Remediation Strategies to Reduce Heavy Metal Contamination in Cassava: A Comprehensive Literature Review

Cassava (*Manihot esculenta* Crantz) stands as the fourth most important source of calories for the global human population, serving as a vital staple crop particularly in Sub-Saharan Africa, Latin America, and parts of Asia. However, cassava cultivation faces an emerging and critical challenge: the accumulation of heavy metals from contaminated soils into edible tubers, which directly threatens the health of millions of consumers who depend on this crop as a dietary staple.

The Cassava Crisis and Heavy Metal Contamination

Global Importance

With production exceeding 215 million tons annually globally [1], and Nigeria accounting for approximately 20.3% of global production [6], cassava provides reliable caloric intake for vulnerable populations [2]. The crop's adaptability to marginal and nutrient-poor soils, combined with its drought tolerance and high productivity potential, has made it indispensable for food security in resource-poor communities.

The Contamination Threat

Heavy metal contamination in agricultural soils has become a global environmental concern with far-reaching implications for food safety and human health. The persistence and bioaccumulative nature of metals such as cadmium (Cd), lead (Pb), mercury (Hg), and arsenic (As) means they accumulate in soil environments and are subsequently taken up by food crops, creating a direct pathway to human toxicity through dietary exposure.

The global cassava production system faces unprecedented pressure from both natural and anthropogenic sources of heavy metal contamination. Industrial effluents, mining operations, inappropriate waste disposal practices, atmospheric deposition, and the excessive application of agrochemicals including fertilizers and pesticides all contribute to elevated heavy metal levels in agricultural soils. In developing nations where cassava serves critical food security functions, the regulation and monitoring of soil quality remains inadequate, exacerbating the problem.

Why Cassava Accumulates Heavy Metals

Physiological Factors

Cassava's propensity to accumulate heavy metals stems from multiple physiological and environmental factors. The crop exhibits specific transport mechanisms for metal uptake, with evidence suggesting differential accumulation patterns across plant tissues.

Tissue Distribution

Studies comparing cassava tuber compartments have revealed that heavy metal concentrations vary significantly between the pith, bark, epidermis, and flesh of tubers, with some tissues showing substantially higher accumulation than others [9].

Storage Function

Root tuber crops like cassava naturally concentrate minerals and trace elements as part of their storage function, and this same mechanism can result in unintended accumulation of toxic metals when soil bioavailability is elevated [10].

Bioaccumulation Evidence

The bioaccumulation characteristics of cassava have been documented in multiple environmental contexts. In crude oil-impacted areas of Niger Delta, Nigeria, cassava demonstrated strong bioaccumulation capacity for copper, with perfect correlation (r = 1.00) between soil and plant concentrations suggesting cassava's potential as a bioindicator crop [11]. Similarly, research from Ghana demonstrated that 30% of cassava samples exceeded permissible lead concentrations set by international standards, with bioconcentration factors for nickel indicating higher absorption capacity into cassava from soil compared to other heavy metals [12].

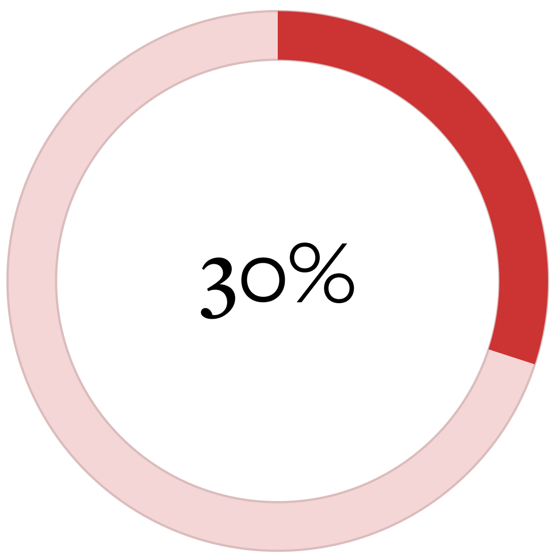
Geographic Hotspots

Geographic distribution of cassava contamination reveals particular vulnerability in regions subject to mining impacts, industrial development, and improper waste disposal. In Ecuador's gold mining areas, cassava and other food crops showed trace element concentrations exceeding maximum permissible levels, with hazard quotients and cancer risk values indicating significant health risks, particularly for children. In Nigeria, cassava grown around cement factories accumulated heavy metals at levels far exceeding WHO/FAO standards, while cassava from crude oil-impacted communities in the Niger Delta showed Hazard Index values exceeding the USEPA safety threshold.

Heavy Metal Contamination: Extent, Sources, and Health Implications

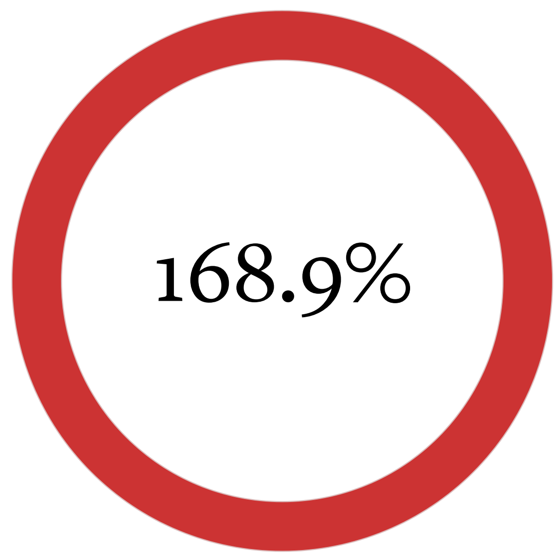
Concentration Levels and Accumulation Patterns

Numerous studies have documented heavy metal levels in cassava grown across various contamination contexts. In Machakos County, Kenya, single-cropped cassava farms showed cadmium levels ranging from 0.09-0.59 mg/kg in soil, with cassava tuber pith accumulating mean values of 4.7 mg/kg for cadmium [9]. Intercropped systems showed even higher accumulation, with cadmium values reaching 7.8 mg/kg in tuber pith, indicating that agricultural management practices influence metal bioavailability and plant uptake.



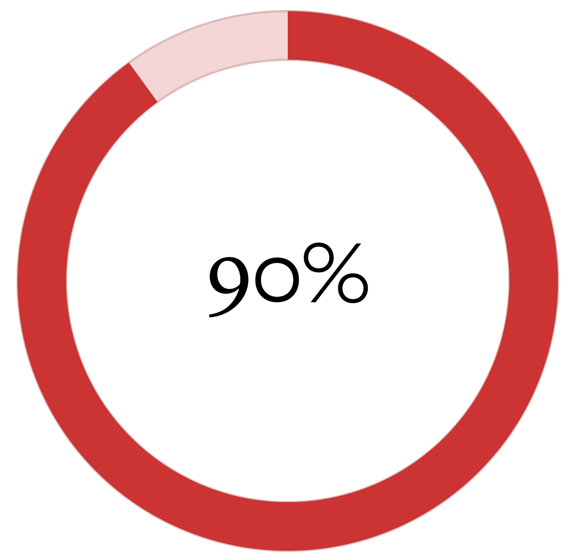
Cassava Samples Exceeding Lead Limits

Research from Ghana demonstrated that 30% of cassava samples exceeded permissible lead concentrations set by international standards



Arsenic Reduction with Biochar

Biochar amendment reduced arsenic accumulation in cassava by 168.9% compared to control soils in mining-degraded landscapes



Cadmium Transfer Reduction

Application of cow dung and urban waste compost to cadmium-contaminated soil reduced cadmium transfer to amaranth by 90%

The distribution of heavy metals within cassava tubers is not uniform. Tissue-specific analysis reveals that the pith and bark accumulate substantially higher metal concentrations than the flesh [9], an important finding for food safety implications given that different populations consume cassava in varied forms. In crude oil-impacted communities where cassava grows, zinc was the dominant metal, with concentrations reaching 7.91×10^{-1} mg/kg/day in estimated daily intake for children, far exceeding safe exposure levels and indicating the magnitude of dietary risk from cassava consumption in these areas [4].

Source Attribution and Soil-to-Cassava Transfer Mechanisms

Contamination Drivers

Heavy metal contamination of cassava-growing soils originates from diverse sources, with scientific understanding advancing through source apportionment studies. The dominant sources include mining activities (both artisanal and industrial), industrial emissions, atmospheric deposition, agricultural intensification through fertilizer and pesticide application, and improper waste disposal [15].

Mining Operations

In mining-affected cassava-growing regions, mining operations represent the primary contamination source. In Ghana's illegal mining areas, cassava roots accumulated mercury at concentrations ranging from 0.097 to 5.09 mg/kg dry weight

Industrial Emissions

Industrial effluents and atmospheric deposition from factories contribute significantly to soil contamination, with cassava near cement factories showing levels far exceeding WHO/FAO standards

Agricultural Chemicals

Policy factors controlling fertilizer and pesticide use emerged as the dominant influence on heavy metal accumulation in agricultural soils

Transfer Mechanisms

Understanding how heavy metals move from soil into cassava tissues represents a critical knowledge area for developing remediation strategies. The soil-plant transfer depends on multiple interacting factors including soil pH, organic matter content, metal speciation, and plant-available metal concentration in the rhizosphere. Soil pH emerges as a particularly critical parameter, with acidic soils promoting greater metal mobility and plant uptake. Low soil pH directly increases the concentration of metals in soil solution, enhancing bioavailability to plant roots, while neutral to slightly basic pH reduces solubility of many metals, limiting uptake.

The bioaccumulation capacity of cassava for specific metals appears partly dependent on soil chemical properties. In studies of cassava from illicitly mined areas in Ghana, mercury showed weak or negative correlations between soil and plant concentrations, suggesting limited bioavailability influenced by soil pH and organic matter. In contrast, copper exhibited a perfect positive correlation ($r = 1.00$) between soil and plant concentrations, indicating direct proportional relationships. Root morphology and the rhizosphere ecology of cassava influence metal uptake dynamics. Arbuscular mycorrhizal fungi (AMF) associated with cassava roots can both increase and decrease metal availability depending on the metal type and soil conditions.

Health Risks and Dietary Exposure from Cassava Consumption

CRITICAL HEALTH CONCERN

The health significance of cassava contamination emerges clearly when dietary exposure is quantified through risk assessment methodologies. **Children consistently face higher health risks than adults** due to their lower body weight relative to intake, as well as developmental sensitivity to heavy metal toxicity.

5.5

Hazard Index Peak

In crude oil-impacted areas of Nigeria, zinc Hazard Index (HI) values peaked at 5.5, with cassava also showing concerning values

1.5×10^{-4}

Cancer Risk

Total lifetime cancer risk for arsenic reached 1.5×10^{-4}, exceeding the USEPA acceptable limit of 1×10^{-6}[4]

7.91×10^{-1}

Daily Zinc Intake

Estimated daily intake (EDI) calculations for children revealed maximum values for zinc of 7.91×10^{-1} mg/kg/day

Risk Profiles by Metal and Population

The carcinogenic and non-carcinogenic risk profiles vary by metal and population. In Ghanaian mining communities, the target hazard quotient (THQ) for lead in cassava exceeded 1 in children from multiple communities (Techiman, Wangarakrom, Samahu, and Tebe), indicating unacceptable health risk[12]. A systematic review of Nigerian food crops revealed that among heavy metals and organochlorine pesticides, cadmium was present at the lowest average concentrations while iron had the highest, but the HQ-based non-carcinogenic risk (NCR) estimates for lead, cadmium, copper, and manganese exceeded 1 in both adults and children[20].

Heavy metal toxicity mechanisms in human health include: disruption of cellular homeostasis, generation of oxidative stress, interference with nutrient metabolism, and in the case of carcinogens like cadmium and arsenic, direct mutagenic effects. Lead exposure impairs cognitive development in children and increases hypertension risk in adults. Cadmium accumulates in kidney and bone tissues, causing renal dysfunction and osteoporosis with long-term exposure.

Soil Amendment-Based Remediation Strategies

Biochar Application for Heavy Metal Stabilization

Biochar, a carbon-rich material produced through pyrolysis of agricultural and forestry waste, has emerged as one of the most promising soil amendments for reducing heavy metal bioavailability in contaminated soils. The mechanisms underlying biochar's effectiveness include high surface area and porosity providing adsorption sites for metal ions, abundant surface functional groups (carboxyl, hydroxyl, amino) that chelate metals, and elevated soil pH increasing metal precipitation and reducing solubility[21].

Effectiveness for Cassava

The effectiveness of biochar for cassava-specific contamination remediation has been directly evaluated. In mining-degraded cassava-growing landscapes in Ghana, biochar amendment reduced arsenic accumulation in cassava by 168.9% compared to control soils, while lead accumulation decreased by 149.8%[22]. This dramatic reduction occurred even in severely contaminated mining-degraded soils, demonstrating biochar's potential for remediation of highly contaminated cassava production systems. When combined with poultry manure, biochar enhanced both remediation effectiveness and cassava stover biomass production, suggesting additive or synergistic effects of combined amendments[22].

Application Rates

5-20 tons per hectare

Key Benefits

High surface area, pH elevation, metal chelation

Organic Amendments and Compost-Based Strategies

Organic amendments including compost, manure, and agricultural residues represent accessible remediation tools particularly suitable for smallholder cassava farmers in resource-limited settings. These materials reduce metal bioavailability through multiple mechanisms: increased organic matter binds metals through chelation and sorption; elevated pH from organic matter decomposition reduces metal solubility; and stimulation of beneficial soil microorganisms creates additional binding sites for metals in the rhizosphere.

Application of cow dung and urban waste compost to cadmium-contaminated soil reduced cadmium transfer to amaranth by 90%, while lead transfer was reduced by 70%, demonstrating substantial protective effects for food crops. Bone meal and chicken manure amendments applied to cassava grown on cadmium-contaminated soil reduced cadmium bioavailability, achieving low accumulation values of 3.2 mg/kg in cassava tissues despite substantial soil concentrations of 3.1 mg/kg.

Phytoremediation and Microbial Remediation Approaches

Phytostabilization Using Amended Cassava Varieties

Phytostabilization, where plants restrict metal uptake and accumulation while immobilizing metals in soil, offers a practical approach compatible with continued cassava cultivation in mildly to moderately contaminated areas. Rather than extracting metals from soil, phytostabilization confines metals to root zones or accumulates them in root tissues rather than edible shoots. This approach is particularly suitable for cassava since the edible portion is the underground tuber, making root-concentrated accumulation patterns preferable to shoot accumulation[31].

01

Soil Amendment Application

Apply biochar, organic matter, or combined amendments to contaminated soils at appropriate rates

02

Variety Selection

Select or breed low-metal-accumulating cassava varieties maintaining productivity while accumulating less metal

03

Microbial Inoculation

Introduce beneficial microorganisms that enhance metal tolerance and reduce bioavailability

04

Monitoring and Adaptation

Continuously monitor metal levels and adjust management practices based on results

Plant Growth-Promoting Rhizobacteria (PGPR) and Endophytes

Beneficial microorganisms residing in cassava root systems can substantially reduce heavy metal stress and accumulation through multiple mechanisms including metal chelation, precipitation, and enzymatic transformation. Exopolysaccharide-producing *Bacillus* species (Z23 and Z39) screened from heavy metal-contaminated farmland achieved 88.6–93.2% removal efficiency for cadmium and lead through precipitation of metal-phosphate complexes in soil solution. These bacteria simultaneously enhanced plant growth and reduced metal accumulation in lettuce tissues by 40.1–61.7%, while increasing soil microaggregate content and exopolysaccharide concentrations in the rhizosphere.

The endophytic microorganisms residing within cassava tissues can employ chelation, complexation, precipitation, and enzymatic transformation to mitigate heavy metal toxicity at the cellular level. Endophytes enhance plant growth in metal-contaminated soils while contributing to reduced heavy metal accumulation through both direct metal immobilization and indirect enhancement of plant stress tolerance mechanisms.

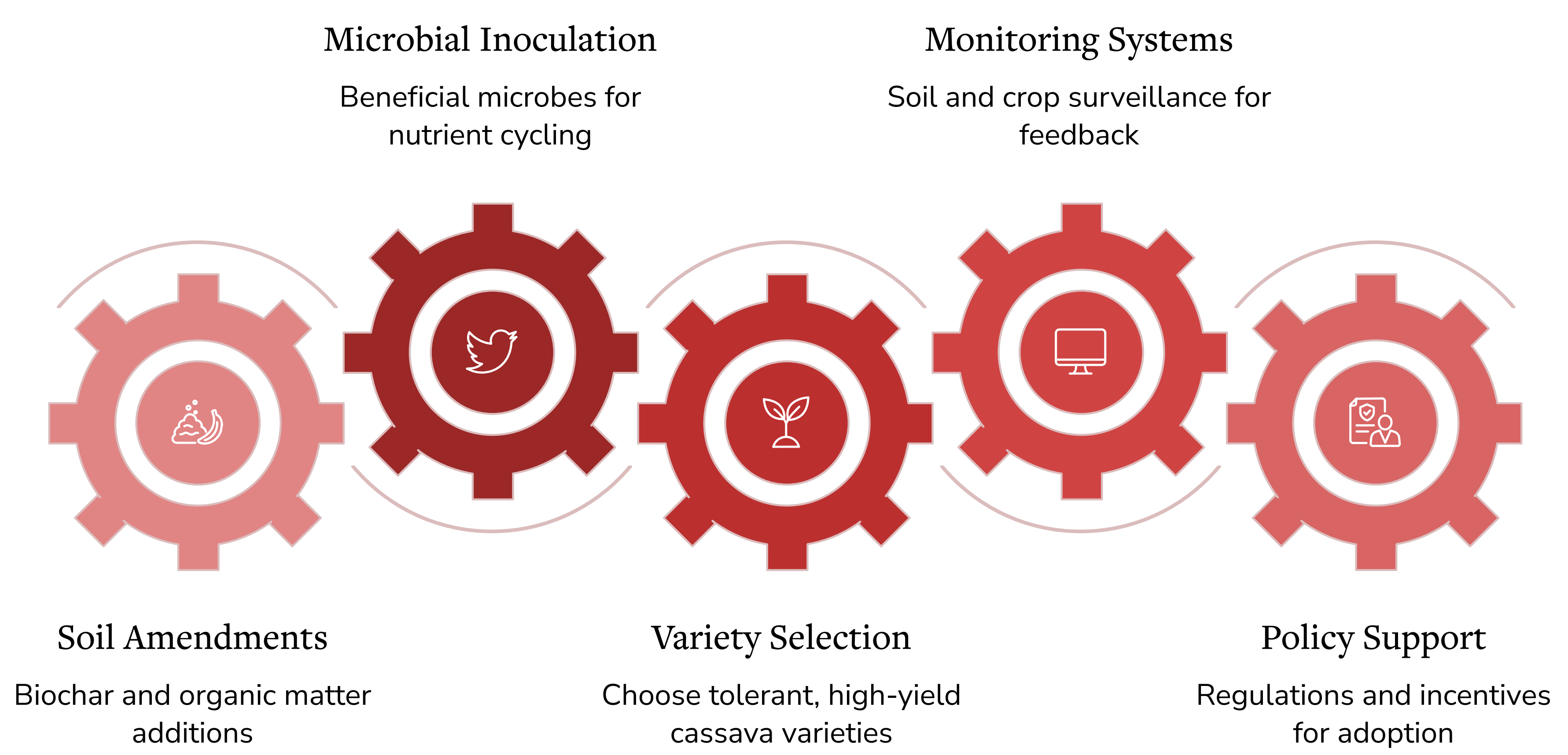
Mycorrhizal Fungi Associations

Mycorrhizal fungi associated with cassava roots demonstrate similar potential for reducing metal stress and accumulation. Arbuscular mycorrhizal fungi (AMF) increased cassava root morphological traits and enhanced secretion of low-molecular-weight organic acids (LMWOA) in the rhizosphere. However, the relationship between AMF-enhanced root growth and metal accumulation is complex, as improved root systems could theoretically increase metal uptake if bioavailability is not simultaneously reduced.

Integrated and Emerging Approaches: Multi-Sectoral Solutions

Integrated Soil Fertility Management (ISFM) Approaches

The principle of Integrated Soil Fertility Management (ISFM) adapted for contaminated cassava-growing systems combines multiple strategies—inorganic and organic amendments, soil- and plant-based interventions, agronomic practices, and biological approaches—into comprehensive soil management packages addressing both heavy metal contamination and nutrient deficiency. This systems approach recognizes that cassava production on contaminated soils requires addressing multiple constraints simultaneously: excessive heavy metal levels, declining soil organic matter, nutrient imbalances, and suboptimal soil biological activity[38].



The empirical basis for ISFM in contaminated cassava systems comes from studies demonstrating that single interventions often provide incomplete remediation, while combinations of approaches achieve superior outcomes. The combination of biochar, organic amendments, selected crop varieties, and microbial inoculations created synergistic effects exceeding the sum of individual component benefits[22]. The context-specific optimization of amendment combinations—considering local soil properties, contamination profiles, available resources, and farmer capacity—creates ISFM packages tailored to distinct agroecological zones and contamination scenarios.

Policy, Regulatory, and Monitoring Frameworks

Effective cassava contamination remediation requires supportive policy environments regulating heavy metal sources, monitoring soil and crop contamination, and establishing safe consumption thresholds. Nigeria's existing legislative framework for heavy metal pollution, while robust on paper, faces implementation challenges including insufficient funding, limited regulatory capacity, and weak enforcement. Similar regulatory gaps exist across cassava-producing regions, creating conditions where contamination persists unchecked and remediation receives inadequate priority in agricultural extension services.

Mandatory Soil Testing

Establish soil testing programs before cassava cultivation, combined with certification of safe cassava production areas

Laboratory Capacity

Develop regional soil testing networks and capacity strengthening initiatives for evidence-based remediation decision-making

Public-Private Partnerships

Integrate cassava contamination monitoring with broader agricultural surveillance systems through collaborative approaches

Biofortification and Nutritional Enhancement

While reducing heavy metal contamination remains essential, simultaneously enhancing the nutritional quality of cassava through biofortification addresses the reality that cassava-based diets often fail to meet micronutrient requirements. Biofortified provitamin A-rich cassava varieties have benefited 2.6 million people in sub-Saharan Africa and Brazil, demonstrating the potential of genetic improvement in cassava quality. The integration of enhanced micronutrient content (zinc, iron, vitamin A) alongside reduced heavy metal accumulation creates varieties addressing multiple nutritional constraints simultaneously.

Synthesis and Recommendations: A Pathway Forward

Cassava contamination with heavy metals represents a critical threat to food security and human health

The evidence presented throughout this review demonstrates that heavy metal contamination of cassava represents a serious but addressable challenge[3] to food security and human health in developing regions. The range of remediation strategies documented—from simple soil amendments to advanced biotechnologies—provides multiple options for contamination management[21, 23]. However, no single approach universally works across all contexts. Instead, successful remediation requires integration of context-specific strategies accounting for local contamination profiles, soil properties, farmer capacity, available resources, and broader development priorities[37].

Practical Recommendations by Contamination Level

Mild to Moderate Contamination

Organic amendment-based strategies combined with selection of low-accumulating varieties offer practical, cost-effective approaches compatible with smallholder farming systems. Application of compost, animal manure, and biochar at rates appropriate for local soil conditions can substantially reduce metal bioavailability while improving overall soil quality and productivity.

Severe Contamination

More intensive interventions including biochar application at rates of 10-20 tons/hectare, combined with microbial inoculation and targeted soil management, may be necessary to achieve sufficient metal immobilization[22]. The phytostabilization strategy maintaining cassava cultivation on contaminated soils through amendment-assisted growth represents a livelihood-preserving approach for communities unable to relocate production.

Critical Success Factors

The critical importance of monitoring programs and community engagement cannot be overstated. Remediation strategies succeed only when farmers understand contamination risks, perceive concrete benefits from management practices, and have access to reliable feedback on effectiveness. The integration of cassava contamination remediation with broader food safety and agricultural development initiatives increases the likelihood of adoption and sustained implementation. Public investment in monitoring infrastructure, farmer training, and research on locally adapted remediation strategies represents the foundation for meaningful progress.

Future Research Priorities

1. Field-scale validation of integrated remediation approaches in diverse agroecological and contamination contexts
2. Development and evaluation of locally-adapted cassava varieties with reduced metal accumulation
3. Investigation of policy instruments and market incentives promoting safe cassava production
4. Integration of contamination monitoring with early warning systems for food safety threats
5. Capacity strengthening in cassava-producing regions enabling sustained implementation of evidence-based remediation strategies

> **The remediation of heavy metal contamination in cassava production is fundamentally solvable through application of available knowledge, technologies, and management practices.** The challenge lies not in technical limitations but in bridging the gap between scientific evidence and farmer implementation, within the constraints of limited resources, inadequate infrastructure, and competing development priorities in resource-limited regions.

The transformation of cassava from a potential health risk into a reliable safe food source requires commitment from multiple stakeholders: agricultural researchers developing and validating context-appropriate solutions; policymakers establishing supportive regulatory frameworks and resource allocation; development practitioners facilitating farmer adoption and knowledge exchange; and cassava farmers themselves taking ownership of contamination management as integral to production. When these actors work synergistically within integrated programs addressing multiple development goals simultaneously, cassava can continue fulfilling its critical role in food security while protecting the health of the millions who depend on this essential crop.

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