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HEAVY METAL AND PESTICIDE REMEDIATION STRATEGIES IN CULTIVATED AYURVEDIC SOILS: ADVANCING SUSTAINABLE, SAFE, AND GLOBALLY ACCEPTED MEDICINAL PLANT PRODUCTION

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ABSTRACT
The global demand for Ayurvedic medicinal plants has increased substantially due to rising acceptance of traditional medicine and plant-based therapeutics [1-6]. This expansion has intensified cultivation systems, leading to increased exposure of medicinal plants to soil contamination by heavy metals and pesticide residues [18-23,29-35]. Heavy metals such as Cd, Pb, As, Hg, Cr and Ni originate from industrial emissions, mining activities, wastewater irrigation and fertilizers [18-23]. Pesticide residues further disrupt soil microbial ecosystem and plant metabolic functions [29-33].
These contaminants significantly compromise medicinal plant safety, phytochemical integrity and international market acceptance [24,36,43]. Bioaccumulation of toxic elements can lead to severe human health risks including neurotoxicity and carcinogenicity [25,43]. Therefore, sustainable remediation of contaminated soils is essential.
Advanced remediation technologies such as phytoremediation [1-6,37-41], microbial-assisted remediation [9-12,44-45], biochar-based immobilization [13-18,46-50], nanotechnology [53-56] and integrated systems [50,57-60] offer promising solutions. This review proposes the Ayurvedic Clean Soil Certification System (ACSCS) as a global framework for safe medicinal plant production.

KEYWORDS: Ayurveda, medicinal plants, heavy metals, pesticides, phytoremediation, biochar, microbial remediation, nanotechnology, soil contamination, sustainable agriculture.

1. INTRODUCTION
Ayurveda Is a holistic medicinal system relying heavilyn on plant-based formulation [1-3]. Medicinal plants such as Withania somnifera, Ocimum sanctum and Tinospora cordifolia are widely used due to their pharmacological activities [4-6,43].
Increasing global demand has led to intensified cultivation practices. However, industrialization and agricultural intensification have resulted in soil contamination [18-23]. Heavy metals persist in soils due to their non-biodegradable nature and accumulate in plant tissues [21-23].
Similarly, pesticide residues disrupt soil microbial balance and affect nutrient cycling [29-33]. These contaminants directly affects medicinal quality and global acceptance of Ayurvedic products [25,33,43].

2. Sources of Soil Contamination

2.1 Industrial Emissions
Industrial activities release toxic metal such as Pb, Cd and Hg into surrounding agricultural soils [18-20]'

2.2 Mining Activities
Mining waste introduces As, Ni, and Cr into soil system [18,21]

2.3 Wastewater irrigation
Continuous irrigation with contaminated water leads to gradual metal accumulation [19-21]

2.4 Fertilizers and Agrochemicals
Phosphate fertilizers often contain trace metals like Cd and Pb [21-23]

2.5 Atmospheric Deposition
Airborne particles deposit heavy metal onto soil and crops [20,24]

3. Pesticide Contamination Mechanisms
3.1 Insecticides
Organophosphates and neonicotinoids persist in soils and affect microbial diversity [29-31]

3.2 Herbicides
Herbicides alter enzymatic activity and soil microbial balance [30-32].

3.3 Fungicides
Copper – based fungicides contribute to both pesticide and heavy metal accumulation [31,35].

3.4 Persistent Organic Pollutants
Organochlorine compounds persist in soil for long duration [31-33].

4. Impact on Medicinal Plants
4.1 Physiological Stress
Heavy metals induce oxidative stress and reactive oxygen species production [36,40]

4.2 Growth Inhibition
Contaminants reduce germination, biomass and chlorophyll content [24,36].

4.3 Alteration of Secondary Metabolites
Biosynthesis of alkaloids, flavonoids and terpenoids is significantly altered [36,43].

4.4 Human Health Risks
Consumption of contaminated herbs can lead to neurological and carcinogenic disorders [25,43]

5. Remediation Technologies
5.1 Phytoremediation
Phytoremediation uses plants to extract or stabilize contaminants via phytoextraction and phytostabilization [1-6,37-41].

5.2 Microbial Remediation
PGPR and mycorrhizal fungi enhance contaminant degradation and plant tolerance [9-12,44-45].

5.3 Biochar- Based Remediation
Biochar improves soil fertility and immobilizes heavy metals [13-18,46-50]

5.4 Nanotechnology Applications
Nanomaterials enhance adsorption and degradation of pollutants [53-56].

5.5 Integrated Systems
Combined plant-microbes-biochar systems shows superior remediation efficiency [50,57-60].

6. Table

Table 1. Major Health Metals in Agricultural Soils and Their Sources [18-23,24,25]

Metal	Source	Health impact
Pb	Industry, traffic	Neurotoxicity
Cd	Fertilizers	Kidney damage
As	Mining	Carcinogenic
Hg	Industrial emissions	Neurological damage
Ni	Metallurgical activity	Dermatitis
Cr	Waste disposal	Toxicity

Table 2. Hyper accumulator Plants used in Remediation [37-41]

Plant Species	Target Metals

Brassica juncea	Pb, Cd
Helianthus annuus	Zn, Pb
Vetiveria zizanioides	Multi-metal
Pteris vittata	As
Alyssum murale	Ni

Table 3 Comparison of Remediation Technologies [50,53-60}

Method	**Advantage Limitation**
Phytoremediation	Eco-friendly, slow process
Microbial remediation	Sustainable environmental sensitivity
Biochar	Soil improvement
Nanotechnology	High efficiency cost and safety concers
Integrated systems	Highly effective complex implementation

7. Ayurvedic Clean Soil Certification System (ACSCS)

The ACSCS is proposed as a global framework to ensure contaminant free medicinal plant production.

7.1 AI-Based Soil Monitoring

AI-based geospatial systems enable real-time contamination mapping and risk assessment.

7.2 Mandatory Soil Remediation

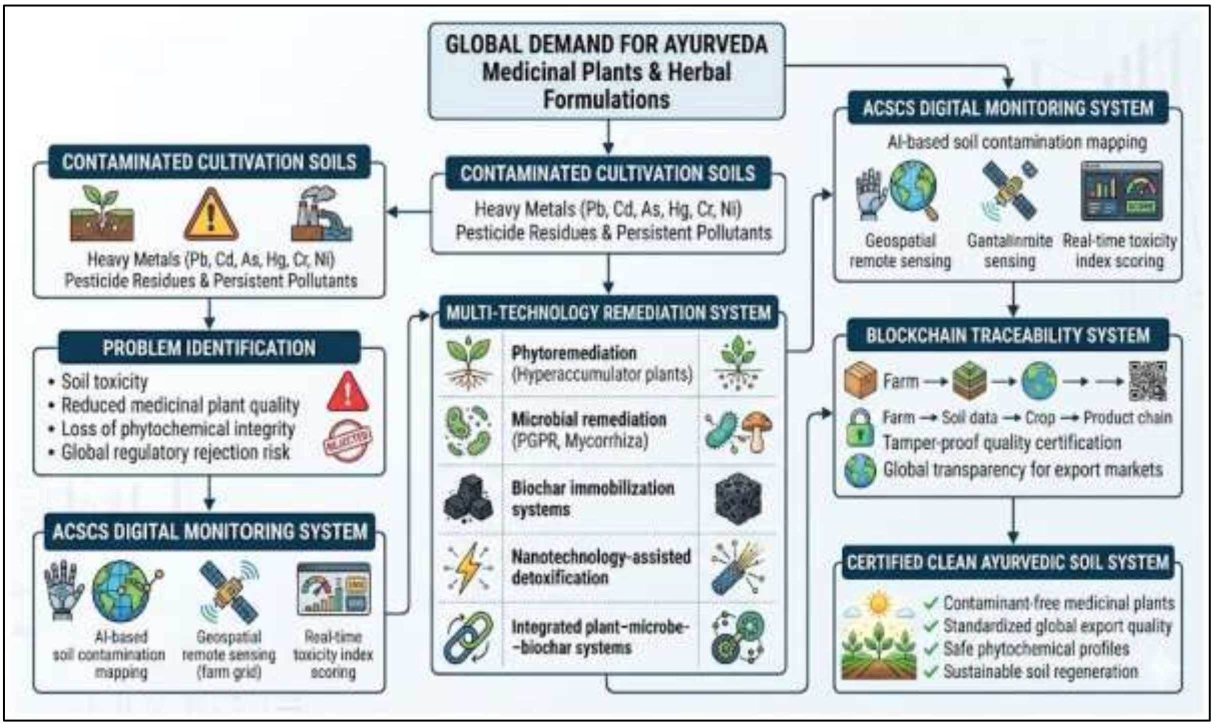
Pre-cultivation detoxification ensures soil safety before cultivation begins.

7.3 Blockchain Traceability

Every medicinal plant batch is linked to soil data and cultivation history for transparency.

7.4 Global Standards Integration

ACSCS aligns with WHO-GACP and international herbal safety regulations [25,33].



8. Future Perspectives

Future research should focus on:

Multi – contaminant remeadiation systems [50,57-60]
Genetic enhancement of hyperaccumulator plants [37-41]
AI-driven soil prediction models

Biochar- microbe synergistic technologies [46-50]
Large scale field validation studies.
Global standardization of herbal soil safety

9. DISCUSSION

Heavy metal and pesticide contamination has emerged as a major challenge in Ayurvedic medicinal plant cultivation because these pollutants adversely affect soil health, plant growth, phytochemical composition, and consumer safety (18–25,29–35,61). Heavy metals such as Pb, Cd, As, and Hg can accumulate in medicinal plants and pose significant toxicological risks, while pesticide residues may disrupt soil microbial communities and alter plant metabolism (24,36,43,62). Among available remediation technologies, phytoremediation, microbial-assisted remediation, and biochar application have shown considerable potential for reducing contaminant levels and improving soil quality (1–18,44–58). Recent evidence suggests that integrated remediation systems combining plants, microorganisms, and biochar are more effective than individual approaches (50,57–60,63). The proposed Ayurvedic Clean Soil Certification System (ACSCS) could provide a practical framework for ensuring contaminant-free medicinal plant production through soil monitoring, remediation, and traceability. Adoption of such sustainable approaches may improve the safety, quality, and global acceptance of Ayurvedic medicinal products.

10. CONCLUSION

Heavy metal and pesticide contamination significantly threaten Ayurvedic medicinal plant cultivation systems [18-23,29-35]. These contaminants reduce soil quality, alter plant metabolism and pose serious human health risks [25,36,43]

Advanced remediation technologies including phytoremediation, microbial system, biochar, nanotechnology and integrated approaches offer effective solutions for restoring soil health [1-6,44-50, 53-60]

The proposed ACSCS framework provides a transformative global model for ensuring safe, traceable and sustainable medicinal plantbproduction.

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