

HEAVY METAL AND FLUORIDE TOXICITY IN CROP PLANTS: MECHANISMS, PHYSIOLOGICAL RESPONSES, AND REMEDIATION STRATEGIES – A REVIEW

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ABSTRACT

Environment-wide heavy metal and fluoride buildup threatens agricultural productivity and food security. Five systematic studies examined the phytotoxic effects of lead, nickel, cadmium, copper, cobalt, chromium, and mercury and sodium fluoride on six economically important crop species. All dose-response experiments indicated concentration-dependent growth suppression for all species. Mercury and cadmium, the most phytotoxic pollutants, decreased root length by 70% and entirely restricted shoot development at 50-100 mg kg⁻¹ soil concentrations. Significant growth suppression of green peas at >200 ppm and full growth inhibition at 500 ppm indicated fluoride toxicity. Roots had 15–30% stronger suppression than shoots. Mercury had a biphasic hormetic response in mung beans: low amounts (1–10 mg/L) boosted growth by up to 31%, while high concentrations (20–50 mg/L) produced severe toxicity. Bengal gram was more tolerant than green gram, while mustard was more fluoride-tolerant. Mechanistic studies found that ROS-mediated oxidative stress causes phytotoxicity, with antioxidant enzymes (SOD, CAT, POD, and APX) overexpression as defensive strategies. Chromium toxicity research showed that Cr(VI) was far more hazardous than Cr(III). Phytoremediation, nanoparticles, plant growth regulators, and beneficial bacteria may reduce pollution. These findings emphasize the need for integrated soil management, stress-tolerant crop varieties, and sustainable remediation technologies to protect agricultural ecosystems and food security in the region.

Keywords: *Heavy metal toxicity, Fluoride stress, Crop plants, Phytotoxicity, Oxidative stress, Antioxidant enzymes, Phytoremediation, Dose-response relationships, Species tolerance, Sustainable agriculture*

INTRODUCTION

The contamination of agricultural soils with heavy metals and fluoride represents an escalating global environmental crisis with profound implications for crop productivity, food security, ecosystem health, and human well-being. Heavy metals, such as lead (Pb), nickel (Ni), cadmium (Cd), copper (Cu), cobalt (Co), chromium (Cr), and mercury (Hg), along with fluoride (F), enter agricultural ecosystems through anthropogenic pathways, including industrial effluents, mining, fertilizers, and wastewater irrigation (Bhargava & Killedar, 1991; George, 2019). Unlike organic pollutants, heavy metals are non-biodegradable and persist indefinitely in the soil, leading to long-term contamination and bioaccumulation (Calabrese & Blain, 2008).

Plants, as sessile organisms rooted in contaminated substrates, are particularly vulnerable because they absorb contaminants through their roots during water and nutrient uptake (Chakrabarti *et al.*, 2017). These contaminants disrupt fundamental physiological processes, including photosynthesis, respiration, nutrient acquisition, and enzyme activity, ultimately reducing crop yields (Chakrabarti *et al.*, 2017). Phytotoxic effects manifest through the generation of reactive oxygen species (ROS), disruption of cellular ionic homeostasis, inhibition of enzymatic reactions, and impairment of chlorophyll biosynthesis (Chen, 2012; George, 2021).

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Pulse crops, including green gram (*Vigna radiata*), Bengal gram (*Cicer arietinum*), cowpea (*Vigna unguiculata*), and black gram (*Vigna mungo*), are vital protein sources in developing countries and play crucial roles in sustainable agriculture through biological nitrogen fixation (Elloumi *et al.*, 2005). Similarly, oilseed crops such as mustard (*Brassica juncea*) and vegetable crops, such as green peas (*Pisum sativum*), contribute significantly to nutritional security (George, 2022). However, the cultivation of these crops is increasingly vulnerable to soil pollution, which can severely hinder plant growth and the nutritional quality of harvested yields (Guo *et al.*, 2008).

Fluoride contamination has emerged as a significant concern driven by industrialization and the application of phosphate-based fertilizers (George, 2022). Elevated fluoride levels disrupt photosynthesis, respiration, nutrient uptake, and enzymatic activity (Gupta & Banerjee, 2019).

Seed germination and early seedling establishment are the most sensitive phases to environmental stressors, making them critical indicators for assessing phytotoxicity (George 2022). Root and shoot elongation are sensitive biomarkers of environmental stress (Gupta & Sanderson, 1994).

This review synthesizes findings from five systematic investigations (2017–2022) examining heavy metal effects on pulse crops (Calabrese & Blain, 2008), fluoride toxicity in mustard and green pea (Chakrabarti *et al.*, 2017), mercury responses including hormetic effects and fluoride stress in cowpea and black gram (Elloumi *et al.*, 2005), and chromium toxicity mechanisms and remediation strategies (Mei *et al.*, 2002). These investigations provide critical insights into crop vulnerability, mechanisms of phytotoxicity, species-specific tolerance patterns, and mitigation strategies for sustainable agricultural production.

2. Sources and Entry of Pollutants into Agricultural Soils

2.1 Heavy Metal Sources

Human activities, such as industrialization and agricultural modernization, have increased heavy metal deposition in soil. Chrome, lead, cadmium, and mercury contamination originates from leather tanning, electroplating, metal processing, pigment manufacturing, and mining (Miller, 1993). Tailings disposal, acid mine drainage, and mining and ore processing air emissions release heavy metals (Mitra *et al.*, 2023).

Heavy metals accumulate in agricultural products. Multiple chemical fertilizer applications, especially phosphate fertilizers, have been shown to accumulate trace amounts of Cd, Pb, and other heavy metals in soil (Mohapatra *et al.*, 2021). Pesticides and fungicides increase the load of mercury, copper, and arsenic (Nagajyoti *et al.*, 2010). Although sewage sludge supplies organic matter and nutrients, it frequently contains significant quantities of Cd, Pb, Hg, and other metals from industrial and household wastewaters (Pant *et al.*, 2008).

Wastewater irrigation leaches heavy metals into crop root zones in peri-urban agricultural areas (Patel *et al.*, 2019). Air pollution from fossil fuel combustion, industries, and vehicles pollutes agricultural soil with mercury, Pb, and Cd (George 2022). Chromium naturally occurs in rocks and soils at 10–50 mg/kg, but anthropogenic additions have increased terrestrial ecosystem concentrations, often exceeding the limitations of plant growth (George, 2022).

2.2 Fluoride Sources

Industrial emissions contribute to the infiltration of fluoride into agricultural ecosystems (Poschenrieder *et al.*, 2013). Fluoride emissions from the aluminum, phosphate fertilizer, steel, and ceramic processing industries pollute agricultural regions (Pourrut *et al.*, 2011). Due to the widespread use of phosphate fertilizers, which contain fluoride as an impurity, agricultural soils have accumulated fluoride over time (Pourrut *et al.*, 2011).

Fluoride-contaminated groundwater irrigation, especially in areas with high-fluoride aquifers, directly deposits fluoride into the crop root zones (Pramanik *et al.*, 2017). Anthropogenic activity can intensify the geological weathering of fluoride-containing minerals in some geological formations, thereby producing a natural background fluoride concentration (Rai *et al.*, 2010). Fluoride contamination in agricultural areas worldwide is increasing because of these factors (Pramanik *et al.*, 2017).

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2.3 Environmental Persistence and Bioavailability

The non-biodegradable nature of heavy metals, which persist indefinitely in soil environments, is a critical distinction between heavy metals and organic contaminants. Heavy metals undergo chemical changes that alter their bioavailability, mobility, and toxicity, unlike organic molecules, which are subject to biological degradation (Rai *et al.*, 2010). Heavy metal speciation, and hence their availability to plants, depends on several soil variables, such as pH, organic matter content, clay mineralogy, redox potential, and the presence of competing ions.

Chromium is predominantly found in two stable oxidation states: Cr(III) and Cr(VI). The mobility, bioavailability, and toxicological effects of these forms differ significantly from each other. Plants readily absorb Cr(VI) through sulfate transport mechanisms and produce intracellular free radicals that damage their cellular components. Additionally, Cr(VI) is more hazardous and transportable (Reddy & Kaur, 2021). The bioavailability and toxicity (Poschenrieder *et al.*, 2013). Legacy contamination by heavy metals and fluoride in agricultural soils can threaten the agricultural systems of future generations. This highlights the necessity of proactive management to reduce pollution and rehabilitate impacted areas (Reddy & Kaur, 2021).

3. Effects on Seed Germination and Seedling Growth

3.1 Heavy Metal Effects on Pulse Crops

Systematic dose-response studies examining the effects of seven heavy metals (Pb, Ni, Cd, Cu, Co, Cr, and Hg) at concentrations of 0, 25, 50, and 100 mg/kg soil on green gram and Bengal gram revealed progressive, concentration-dependent declines in all measured growth parameters for both species. At the highest concentration tested (100 mg/kg), Hg and Cd were the most phytotoxic, inducing severe reductions in shoot and root lengths and total biomass in both pulse species (George, 2022). (Yuan-hua, 2012).

Table 1. Growth Parameters of Green Gram and Bengal Gram Under 100 mg/kg Heavy Metal Stress

Crop	Metal	Shoot Length (cm)	Root Length (cm)	Biomass (g)
Green Gram	Control	34.58	15.54	4.32
	Mercury (Hg)	4.69	1.46	0.24
	Cadmium (Cd)	6.11	2.18	0.29
	Lead (Pb)	14.93	5.62	1.12
	Nickel (Ni)	17.98	6.05	1.61
	Chromium (Cr)	17.50	7.15	1.83
	Copper (Cu)	20.88	9.36	2.18
	Cobalt (Co)	24.12	9.79	2.44
Bengal Gram	Control	39.99	17.00	5.25
	Mercury (Hg)	3.90	1.68	0.30
	Cadmium (Cd)	26.81	2.47	0.34
	Lead (Pb)	17.16	6.20	1.57
	Nickel (Ni)	18.89	7.42	2.24
	Chromium (Cr)	22.03	8.12	2.29
	Copper (Cu)	24.38	9.67	2.58
	Cobalt (Co)	27.59	11.49	3.20

In green gram, exposure to 100 mg/kg of mercury reduced shoot length to 4.69 cm (86.4% reduction from the control), root length to 1.46 cm (90.6% reduction), and total biomass to 0.24 g (94.4% reduction) (George 2022). Cd produced similarly severe effects, reducing the shoot length to 6.11 cm (82.3% reduction), root length to 2.18 cm (86.0% reduction), and biomass to 0.29 g (93.3% reduction). Bengal gram exhibited comparable sensitivity patterns, with mercury reducing shoot length to 3.90 cm (90.2% reduction), root length to 1.68 cm (90.1% reduction), and biomass to 0.30 g (94.3% reduction).

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Chromium, lead, and nickel demonstrated intermediate toxicity levels, whereas copper and cobalt produced comparatively milder effects on plant growth (Reddy and Kaur 2021). At 100 mg/kg, cobalt induced the least growth reduction in both species, with green gram retaining 69.8% of the control shoot length and Bengal gram retaining 69.0% of the control shoot length (Riaz *et al.*, 2020). The clear dose-response relationship observed across all metals and both species confirmed that heavy metal toxicity increases proportionally with soil concentration (Riaz *et al.*, 2020).

3.2 Mercury-Specific Concentration-Dependent Responses

A detailed investigation of the effects of mercuric chloride (HgCl₂) on mung beans (*Vigna radiata*) across a broader concentration range (0, 1, 5, 10, 20, and 50 mg/L) revealed a remarkable biphasic response. Low mercury concentrations (1–10 mg/L) exhibit hormetic effects, stimulating seedling growth relative to controls, whereas higher concentrations (20–50 mg/L) induce severe phytotoxicity (Roy and Bera 2002).

Table 2. Concentration-Dependent Effects of Mercuric Chloride on Mung Bean Growth

HgCl ₂ Concentration (mg/L)	Root Length (cm)	Shoot Length (cm)	Root Response (% Change)	Shoot Response (% Change)
0 (Control)	3.2	6.2	—	—
1	3.4	6.7	+6.3%	+8.1%
5	3.6	7.2	+12.5%	+16.1%
10	4.2	7.4	+31.3%	+19.4%
20	2.9	1.5	-9.4%	-75.8%
50	2.5	0.0	-21.9%	-100.0%

Maximum growth stimulation occurred at 10 mg/L, where root length increased to 4.2 cm (31.3% above the control) and shoot length increased to 7.4 cm (19.4% above the control). However, at 20 mg/L, growth parameters declined sharply, with shoot length reduced to 1.5 cm (75.8% reduction) and root length to 2.9 cm (9.4% reduction) respectively. At the highest concentration tested (50 mg/L), shoot development was completely inhibited (100% reduction), whereas root growth was markedly reduced to 2.5 cm (21.9% reduction). This biphasic response pattern demonstrates the critical importance of mercury concentration thresholds in determining plant responses and highlights the complexity of heavy metal-plant interactions.

3.3 Fluoride Effects on Crop Seedlings

Sodium fluoride (NaF) toxicity studies on mustard and green pea at concentrations of 0, 10, 50, 100, 200, 500, and 700 ppm revealed clear concentration-dependent growth suppression, although the two species differed markedly in their sensitivity to NaF. Green pea seedlings were considerably more susceptible to fluoride toxicity, with complete growth inhibition observed at 500 and 700 ppm of NaF. In contrast, mustard seedlings exhibited limited but measurable growth, even at the highest herbicide concentration.

Table 3. Effect of Sodium Fluoride on Mustard and Green Pea Seedling Growth

NaF Concentration (ppm)	Mustard		Green Pea	
	Root (cm)	Shoot (cm)	Root (cm)	Shoot (cm)
Control	7.0	4.0	3.5	0.8
10	6.6	3.6	3.0	1.0
50	5.5	2.8	2.7	1.3
100	4.0	2.5	1.3	0.8
200	3.5	2.2	0.5	0.0
500	2.0	1.0	0.0	0.0
700	0.5	0.2	0.0	0.0

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In mustard, root length decreased progressively from 7.0 cm in the control to 0.5 cm at 700 ppm (92.9% reduction), whereas shoot length declined from 4.0 cm to 0.2 cm (95.0% reduction) at the same concentration. Green pea showed greater sensitivity, with root length declining from 3.5 cm in the control to 0.5 cm at 200 ppm, followed by complete inhibition at 500 ppm and higher DMSO concentrations. Shoot growth in green peas was completely inhibited at concentrations of 200 ppm or higher. Similar fluoride toxicity patterns were observed in cowpeas and black grams, two additional pulse species examined across the same concentration range. Both species exhibited concentration-dependent growth reduction, with severe inhibition at concentrations exceeding 200 ppm in both species.

Table 4. Effect of Sodium Fluoride on Cowpea and Black Gram Seedling Growth

NaF Concentration (ppm)	Cowpea		Black Gram	
	Root (cm)	Shoot (cm)	Root (cm)	Shoot (cm)
Control	12.0	6.0	6.0	3.5
10	11.0	5.2	5.5	4.6
50	8.4	4.0	4.5	2.8
100	6.4	2.2	3.6	2.4
200	3.5	1.5	2.2	1.5
500	2.2	0.5	1.4	0.9
700	1.2	0.2	0.6	0.2

Cowpea plants developed robustly under control conditions, achieving mean root and shoot lengths of 12.0 cm and 6.0 cm, respectively. At 700 ppm NaF, root length was reduced to 1.2 cm (90% reduction), and shoot length was reduced to 0.2 cm (97% reduction). Black gram exhibited similar concentration-dependent patterns, with root length declining from 6.0 cm in the control to 0.6 cm at 700 ppm (90% reduction) and shoot length declining from 3.5 cm to 0.2 cm (94% reduction) at the same concentration. Growth remained relatively tolerable at low concentrations (10–50 ppm) but declined sharply at and above 200 ppm, suggesting a critical threshold beyond which fluoride toxicity becomes severe (Saminathan 2013).

3.4 Comparative Toxicity Rankings

Numerous studies have consistently identified mercury and Cd as the most phytotoxic heavy metals, leading to substantial decreases in plant development, specifically 80–90% in root length and 75–90% in shoot length at a concentration of 100 mg/kg in soil. Chromium, lead, and nickel demonstrated moderate toxicity, resulting in 40–60% growth reduction, whereas copper and cobalt had lesser effects, with a 20–40% growth reduction. A critical threshold of approximately 200 ppm for fluoride toxicity was identified, above which significant growth suppression was observed in all species tested. Complete growth suppression was observed at 500–700 ppm in sensitive species, such as green peas, whereas more durable plants, such as mustard, exhibited restricted growth even at the highest doses tested (Saminathan, 2013).

4. Differential Sensitivity of Root vs. Shoot Systems

A particularly noteworthy and consistent finding across all investigations was the greater sensitivity of root systems compared to that of shoot tissues under heavy metal and fluoride stress conditions. Root growth was more severely inhibited than shoot elongation for all pollution types, concentrations, and crop species in this study.

4.1 Quantitative Root-Shoot Differential Responses

A study on the impact of heavy metals on pulse crops found that root systems are more sensitive to Cd and Hg stress than are shoots. Exposure to 100 mg/kg of heavy metals resulted in an 85-90% drop in root length and a 75-86% decrease in shoot length. This pattern was apparent in both green gram and Bengal gram across all seven metal treatments, with significant differences, such as a 90.6% reduction in green gram roots after mercury exposure compared to an 86.4% loss in shoots, demonstrating a consistent differential sensitivity favoring the roots over the shoots. Analogous patterns were observed under Cd stress: green

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gram roots exhibited an 86.0% reduction, whereas shoots showed an 82.3% decrease, resulting in a disparity of 3.7 percentage points between the two. Analogous trends were observed in Bengal gram, with mercury decreasing root length by 90.1% compared to 90.2% for shoots, while Cd decreased roots by 85.5% compared to 33.0% for the shoots.

Fluoride toxicity tests revealed notable disparities between the development of roots and shoots. Mustard plants exposed to 700 ppm sodium fluoride showed a 92.9% decrease in root length and a 95.0% decrease in shoot length, indicating a significant detriment to both growth systems (George, 2019). Similarly, green pea plants exposed to 200 ppm NaF exhibited minimal root growth (0.5 cm, an 85.7% decrease), and their shoot development was completely suppressed (100% suppression). This demonstrates that elevated fluoride stress can adversely affect both the root and shoot systems equally (Saminathan, 2013).

Cowpea and black gram demonstrated comparable root-shoot differentials under fluoride stress. At 700 ppm NaF, cowpea root length decreased by 90%, and shoot length diminished by 97%; black gram roots decreased by 90%, and shoots declined by 94% compared to the control. Within the intermediate concentration range (100–500 ppm), roots exhibited a constant growth inhibition of 10–20%, which was greater than that of shoots in both species (Sharma and Dubey, 2005).

The mercury concentration-response investigation in mung beans provided a better understanding of the differential sensitivity between roots and shoots. At low mercury doses demonstrating hormetic effects (1–10 mg/L), roots exhibited a more pronounced growth stimulation than shoots, with a peak root enhancement of 31.3% compared to 19.4% for shoots at 10 mg/L concentration. At hazardous dosages (20–50 mg/L), shoots showed heightened sensitivity, with a 75.8% decrease at 20 mg/L compared to a mere 9.4% for roots, and total shoot inhibition at 50 mg/L, whereas roots maintained 78.1% of the control length.

4.2 Mechanistic Basis for Differential Sensitivity

Several interrelated mechanisms render root systems susceptible to soil-borne contaminants. Roots have higher local concentrations of heavy metals and fluoride than aerial plant components because they are directly exposed to these contaminants. Second, roots absorb the most metals and fluoride, increasing tissue concentrations and damage. These pollutants target actively proliferating cells in the root meristems, notably the root apical meristem, owing to their rapid cell division and high metabolic activity. Fluoride deposition in root tissues directly inhibits cell elongation and mitotic activity, thereby obstructing proper root system growth. The marked suppression of root development substantially affects overall plant performance, as compromised root systems have a reduced capacity for water and nutrient absorption. This intensifies stress responses and reduces plant output in polluted soil, resulting in a cascade effect in which initial root injury induces secondary stress, negatively affecting shoot growth and overall plant vitality (Shoaib *et al.*, 2015).

4.3 Implications for Plant Survival and Productivity

The differential sensitivity of root and shoot systems has profound implications for plant survival and productivity in contaminated environments. Severe root growth inhibition limits the plant's ability to explore soil volume for water and nutrients, reduces anchorage capacity, and compromises the establishment of beneficial rhizosphere associations, including mycorrhizal symbiosis and nitrogen-fixing bacteria in legumes, such as peanuts. These limitations directly translate to reduced crop yields, delayed maturity, and increased vulnerability to environmental stresses, such as drought and nutrient deficiency.

5. Species-Specific Tolerance

Comparative analyses across the six crop species examined revealed significant interspecific variation in tolerance to heavy metal and fluoride stress, with important implications for crop selection in contaminated environments and breeding programs aimed at developing stress-tolerant varieties of these crops.

5.1 Heavy Metal Tolerance in Pulse Crops

Bengal gram exhibited greater resistance to heavy metal stress than green gram, as evidenced by the enhanced preservation of shoot length, root length, and biomass across many treatments. Under 100 mg/kg Hg stress, Bengal gram exhibited 9.8% of its control shoot length, whereas green gram demonstrated 13.6%, showing substantial adverse effects on both species. The greatest disparity occurred under Cd stress, with

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Bengal gram preserving 67.0% of its control shoot length, whereas green gram achieved only 17.7%. Under chromium stress at identical concentrations, Bengal gram maintained 55.1% of its control shoot length and 47.8% of its control root length, whereas green gram maintained 50.6% and 46.0%, respectively. The least hazardous metal evaluated, cobalt, led to Bengal gram maintaining 69.0% of the control shoot length and 67.6% of the control root length, whereas green gram maintained 69.8% and 63.0%, respectively. These findings suggest that Bengal gram may possess more efficient tolerance mechanisms, possibly associated with superior antioxidant defenses, improved metal sequestration, and unique metal absorption kinetics (Shoaib *et al.*, 2015).

5.2 Fluoride Tolerance Comparisons

Of the four species examined for fluoride tolerance, mustard (*Brassica juncea*) showed the greatest tolerance compared to green pea (*Pisum sativum*), cowpea (*Vigna unguiculata*), and black gram (*Vigna mungo*). Mustard maintained substantial root and shoot development at all fluoride doses, including 700 ppm, with a root length of 0.5 cm and shoot length of 0.2 cm. In contrast, green peas showed no growth at 500 ppm and above, with complete suppression of both root and shoot development.

At 100–200 ppm fluoride, mustard retained 50–57% and 55–63% of the control root and shoot lengths, respectively. Green peas retained only 14–37% of their root length and 0–100% of their shoot length, indicating a lower resilience. This suggests that mustard has greater physiological resilience owing to differences in antioxidant defenses, ion transport regulation, and tissue-based sequestration.

Cowpea and black gram tolerated fluoride better than green peas but less than mustard plants. At 200 ppm NaF, cowpea preserved 29.2% and 25.0% of root and shoot lengths, respectively, whereas black gram preserved 36.7% and 42.9%, respectively. At 500 ppm, cowpea retained 18.3% and 8.3% of the control root and shoot lengths, respectively, whereas black gram retained 23.3% and 25.7% of the control values, respectively. These data suggest that pulse crops are more fluoride-sensitive than are Brassica species.

5.3 Mechanistic Basis for Species-Specific Tolerance

Physiological and metabolic factors explain the species-specific tolerance to heavy metals and HF. More tolerant species have stronger antioxidant defenses that scavenge reactive oxygen species (ROS) and reduce oxidative damage. The increased synthesis and activity of antioxidant enzymes, including SOD, CAT, POD, and APX, are key mechanisms underlying tolerance.

Tolerant species can sequester heavy metals and reduce their bioavailability to sensitive cells by producing more metal-binding molecules, such as phytochelatins, metallothioneins, and organic acids. Root architecture, metal uptake kinetics, and translocation patterns affect species tolerance. Some species inhibit metal absorption at the root surface or in aerial tissues, thereby protecting delicate photosynthetic organs from metal toxicity.

Ion transport regulation and fluoride compartmentalization are essential for plant tolerance to fluorides. Species that tolerate fluoride may store it more effectively in vacuoles or cell walls, thereby preventing its accumulation in the metabolically active cytoplasm of the cell. Different membrane integrity, repair processes, and stress signaling systems may also affect the fluoride tolerance of species (Sinha *et al.*, 2009).

5.4 Implications for Crop Selection and Breeding

Understanding species-specific tolerance patterns is essential for selecting crops for polluted soils and developing stress-tolerant crops. Choose Bengal gram over green gram or mustard over green pea in regions with heavy metal contamination to maintain productivity during the rehabilitation phase. Identifying tolerant genotypes in a species provides germplasm for traditional and marker-assisted selection. Understanding the genetic and physiological roots of tolerance processes enables targeted breeding to combine multiple tolerance traits and create stress-resistant cultivars with improved tolerance to abiotic stressors. Faced with rising environmental pollution, such measures are essential for agricultural production and ensuring food security (Somngam *et al.*, 2013).

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6. Mechanisms of Phytotoxicity

The phytotoxic effects of heavy metals and fluoride manifest through multiple interconnected mechanisms that disrupt the fundamental physiological and biochemical processes essential for plant growth and development. Understanding these mechanisms is critical for developing effective mitigation strategies and breeding stress-tolerant crop varieties.

6.1 Reactive Oxygen Species (ROS) Generation and Oxidative Stress

Oxidative stress, caused by reactive oxygen species (ROS) such as superoxide radicals (O_2^-), hydrogen peroxide (H_2O_2), hydroxyl radicals ($OH\cdot$), and singlet oxygen (1O_2), is a major mechanism underlying heavy metal and fluoride phytotoxicity in plants. Heavy metals increase ROS generation by disrupting the chloroplast and mitochondrial electron transport chains, activating NADPH oxidase, and catalyzing Fenton-type reactions.

During intracellular reduction to Cr(III), hexavalent chromium [Cr(VI)] produces reactive oxygen species (ROS) such as superoxide radicals and hydrogen peroxide. Mercury also disrupts mitochondrial electron transport and antioxidant enzyme systems, resulting in ROS production. Fluoride also disrupts cellular metabolism and inhibits enzymes, thereby generating ROS (Zeng *et al.*, 2014).

ROS buildup damages lipids, proteins, and DNA. Lipid peroxidation increases membrane permeability and ion leakage, compromising compartmentalization. Protein oxidation also inactivates important enzymes and structural proteins, altering metabolic pathways and cellular architecture. DNA damage inhibits development by affecting gene expression and cell division (Somngam *et al.*, 2013).

6.2 Enzyme Inhibition and Metabolic Disruption

Heavy metals and fluoride reduce energy production and biosynthesis by impairing photosynthesis, respiration, and the activities of enzymes involved in nutritional metabolism. Mercury binds to cysteine residues and affects enzyme structure and activity by targeting protein sulfhydryl (-SH) groups. This disruption affects carbon fixation, nitrogen assimilation, and ATP generation.

Photosynthesis is negatively affected by Cr interference with electron transport chain enzymes, particularly those in photosystem II and the Calvin cycle. Cd and Pb block chlorophyll synthesis enzymes, causing chlorosis and reduced photosynthetic efficiency. Fluoride affects the cellular energy balance by inhibiting glycolytic and energy metabolism enzymes (Stevens *et al.*, 2009).

Enzyme inhibition in metabolic pathways impairs cellular homeostasis. Energy is depleted, and toxic metabolic intermediates such as lactate accumulate. Metabolic disorders limit plant growth, biomass, and reproduction.

6.3 Nutrient Uptake and Translocation Interference

Heavy metals hinder the digestion and transport of plant nutrients, leading to secondary deficiencies that adversely affect plant growth. Chromium competes with iron, manganese, and sulfur for absorption, limiting their availability. Cd blocks Ca, Mg, and Fe absorption and control, whereas Pb blocks phosphorus and N absorption. These imbalances worsen heavy metal damage and cause complex stress syndromes that weaken plant tolerance. Nutrient deficiencies reduce photosynthesis, protein synthesis, and antioxidant defense, thereby lowering plant health.

6.4 Photosynthesis Disruption

Heavy metals and fluoride substantially hinder photosynthesis via several routes, affecting processes from light absorption to carbon fixation. Metals such as chromium, cadmium, and mercury inhibit chlorophyll production, leading to reduced chlorophyll levels and foliar chlorosis in plants. They also impair photosystem II reaction centers, resulting in diminished quantum yield and reduced electron transport efficiency. Moreover, stomatal closure induced by heavy metals restricts CO_2 availability, thereby aggravating the reduction in the photosynthetic rate. Disruption of the Calvin cycle, specifically affecting the enzyme ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO), further reduces carbon fixation capacity. The cumulative result of these impacts is a significant reduction in photosynthetic efficiency, limiting the plant's capacity to produce vital carbohydrates and energy for growth and stress defense.

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6.5 Water Relations and Membrane Integrity

Heavy metals and fluoride harm plant-water interactions in numerous ways. They alter membrane permeability, root hydraulic conductivity, and stomatal function. Mercury and Cd damage aquaporins, which transport water, thereby reducing the water absorption efficiency (George, 2019). Lipid peroxidation increases membrane permeability, allowing ion leakage and decreasing cellular turgor. These changes reduce the leaf water potential, wither leaves, and inhibit cell division, thereby inhibiting plant growth. Even in soils with sufficient moisture, poor water absorption and increased water loss from damaged membranes can cause water stress in plants.

6.6 Cell Division and Elongation Inhibition

Mercury and Cd affect cell division and elongation, particularly in the meristematic tissues. They disrupt mitotic microtubule assembly and spindle formation, leading to chromosomal abnormalities and cell cycle arrest. This interference affects DNA replication and repair, leading to genotoxicity and cell division inhibition. Disruptions in cell wall production, turgor pressure, and auxin signaling pathways limit the cell elongation. In numerous studies, cell division rates in root meristems have been shown to increase, leading to significant suppression of root development (Weinstein & Davison, 2004).

6.7 Integrated Stress Response

Complex stress syndromes arise when phytotoxicity pathways interact, leading to ROS-induced oxidative damage, enzyme dysfunction, metabolic disruption and ROS production. These feedback loops increase stress levels. Nutrient deficits decrease antioxidant defenses, increasing the risk of oxidative damage, whereas lower photosynthesis reduces stress defense and energy repair. Understanding these interrelated pathways is essential for developing comprehensive remediation techniques for heavy metal- and fluoride-induced toxicity. Plant stress responses are complex; therefore, remediation must address multiple pathways to enhance plant performance in polluted environments (Weinstein & Davison, 2004; Vu et al. 2018).

7. Hormetic Effects of Mercury

A particularly intriguing finding from the mercury concentration-response study was the observation of hormetic effects at low mercury concentrations, with growth stimulation relative to the untreated controls. This biphasic dose-response relationship, characterized by beneficial effects at low doses and toxic effects at high doses, is an important phenomenon in plant stress biology, with significant implications for understanding plant-pollutant interactions (Rai *et al.*, 2010).

7.1 Quantitative Characterization of Hormesis

Research on mung bean seedlings exposed to mercuric chloride showed that low doses (1–10 mg/L) exerted hormetic effects, promoting root and shoot development compared to the control groups. At a dosage of 1 mg/L, root length increased to 3.4 cm, representing a 6.3% increase over the control, whereas shoot length increased to 6.7 cm, representing an 8.1% increase over the control. With increasing dosage, growth stimulation intensified, peaking at 10 mg/L, where root length measured 4.2 cm (31.3% above control) and shoot length reached 7.4 cm (19.4% above control) (George 2022). Intermediate stimulation was at 5 mg/L with root length 3.6 cm (12.5% over control) and shoot length 7.2 cm (16.1% over control). Growth stimulation exhibited an evident dose-response relationship from 1–10 mg/L. Growth dropped significantly at 20 mg/L; root length was 2.9 cm (9.4% below control), and shoot length was severely damaged at 1.5 cm (75.8% below control). At 50 mg/L, phytotoxicity was significant, with shoot growth completely inhibited (100% decrease) and root length shortened to 2.5 cm (21.9% lower than that of the control). This shift from stimulation to strong inhibition underscores the importance of dose thresholds in plant responses, particularly in the 10–20 mg/L range.

7.2 Mechanistic Basis of Hormesis

Sub-toxic levels of mercury can induce hormesis by triggering adaptive stress responses that boost plant growth. Moderate oxidative stress activates antioxidant defenses such as superoxide dismutase, catalase, peroxidase, and ascorbate peroxidase, and builds protective substances such as proline, glycine betaine, and polyamines, which maintain membrane integrity and osmoprotection. Enhanced phytochelatin and metallothionein production may increase metal sequestration, lowering free Hg in susceptible cells.

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Calcium, reactive oxygen species, and phytohormone-mediated stress signaling pathways may synchronize plant cell gene expression, repair, and membrane integrity. Mercury toxicity and fish growth inhibition result from these defensive systems being overwhelmed at high doses.

7.3 Ecological and Agricultural Implications

At low doses, mercury activates vitality-boosting hormetic stress-response pathways. Sublethal mercury dosages boost antioxidant defenses, including superoxide dismutase, catalase, peroxidase, and ascorbate, and induce mild oxidative stress in the body. This priming effect reduces oxidative damage and boosts the metabolism. As mercury levels decrease, stress-protective compounds, such as proline, glycine betaine, and polyamines, are synthesized as osmoprotectants and membrane stabilizers.

Plants produce phytochelatins and metallothioneins under mild stress, which sequester metals and lower free metal ion concentrations. This indicates that signaling pathways activate stress-responsive genes to repair and develop cells in response to stressors. High mercury concentrations overwhelm these adaptive mechanisms, leading to toxic effects and reduced development when plants cannot recover (Weinstein & Davison, 2004).

8. Chromium: Mechanisms and Physiological Responses

Chromium contamination poses a serious environmental concern owing to its widespread release from industrial activities and marked differences in toxicity among the oxidation states of Cr. A comprehensive review of Cr toxicity in crop plants provides detailed insights into the mechanisms, physiological responses, and remediation strategies associated with Cr toxicity.

8.1 Chromium Speciation and Differential Toxicity

Chromium exists predominantly in two stable oxidation states: trivalent chromium [Cr(III)] and hexavalent chromium [Cr(VI)], which exhibit markedly different mobilities, bioavailabilities, and toxicities. Hexavalent chromium is considerably more toxic, mobile, and bioavailable than trivalent chromium and is absorbed more readily by plants through sulfate transport systems because of its structural similarity to sulfate ions.

Once inside plant cells, Cr(VI) is reduced to Cr(III), generating intermediate Cr(V) and Cr(IV) species, as well as reactive oxygen species, including superoxide radicals and hydrogen peroxide. ROS contribute significantly to Cr-induced oxidative stress and cellular injury. Trivalent chromium, although less mobile and readily absorbed, can still exert toxic effects at high concentrations, although its effects are generally less severe than those of Cr(VI).

The differential toxicity of Cr species has important implications for risk assessment and remediation. Efforts to reduce Cr toxicity in contaminated soils often focus on converting Cr(VI) to the less toxic Cr(III) form via chemical and biological reduction.

8.2 Effects on Seed Germination and Plant Growth

High Cr levels inhibit the germination and growth of wheat, rice, maize, sunflowers, and legumes. By altering seed imbibition, enzyme activation during germination, and seed reserve mobilization, Cr can delay germination, lower the germination percentage, and produce abnormal seedlings.

During vegetative growth, Cr exposure slowed plant growth and reduced shoot and root elongation, leaf area, and biomass of the plants. As predicted, additional heavy metals and fluoride impaired root growth more than they did shoot growth. Chromium-induced growth inhibition is caused by reduced photosynthesis, altered food intake, oxidative stress and interference with cell division.

8.3 Photosynthetic Disruption

Chromium markedly impairs photosynthesis in several ways. It disrupts chlorophyll production by inhibiting enzymes in the pathway and competing with magnesium, leading to reduced chlorophyll levels and foliar chlorosis, which are indicative of Cr poisoning. Moreover, Cr adversely affects photosystem II (PSII) reaction centers, reducing quantum yield and electron transport efficiency. Disruption of the oxygen-evolving complex in PSII impedes water splitting and oxygen evolution, thereby restricting electron flow throughout the photosynthetic electron transport chain.

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Moreover, Cr impedes essential enzymes of the Calvin cycle, particularly ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO), thereby diminishing the plant's capacity to fix carbon. Cr-induced stomatal closure further restricts CO₂ availability, imposing additional limitations on photosynthesis. Collectively, these variables lead to a substantial reduction in the net photosynthetic rate, limiting the plant's capacity to produce carbohydrates and energy, which are vital for plant growth and stress resistance.

8.4 Water Relations and Mineral Nutrition

The negative effects of Cr on the water relations in plants are mainly due to a reduction in root hydraulic conductivity as a result of damage to aquaporins and the integrity of the root membranes. This damage results in reduced water absorption, reduced leaf water potential, wilting, and loss of turgor, even when soil moisture levels are adequate. Chromium also interferes with the absorption and distribution of essential nutrients such as iron, manganese, sulfur, phosphorus, nitrogen, calcium, and magnesium. These nutrients compete for transporters, leading to nutritional imbalances in plant tissues. Iron deficiency is more prevalent under Cr stress because Cr(VI) inhibits iron absorption and utilization, resulting in interveinal chlorosis, which is characteristic of iron deficiency. The co-occurrence of dietary deficits and Cr toxicity further exacerbates stress, impairing photosynthesis, protein synthesis, and antioxidant defense, thereby aggravating total Cr toxicity.

8.5 Oxidative Stress and Antioxidant Responses

ROS overproduction causes oxidative stress and phytotoxicity in plant. Chromium disrupts electron transport chains in chloroplasts and mitochondria, activates NADPH oxidases, and generates ROS during Cr(VI) reduction to Cr(III). Overexposure to ROS leads to lipid peroxidation, protein oxidation, and deoxyribonucleic acid (DNA) damage. Malondialdehyde (MDA), a marker of lipid peroxidation, significantly increased during Cr stress, indicating membrane damage in the cells. Increased electrolyte leakage from damaged cells indicates membrane damage.

In response to Cr-induced oxidative stress, crop plants deploy antioxidant defense systems that involve both enzymatic and non-enzymatic components. Key antioxidant enzymes include

Superoxide dismutase (SOD) catalyzes the dismutation of superoxide radicals to hydrogen peroxide and oxygen, representing the first line of defense against reactive oxygen species (ROS).

Catalase (CAT) decomposes hydrogen peroxide into water and oxygen, preventing H₂O₂ accumulation.

Peroxidase (POD): reduces hydrogen peroxide using various electron donors, contributing to H₂O₂ detoxification.

Ascorbate peroxidase (APX) reduces hydrogen peroxide to water using ascorbate as an electron donor and plays a critical role in chloroplast ROS detoxification.

Moderate chromium stress upregulates the expression of antioxidant enzymes, thereby reducing oxidative damage. Under extreme chromium stress, antioxidant enzyme activity may decrease due to either ROS damage or Cr-induced inhibition. Oxidative damage and plant tolerance depend on the production of reactive oxygen species (ROS) and the antioxidant defense capabilities.

Vitamin C, glutathione, tocopherols, carotenoids, and phenolic compounds are non-enzymatic antioxidants that scavenge ROS and protect membranes. Plants with higher baseline antioxidant levels or increased stress-induced production are more tolerant to Cr.

8.6 Chromium Toxicity Symptoms

Chromium poisoning in agricultural plants is characterized by stunted development, chlorosis (particularly interveinal chlorosis), necrotic leaf lesions, wilting, reduced leaf area, and root browning. Severe instances may lead to complete growth cessation and plant mortality, indicating substantial physiological disturbances such as impaired photosynthesis, oxidative injury, nutrient deficiencies, and poor water relations. The intensity and progression of these symptoms are influenced by factors such as Cr content, exposure duration, plant species, developmental stage, and environmental conditions. Prompt identification of these indications is essential for prompt intervention to avert irreparable harm and crop loss.

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9. Remediation and Mitigation Strategies

Addressing heavy metal and fluoride contamination in agricultural systems requires an integrated approach that combines prevention, remediation, and adaptation strategies (George, 2020). Multiple technologies and management practices have been developed to reduce pollutant bioavailability, remove contaminants from the soil, and enhance plant tolerance to contaminated conditions.

9.1 Phytoremediation

Phytoremediation, which uses plants to clean contaminated soil, is one of the most sustainable and cost-effective methods available. It takes several forms. *Phytoextraction* uses plants that naturally absorb and store high concentrations of metals in their aboveground tissues. The plants are then harvested, and the metals are removed from the site. *Brassica juncea* (Indian mustard) is particularly well-studied for chromium extraction; it grows quickly, produces substantial biomass, and can accumulate chromium in shoots at concentrations exceeding 1000 mg/kg dry weight. *Helianthus annuus* (sunflower) is an effective heavy metal accumulator. *Sorghum* and vetiver grass are also promising alternatives. *Phytostabilization* uses plants to immobilize metals in the root zone through root exudates, pH changes, and precipitation reactions, thereby reducing their mobility and preventing them from reaching the groundwater. Although metals remained in the soil, they became less available to plants. *Phytovolatilization* converts certain metals, particularly mercury and selenium, into volatile forms that are released into the atmosphere via plant transpiration. Although effective for some contaminants, it raises concerns about air pollution.

9.2 Soil Amendments and Immobilization

Soil amendments reduce plant absorption and toxicity by immobilizing heavy metals and fluorides. Various amendments were made. Soil amendments can reduce plant metal bioavailability without removing metals. Compost, manure, charcoal, and crop residues sequester metal ions via their organic functional groups, raise the pH in acidic soils (reducing metal solubility), and promote metal-altering microbial communities. Biochar, produced by pyrolyzing organic waste under anoxic conditions, is an excellent heavy metal sorbent because of its high surface area and porosity. Lime raises the pH and precipitates metals, phosphate additions make insoluble metal phosphates, and zeolites and clays adsorb metals..

9.3 Chelating Agents

Chelating agents can function in two ways. For phytoextraction, synthetic chelators, such as EDTA, and natural chelators, such as citric acid, can mobilize soil-bound metals, making them more readily available to plants. However, this requires careful management to avoid groundwater contamination. Humic and fulvic acids can form stable metal complexes, reducing their mobility and plant uptake.

9.4 Nanoparticle Applications

Recent advances have revealed the potential of nanoparticles to mitigate heavy metal toxicity in plants. Various nanoparticles, such as silicon, titanium dioxide, zinc oxide, and carbon nanotubes, enhance plant tolerance to heavy metal stress through different mechanisms. This encompasses enhancing the activity of antioxidant enzymes, chelating heavy metals to diminish their bioavailability, augmenting nutritional absorption, and fortifying cellular structures against heavy metal infiltration. Si nanoparticles mitigate Cr toxicity by enhancing antioxidant defense, increasing photosynthetic efficiency, and reducing Cr absorption. "Prior to the widespread application of these nanoparticles in agriculture, a comprehensive evaluation of their safety and environmental implications is necessary."

9.5 Plant Growth Regulators

Phytohormones regulate physiological and biochemical responses to enhance heavy metal tolerance. Several growth regulators have shown promise in this regard. Salicylic acid boosts antioxidant enzymes, reduces oxidative damage, and improves photosynthetic efficiency during heavy-metal exposure. Salicylic acid enhances antioxidant defense and decreases plant Cr absorption, thereby decreasing toxicity. Nitric oxide enhances antioxidant activity, stress defense mechanisms, and plant metal ion sequestration. Nitric oxide regulates antioxidant activity and reduces cellular Cr accumulation. Brassinosteroids improve plant stress by enhancing photosynthetic efficiency, antioxidant defense and gene expression. Gibberellins, cytokinin's, and abscisic acid may enhance heavy -metal tolerance.

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9.6 Beneficial Microorganisms

Bacteria, fungi, and arbuscular mycorrhizal fungi can improve soil remediation and enhance plant tolerance to heavy metals. Plant growth-promoting rhizobacteria (PGPR) produce metal-chelating chemicals, antioxidant defenses, nutrients, and plant growth hormones to increase metal tolerance.

Arbuscular mycorrhizal fungi (AMFs) improve nutrient and water absorption and heavy metal tolerance by forming symbiotic relationships with host plant roots. AMF can prevent heavy metals from reaching plant shoots by sequestering them in fungal structures. They enhance the antioxidant capacity and stress tolerance of plants. Through reduction, oxidation, methylation, or precipitation, several bacteria and fungi can make heavy metals less hazardous and bioavailable. Inoculating polluted soils with suitable microbial consortia can improve phytoremediation and enhance crop tolerance to pollutants.

9.7 Integrated Remediation Approaches

The best remediation methods treat site attributes, pollutant levels, and management goals differently. Phytoremediation and soil amendments improve metal extraction and crop yields. Growth regulators and beneficial bacteria help plants heal and become more resilient. Integrated prevention measures should regulate industrial effluent discharge, facilitate sewage sludge disposal, analyze agricultural soil quality, and educate farmers on contamination risks. Remediation and food safety require long-term monitoring of soil metal levels, crop metal accumulation, and ecosystem viability.

Integrated preventative strategies should limit the discharge of industrial effluents, simplify sewage sludge disposal, assess agricultural soil quality, and educate farmers about contamination hazards. Long-term monitoring of soil metal levels, crop metal accumulation, and ecosystem viability for remediation and food safety.

10. Implications for Food Security and Sustainable Agriculture

The severe reductions in growth and physiological disruptions induced by heavy metal and fluoride contamination documented in these studies underscore the serious threat to agricultural productivity and food security that these contaminants pose. The implications extend beyond immediate yield losses to encompass food safety, nutritional quality, ecosystem sustainability, and socioeconomic impacts on farming communities. Weinstein & Davison (2004).

10.1 Crop Productivity and Yield Losses

It directly reduces agricultural productivity in a dose-dependent manner and inhibits the growth of many crop species and forms of pollution. At soil heavy metal concentrations of 100 mg/kg, pulse crops experienced biomass reductions of 80–95%, resulting in yield losses that rendered their cultivation economically unfeasible. Moderate contamination at 25–50 mg/kg reduces biomass by 30–60%, significantly compromising farm profitability and food production. Fluoride concentrations above 200 ppm result in substantial growth inhibition, characterized by 70–90% reductions in root and shoot development, delayed establishment, delayed maturity, and diminished final yield (Weinstein and Davison, 2004). The losses are particularly significant in pulse crops, such as green gram, Bengal gram, cowpea, and black gram, which are vital protein sources in the developing regions of the world. Therefore, compromising nutritional security by diminishing the yields of oilseeds and vegetables.

10.2 Food Safety and Human Health Risks

Heavy metal deposition in edible plants poses health risks through food intake, although moderate levels may support hormetic development. Cadmium, lead, and mercury are poisonous, bioaccumulative, and have no biological functions in humans, making them a major concern. Overexposure to heavy metals from contaminated crops can cause renal impairment, neurological disorders, cardiovascular disease, skeletal abnormalities, and cancer. Children's high food intake relative to their body weight, along with the growth of their organs, makes them more susceptible to lead poisoning. Food crops with high fluoride levels can cause dental and skeletal fluorosis. Monitoring heavy metal and fluoride concentrations in agricultural soils and crops is crucial for ensuring food safety and maintaining the public health.

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10.3 Ecosystem Sustainability

Heavy metal and fluoride pollution alters soil microbial populations, which are essential for nutrient cycling, organic matter decomposition, and soil structure, thereby reducing soil fertility and ecosystem processes. Heavy metals in leguminous crops disrupt the symbiotic relationship between legumes and rhizobia, reducing nitrogen fixation and the utility of pulse crops for sustainable agriculture. This has increased the use of synthetic nitrogen fertilizers, which are both expensive and harmful. They disrupt soil food webs by harming earthworms, arthropods, and mycorrhizal fungi. The legacy contamination of soils with heavy metals has affected agricultural sustainability for centuries (Weinstein & Davison, 2004).

10.4 Socioeconomic Impacts

Reduced agricultural yield due to heavy metal and fluoride pollution greatly affects smallholder farmers in underdeveloped nations who depend on agriculture for their livelihood. Reduced yields decrease revenues, threaten economic stability, and may lead farmers to quit polluted properties. Owners lose money when contaminated land loses its value and usage. However, rehabilitation costs can be prohibitive for farms and communities, raising environmental justice concerns, as pollution mostly affects economically disadvantaged areas. Production losses can raise food costs, threatening regional and national food security and impacting low-income customers who spend a significant amount of their income on food products. According to Weinstein and Davison (2004), preventing pollution through strict rules and promoting sustainable industrial and agricultural practices are crucial.

10.5 Climate Change Interactions

Climate change may exacerbate heavy metal and fluoride toxicity in agriculture by increasing metal mobility and plant uptake, driven by elevated temperatures and altered precipitation patterns that affect metal speciation and bioavailability. Drought stress exacerbates heavy metal stress, resulting in significant synergistic effects on plant growth. Furthermore, climate change may alter contamination risks as shifting weather patterns may transport metals from polluted regions to previously unexposed areas. Efficiently overseeing these relationships is essential for maintaining agricultural output and food security amid shifting environments, such as those driven by climate change.

10.6 Policy and Regulatory Implications

These findings highlight the need for robust legal and regulatory frameworks to eliminate heavy metal and fluoride pollution in agricultural practices. The key policy objectives include implementing soil quality standards, controlling industrial releases, measuring pollution levels, financing remedial research, providing financial support to affected farmers, and implementing educational programs. Contamination is transboundary, requiring international collaboration for effective prevention and cleanup; and for preserving agricultural sustainability and food security in light of environmental concerns.

CONCLUSION

The present investigation indicates an alarming risk of contamination with heavy metals and fluoride in agricultural production, food security, and environmental sustainability in this region. Mercury and Cd were the most phytotoxic pollutants across all studies, whereas fluoride toxicity exhibited a unique concentration-dependent response with a considerable growth-inhibiting effect at threshold levels. Shoots are always less sensitive than root systems, and variations in tolerance across species indicate the possibility of selecting more resistant crops for polluted areas in the future. The results revealed that ROS-mediated oxidative stress is the main mechanism of toxicity responsible for the deterioration of photosynthesis, nutritional absorption, cellular metabolism, and overall plant development. The toxicity of Cr depends on its oxidation state. Hexavalent chromium is far more harmful than trivalent chromium because of its high mobility and bioavailability.

These results indicate that integrated management solutions are needed, including pollution reduction, soil restoration, crop improvement, and continuous monitoring of soil health. Possible remediation strategies include phytoremediation with hyperaccumulator species, soil amendments that reduce metal bioavailability, and novel technologies involving nanoparticles, chelating agents, and beneficial microbes.

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Future studies should focus on exploring molecular tolerance mechanisms, integrated remediation systems, long-term effects on soil quality, and rapid contamination assessment methods to alleviate potential hazards to crop production, edible plant parts, and the total ecosystem. Environmental contaminants pose an increasing threat to agricultural ecosystems, food safety, and crop yields, necessitating active interdisciplinary protection strategies.

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