliable fluoride-management strategies is constrained by several knowledge gaps. First, we need to determine the thresholds of fluoride in soil and water for the major crops under realistic field conditions. Thresholds should consider soil pH, calcium status, organic matter, irrigation regime and atmospheric deposition.

Second, additional research is needed on fluoride speciation in the rhizosphere and interaction with roots, microbes and soil amendments. Total fluoride measurements do not predict plant uptake well. Quantifying bioavailable fluoride and how it correlates with plant response would improve risk assessment.

Third, molecular studies should identify transporters, regulatory genes, signalling pathways and metabolic traits that discriminate tolerant from sensitive crops. FEX transporters are important, but they probably work together with channels, anion transport systems, membrane regulators and vacuolar sequestration mechanisms.

Fourth, remediation technologies need long-term field validation. Many studies have been done in hydroponics, pots or short-term experiments. Field-scale trials should look at yield, fluoride concentrations in edible tissues, soil health, economic feasibility, persistence of amendments, and potential unintended effects.

Finally, fluoride management should be incorporated into public health surveillance. In cases where fluoride-rich water is used for irrigation, coordinated testing of water, soil, crops, livestock feed and human dietary exposure may be required. Integrated surveillance of this kind can aid in the identification of contamination hotspots and guide crop selection, water treatment and land-use planning.

Conclusion

The fluoride exposure and fluoride toxicity problem in crop production is increasing with geogenic fluoride, fluoride contaminated irrigation water, atmospheric emissions and fertiliser associated inputs. Excess fluoride inhibits growth through enzyme inhibition, membrane injury, calcium imbalance, oxidative stress, impaired photosynthesis, altered mineral nutrition and reproductive damage . Crop sensitivity varies with species, genotype, environmental conditions, route of exposure, and soil chemistry.

Plants possess adaptive mechanisms such as antioxidant defence, osmotic adjustment, restricted uptake, compartmentalisation and fluoride export using FEX transporters. However, these defences may be insufficient when fluoride concentrations are high or exposure is chronic. What works is source control, low-fluoride irrigation, calcium and organic-based soil amendments, nutrient optimisation, microbial support, tolerant cultivars and careful phytoremediation. Future research should include thresholds in the field, edible-tissue monitoring, molecular breeding for low accumulation and integrated soil-water-crop-health management.

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