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NANOMATERIALS IN SUSTAINABLE SOIL REMEDIATION – CURRENT ADVANCES AND FUTURE PERSPECTIVE

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INTRODUCTION

- ✓ Soil contamination – a threat to environmental quality and food security.
- ✓ Phytoremediation – an eco-friendly approach to soil remediation.
- ✓ Nanomaterials – enhancing plant growth, soil health and contaminant availability.
- ✓ Nano-phytoremediation – a promising sustainable approach for efficient soil remediation and ecosystem restoration.

NANOMATERIALS AND THEIR INFLUENECE ON PLANTS

NANOPARTICLE TYPE	MAIN EFFECTS ON PLANT PERFORMANCE
Iron oxide nanoparticles (Fe_3O_4, FeNPs)	Enhance plant growth and photosynthesis Increase stress tolerance Improve antioxidant defense
Nano zero-valent iron (nZVI)	Increase metal bioavailability Enhance phytoextraction Improve remediation efficiency
Titanium dioxide nanoparticles (TiO_2 NPs)	Enhance photosynthesis Promote pollutant degradation Increase stress tolerance
Zinc oxide nanoparticles (ZnO NPs)	Promote plant growth Improve nutrient uptake Enhance stress resistance
Carbon nanotubes (CNTs)	Enhance pollutant adsorption Promote contaminant degradation Improve phytoremediation efficiency
Graphene oxide (GO)	Adsorb contaminants Improve pollutant availability Support rhizosphere remediation
Chitosan nanoparticles	Enhance metal uptake Improve adsorption capacity Increase stress tolerance
Polymeric nanoparticles	Controlled delivery of nutrients Promote plant growth Increase biomass production
Magnetic nanocomposites / Magnetic biochar–CuO	Immobilize contaminants Improve root-zone conditions Enhance remediation efficiency

SUSTAINABLE SOIL PHYTOREMEDIATION MECHANISMS

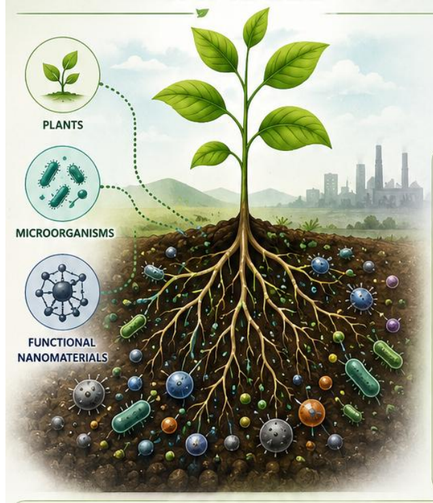
➢ ADSORPTION AND IMMOBILIZATION CONTAMINANTS
- ✓ Use of high-surface-area of NPs;
- ✓ Effects: reduced contaminant mobility and bioavailability; enhanced adsorption capacity; enabled magnetic recovery and sustainable reuse.

➢ CONTROLLED NUTRENT DELIVERY
- ✓ Improvement of nutrient-use efficiency;
- ✓ Effects: enhanced crop productivity; improved product quality; identified potential phytotoxicity; Highlighted the need for optimized application rates and further assessment of long-term environmental impacts.

➢ SOIL HEALTH ENHANCEMENT
- ✓ Improvement of soil structure, water retention, nutrient availability, and microbial activity;
- ✓ Effects: reduced nutrient leaching; improved overall soil ecosystem functioning.

Green synthesized nanomaterials support sustainable nano-phytoremediation by enhancing contaminant removal while minimizing environmental impact.

ABSTRACT



Nano-enabled phytoremediation has emerged as a promising strategy for enhancing the remediation of contaminated soils through the combined action of plants, microorganisms, and functional nanomaterials.

HOW NANOMATERIALS ENHANCE REMEDIATION

ADSORPTION	Nanomaterials adsorb contaminants, reducing their bioavailability.
IMMOBILIZATION	Nanomaterials immobilize contaminants, limiting their mobility.
CATALYTIC DEGRADATION	Nanomaterials catalyze the breakdown of contaminants.
STIMULATION OF PLANT PHYSIOLOGICAL PROCESSES	Nanomaterials stimulate photosynthesis, enzyme activity, and antioxidant defenses.

NANOMATERIALS ENHANCE PLANT–MICROBE SYSTEMS

NUTRIENT ACQUISITION	BIOMASS PRODUCTION	STRESS TOLERANCE	PLANT–MICROBIOME INTERACTIONS	SUSTAINABLE NANOMATERIALS
Improved uptake of essential nutrients.	Increased growth and biomass accumulation.	Enhanced tolerance to abiotic and biotic stresses.	Stronger beneficial interactions in the rhizosphere.	Green-synthesized and biodegradable nanomaterials support environmentally sustainable remediation technologies.

CHALLENGES FOR LARGE-SCALE IMPLEMENTATION

NANOPARTICLE FATE	ECOLOGICAL SAFETY	LONG-TERM IMPACTS
Transport, transformation, and persistence in soil–plant–environment systems.	Potential toxicity to non-target organisms and ecological communities.	Effects on soil biodiversity, ecosystem functions, and resilience.

THE WAY FORWARD

SAFE-BY-DESIGN NANOMATERIALS + ROBUST ENVIRONMENTAL RISK ASSESSMENT = ENVIRONMENTALLY SAFE AND EFFECTIVE REMEDIATION

Future progress will depend on integrating safe-by-design nanomaterials with robust environmental risk assessment frameworks.

Key words: sustainable soil remediation; green nanotechnology; nano-enabled phytoremediation; environmental sustainability.

CONCLUSION

The integration of nanotechnology, biotechnology, and microbial systems will drive the future of sustainable soil remediation.

SAFE-BY-DESIGN NANOMATERIALS → LIFE CYCLE ASSESSMENT → INTEGRATED EVALUATION OF RISKS & PERFORMANCE → SUSTAINABLE SOIL RESTORATION → CONTRIBUTION TO THE SDGs

Minimize toxicity and ecotoxicological impacts; protect human health and ecosystems.
Reduce environmental burdens through resource-efficient and sustainable solutions.
Evaluate environmental risks and remediation effectiveness for safe and reliable outcomes.
Restore soil health and biodiversity; enhance ecosystem services and resilience.
Science, innovation and collaboration for a resilient and sustainable future.

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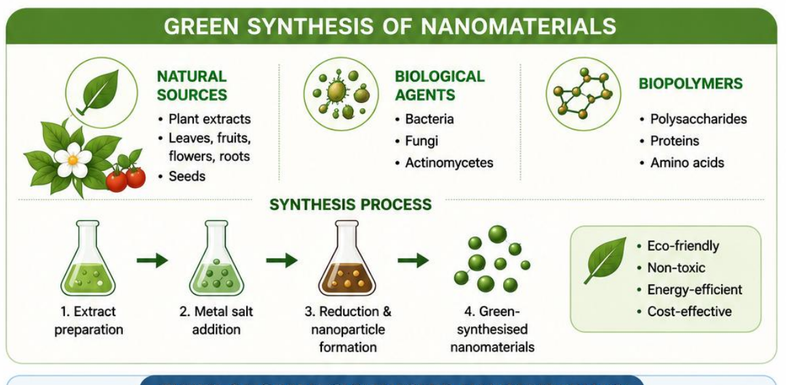
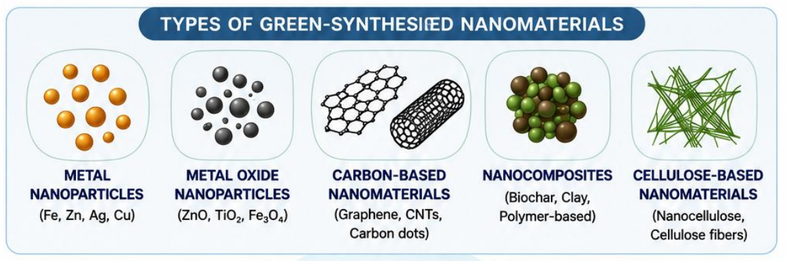
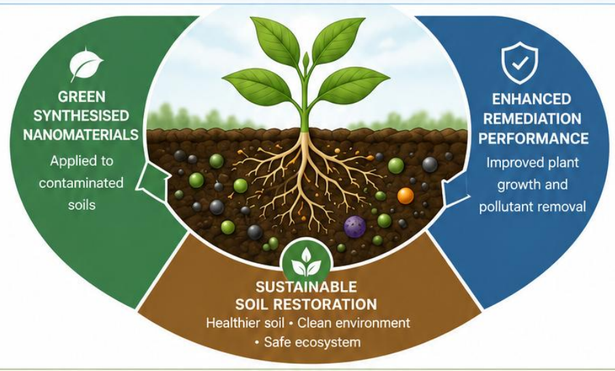
GREEN SYTHESISIS OF NANOMETARIALS







KEY BENEFITS

Sustainable & environmentally friendly	Low toxicity and safe for ecosystems	Cost-effective and scalable	Biodegradable capping agents and supports circular economy	Restores soil quality and ecosystem balance	Supports plant growth and productivity

ENVIRONMENTAL SUSTAINABILITY AND SAFETY

- ✓ Ecotoxicity assessment – effects on soil biota.
- ✓ Long-term environmental monitoring – NPs persistence and mobility.
- ✓ Dose optimization – maximize efficiency, minimize toxicity.
- ✓ Biosafety assessment – ecological impacts of genetically modified plants.
- ✓ Green nanomaterial development – biodegradable alternatives.
- ✓ Life cycle and risk assessment – standardized environmental evaluation.
- ✓ Regulatory harmonization and public engagement – safe and accepted implementation.

FUTURE PERSPECTIVE

RESEARCH AREA	KEY FOCUS & OUTCOME
Advanced Plant Engineering	Engineering stress-resilient plants enhances growth and pollutant uptake, improving remediation efficiency.
Multifunctional Bio-Nanocomposites	Nanomaterials combined with plant–microbe systems enable simultaneous removal and immobilization of diverse pollutants.
Intelligent & Autonomous Systems	AI and remote sensing enable real-time monitoring, predictive modelling, and optimized remediation strategies.
Regulation, Standards & Social Acceptance	Harmonized protocols and life-cycle assessments ensure safe implementation and public trust.
Toward Sustainable Mainstreaming	Circular bioeconomy and biomass valorization promote scalable, economically viable and sustainable restoration.

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