"A DUAL ACTION PHYTONANOPARTICLES FOR ENVIRONMENTAL DETOXIFICATION AND PLANT DISEASES MANAGEMENT"

Dr. N. B. Hirulkar
Department of Microbiology,
Nabira Mahavidyalaya, Katol,
District Nagpur, Maharashtra, India
Email : nhirulkar@rediffmail.com

Sujata D. Palheriya
Department of Microbiology,
Nabira Mahavidyalaya, Katol,
District Nagpur, Maharashtra, India
Email : sujatapalheriya765@gmail.com

Crossref DOI -

Abstract :

The convergence of microbial biotechnology and nanotechnology offers promising sustainable solutions for agricultural resilience and environmental remediation. Microbe-assisted phytonanoparticles (MAPNPs), synthesized through the synergistic action of plant metabolites and beneficial microorganisms, represent eco-friendly nanomaterials with dual applications in crop protection and environmental detoxification. MAPNPs exhibit catalytic, antimicrobial, and plant growth-promoting properties, enabling the degradation of persistent pollutants such as dyes, heavy metals, and agrochemical residues while providing biocontrol against phytopathogens. Their biosynthesis involves secondary metabolites, microbial enzymes, and phytochemicals that contribute to nanoparticle formation, stabilization, and functionalization. Mechanistically, MAPNPs act through reactive oxygen species (ROS) generation, microbial membrane disruption, and redox modulation, while their association with plant growth-promoting rhizobacteria (PGPR) can enhance plant immunity, nutrient uptake, and abiotic stress tolerance. Applications through seed priming, foliar spraying, and soil integration have demonstrated high pollutant degradation and disease reduction, while integration with biopesticides, smart delivery systems, and nanofertilizers supports precision agriculture with reduced environmental impact. Despite their potential, challenges including nanoparticle stability, biosafety, environmental risks, and limited field-scale validation remain. Overall, MAPNPs offer a promising next-generation approach linking microbiology, nanoscience, and plant pathology for sustainable agriculture and environmental restoration.

Keywords : Microbe-Assisted Phytonanoparticles (MAPNPs); Nanotechnology; Green Nanotechnology; Sustainable Agriculture; Environmental Detoxification; Phytopathogen Control; PGPR; Nanofertilizers.

Background & Context :

The manipulation and use of materials at the nanoscale (1–100 nm) is known as nanotechnology, and it has become a revolutionary force in a variety of fields, including electronics, health, energy, catalysis, and agriculture. Since Richard P. Feynman first proposed the idea in 1959, nanotechnology has developed to transform material science because to the special physicochemical characteristics that nanoparticles (NPs) confer, such increased surface

area, quantum effects, and catalytic potential [18,23].

Nanotechnology has enormous potential in agriculture to improve soil health, increase crop productivity, and reduce biotic and abiotic stressors. The use of nanomaterials in plant systems, or phytonanotechnology, has become more popular because it can enhance germination, nutrient delivery, plant resilience, and stress tolerance [11,21].

By acting as nanofertilizers, nanosensors, nanopesticides, and nano-remediators, nanoparticles promote precision farming and lessen their impact on the environment [10,24].

Growing food demand (which is expected to increase by 70% by 2050), rising crop losses from plant diseases (10–40%), and declining soil and water health as a result of excessive use of agrochemicals are some of the many issues facing global agriculture at the same time [6,12,29]. By improving the effectiveness of disease management tools and facilitating the ecologically safe remediation of contaminants such heavy metals, pesticide residues, and industrial wastes, nanotechnology offers a fresh platform for tackling these issues [4,14,28].

Because of their strong antibacterial, catalytic, and detoxifying properties, metallic and metal oxide nanoparticles—especially silver (AgNPs), gold (AuNPs), and zinc oxide (ZnONPs)—are being investigated extensively among nanomaterials [1,17].

However, conventional synthesis techniques need a lot of energy and hazardous chemicals. Green synthesis, which uses plants, fungus, bacteria, and endophytes to produce nanoparticles in an environmentally benign, economical, and scalable manner, has gained popularity as a sustainable alternative [18,30,33]. In particular, fungal systems are becoming effective "biofactories" under the myconanotechnology concept.

Furthermore, interactions between plants, microbes, and nanoparticles are significantly influenced by the rhizosphere. Nanomaterials can work in concert with beneficial microorganisms like endophytes and plant growth-promoting rhizobacteria (PGPR) to enhance nutrient uptake, activate defense mechanisms, and detoxify heavy metals like cadmium [16,38]. Phytonanoparticles' twin functions of pathogen suppression and environmental detoxification provide a comprehensive, long-term strategy to protect food security and rebuild agroecosystem resilience.

Phytonanotechnology offers a timely, multidisciplinary solution that is compatible with precision farming and green chemistry in light of the increasing environmental challenges, such as eutrophication, resistance development, and biodiversity loss [1,25,37].

The synthesis, processes, and uses of phytonanoparticles are examined in this chapter. Future research prospects in the sustainable integration of nanotechnology into agriculture are highlighted, as is their dual function in environmental cleanup and plant disease suppression.

Defined Problem Statement/Research Gap :

The production and use of nanoparticles (NPs) continue to confront substantial obstacles, despite the quick development of nanotechnology in the agricultural and

environmental fields. Traditionally produced NPs using chemical and physical processes frequently contain hazardous precursors and byproducts, endangering ecosystems, human health, and regulatory approval [18,22,26]. In example, the manufacture of metal nanoparticles using plant extracts and microorganisms, which provide safer, more affordable, and environmentally friendly solutions, has caused a global trend toward greener, biologically mediated alternatives [1,30].

However, little is known about the biosynthesis process itself, especially with regard to the function of certain phytochemicals, microbial enzymes, and the metabolic pathways controlling the creation of nanoparticles [27,33]. Further restricting the industrial use of microbial nanoparticles is their synthesis's lack of standardization, scalability, and repeatability [17].Although medicinal applications have received a lot of attention, phytonanoparticle translation into agro-environmental domains is still in its infancy. There is a significant gap in the use of these biogenic nanoparticles for both (1) the sustained and targeted suppression of phytopathogens and (2) the degradation of persistent organic pollutants (POPs) [10,38]. Furthermore, new research indicates that the toxicity, phytotoxicity, and long-term ecological consequences of nanoparticles are still poorly understood, particularly in actual field settings [4,11,23].

Furthermore, the production and functionalization of nanoparticles by Plant Growth-Promoting Rhizobacteria (PGPR) is a developing field. The efficacy of biofertilizers might be revolutionized by nano-enabled PGPR or their encapsulated versions, but little is known about their processes, destiny in soil conditions, and large-scale applications [6,37]. Therefore, the development of a complete, scalable, and biologically safe platform that takes advantage of the dual functionality of microbe-assisted phytonanoparticles for plant disease management and environmental detoxification is urgently needed. The knowledge gaps can be filled and the eco-safe nano-interventions required for future agricultural and environmental sustainability can be sparked by a critical, cohesive understanding of this developing confluence [14,21,29].

Objectives of the Chapter :

The goal of this chapter is to present a thorough and critical synthesis of the most recent developments in the field of microbe-assisted phytonanoparticles (PNPs), highlighting their dual role as biocontrol agents in plant disease suppression and environmentally friendly catalysts for the breakdown of persistent organic pollutants (POPs).

The chapter's specific goals are to:

1. Use microbial and plant-based systems to investigate the biosynthesis processes of phytonanoparticles, with an emphasis on the function of secondary metabolites, microbial enzymes, and bioactive phytochemicals in nanoparticle creation [18,26,27].
2. Describe the structural, physicochemical, and functional characteristics of green-synthesised nanoparticles and how they interact with phytopathogens and contaminants [7,23].
3. Draw attention to the use of phytonanoparticles as catalytic agents in environmental remediation, especially in the breakdown of dangerous POPs in soil and water systems

[14,32].

4. Examine the dual function of phytonanoparticles as nano-enabled carriers of beneficial microorganisms and bioactive chemicals, as well as their involvement in boosting plant immunity against phytopathogens and stimulating plant development [21,29,31].
5. Examine how PGPR and nanotechnology work together, paying particular attention to the encapsulation, effective distribution, and increased stress tolerance that crops receive from nanoformulated PGPR [6,37,38].
6. Discuss important issues and constraints, including biosafety, ecological concerns, nanoparticle toxicity, field-level validation, and the scalability of microbial nanoparticle manufacturing systems [4,11,17].
7. Describe prospects for the sustainable commercialization and regulatory alignment of phytonanoparticles in agro-environmental applications, together with a suggested pathway [22, 24].

This chapter aims to provide a multidisciplinary framework for creating safe, efficient, and scalable green nano-interventions for ecosystem restoration and sustainable agriculture by combining knowledge from nanotechnology, microbiology, plant pathology, and environmental sciences.

Brief Mention of the Chapter's Structure :

An integrated grasp of the biosynthesis, multifunctional uses, processes, and future possibilities of microbe-assisted phytonanoparticles (PNPs) is provided by this methodically organized chapter. The chapter starts with a summary of the scientific underpinnings and historical evolution of phytonanotechnology before delving deeply into green synthesis pathways and highlighting the role of microbial and plant-based systems in the environmentally safe production of nanoparticles [22,26,32]. Following a comparative analysis of nanomaterial characterization methods and their impact on physicochemical properties like shape, size, and stability, subsequent sections examine the biochemical mechanisms involved in nanoparticle biosynthesis, emphasizing the contributions of phenolics, flavonoids, proteins, and microbial enzymes [7,10,23].

The dual-action feature of PNPs takes up a large amount of the chapter:

1. Environmental detoxification, which includes wastewater treatment applications, heavy metal remediation, and the breakdown of persistent organic pollutants (POPs) [11,14,17]; and
2. Agricultural disease control, where PNPs function as biofertilizers, smart delivery systems for antimicrobial chemicals, or boost host plant resistance to phytopathogens such as Alternaria, Curvularia, and Fusarium spp. [29,31,37].

A thorough evaluation of nanotoxicology, regulatory issues, and biocompatibility hazards follows the chapter's discussion of nanoparticle-plant-microbe interactions, with a focus on rhizosphere dynamics, PGPR synergy, biofortification, and stress reduction [8,16,38]. In order to close the gap between lab research and practical agricultural and environmental applications, the last part offers a critical summary of existing knowledge gaps, difficulties in field-scale translation, and upcoming trends in phytonanobiotechnology [21,25,28].

Research Hub International Journal

Background and Literature Review :

The development of nanotechnology has shifted from traditional physical and chemical synthesis methods, which are frequently linked to hazardous byproducts and high energy requirements, to green and bio-based synthesis approaches that provide affordable, sustainable, and environmentally friendly substitutes [1,26,32]. Because of their biocompatibility, high surface-to-volume ratio, redox activity, and low environmental impact, phytonanoparticles (PNPs) made from plant-derived metabolites and microbial agents have drawn a lot of interest [8,18,23].

Biological organisms including bacteria, fungus, algae, and higher plants serve as reducing and capping agents for the creation of nanoparticles in the groundbreaking concept of "green nanotechnology," which is based on the concepts of green chemistry and biotechnology [27, 35]. In this biotransformation process, biological substances such as proteins, sugars, terpenoids, phenolics, and flavonoids play a crucial role in guaranteeing the functioning, stability, and tunability of metallic nanoparticles [10]. For instance, plant extracts and microbial cultures have been used to create silver, gold, copper, and zinc oxide nanoparticles without the use of dangerous chemicals [5,26].

The origins of nanotechnology may be traced back to ancient societies who used metallic gold and silver in Chinese and Ayurvedic medicine [17]. Feynman's groundbreaking 1959 speech "There's Plenty of Room at the Bottom" was the catalyst for the current revival. Since then, nanoparticles have transformed a number of fields, including materials chemistry, biomedical engineering, agriculture, and environmental research [7,18,33]. Notably, plant diseases that cause significant crop losses, such Fusarium oxysporum, Curvularia lunata, and Alternaria alternata, may now be addressed using nano-enabled antimicrobial agent delivery or by nanoformulated PGPR consortia [29, 30].

In addition to breaking down persistent organic pollutants (POPs) in soil and water, such as dyes, hydrocarbons, and heavy metals, phytonanoparticles can alter plant-microbe interactions, stimulating growth and triggering host immunological responses [14,16,38]. Microbial consortia increase the effectiveness of plants like Brassica juncea and Thlaspi caerulescens in phytoextraction and heavy metal detoxification through synergistic interaction in the rhizosphere [9,18,37].

Root exudates, PGPR, and phytonanoparticles interact at the soil-rhizosphere interface to control pathogen suppression, metal immobilization, and nutrient cycling [4,16,20]. A robust agroecosystem with enhanced crop productivity, soil health, and environmental sustainability is fostered by this integration [24, 28, 31].

There are still difficulties in spite of these developments. Further study is necessary to address issues including nanoparticle toxicity, uneven performance in field circumstances, variability in biosynthetic procedures, and regulatory constraints [8,11,22]. However, next-generation nanobioformulations with enormous potential for sustainable agriculture and environmental detoxification are made possible by the confluence of microbial biotechnology, nanoscience, and phytopathology [21, 25].

Research Hub International Journal

Methodology/Strategy :

There was no fresh experimental work done because this was a thorough review-based chapter. The approach, however, is based on a thorough synthesis and critical assessment of peer-reviewed literature that covers biosynthetic pathways, synthesis methods, mechanistic investigations, and application trials of microbe-assisted phytonanoparticles (PNPs) in agricultural and environmental contexts [18,23,26,32].

This chapter organizes the body of available literature according to five major methodological issues in order to take a methodical analytical approach:

1. Synthesis Techniques :

The chapter compares bottom-up (like green biogenic synthesis) and top-down (like milling and lithography) methods for creating nanoparticles [7,23].

Eco-friendly biosynthesis pathways, such as using plant extracts, bacterial and fungal strains, algae, agricultural waste, and actinomycetes as reducing and capping agents, are given particular attention [8,10,17].

Intracellular and extracellular processes involving important biomolecules such phenolics, terpenoids, flavonoids, secondary metabolites, and enzymes (like NADH-dependent reductases) are used to describe microbial production [20].

2. Methods of Characterization (from Reviewed Studies) :

UV-Vis spectroscopy, FTIR, XRD, SEM/TEM, AFM, and dynamic light scattering (DLS) are analytical techniques used in various investigations to determine the size, shape, crystallinity, surface charge, and stability of nanoparticles [1,15,26].

3. Methods of Application :

Seed priming, foliar spraying, soil incorporation, and nano-encapsulation of PGPR strains—all intended to inhibit phytopathogens or improve crop stress tolerance—are among the agricultural application techniques obtained from current investigations [11,37,38].

Based on case studies from the literature and laboratory data, environmental applications such phyto-nano-remediation of pollutants, removal of heavy metals and dyes, and biosorption of toxicants are described [14,28,32].

4. Criteria for Data Compilation and Inclusion :

High-impact peer-reviewed articles from Elsevier, Springer, PubMed, ScienceDirect,

Google Scholar, and Nanomaterials journal databases, with an emphasis on the years 2012–2024, are among the data sources [13,35].

The critical review approach only included publications that reported on biological

Research Hub International Journal

synthesis, green synthesis, agro-environmental applications, or mechanistic insights into nanoparticle activity.

5. Interpretations of Mechanisms :

Reviewed experiments are used to investigate mechanisms of action for detoxification (such as oxidative stress regulation and metal chelation) and plant disease suppression (such as cell wall breakdown, enzyme inhibition, and ROS production) [4,29,31].

Furthermore, a rigorous evaluation has been conducted on the synergistic role of PGPR with nanoparticles, which includes improved root colonization, biofilm development, and induced systemic resistance (ISR) in plants [6,20,24].

Readers may follow the evolution of microbe-assisted phytonanoparticles from lab-scale synthesis to field-scale application using this methodical and empirically supported approach, laying the foundation for further experimental and translational research.

Results and Discussion :

1. Microbe-Assisted Phytonanoparticles' (MAPNPs) Potential for Remediation :

Recent research highlights the remarkable potential of phytonanoparticles produced by microbial and plant-based processes to remove heavy metals, hydrocarbons, and persistent organic pollutants (POPs) from the environment. Nanomaterials (NMs) based on cellulose and chitosan have been found to be efficient adsorbents for heavy metals and dyes, and because of their huge surface area and porosity, nanocellulose aerogels have demonstrated effectiveness in oil spill cleaning [7,14]. After remediation, magnetic nanoparticles make recovery and separation simple [8].

Using microbial and botanical extracts like Datura metel and Capsicum chinense, green-synthesised AgNPs and CuNPs have shown >90% pollutant degradation and notable antibacterial action [7,18]. For example, within an hour, MAPNPs made from Vitis rotundifolia showed 98% degrading efficiency [14].

2. Antimicrobial and Catalytic Action :

Because of their diverse morphologies and strong surface reactivity, silver nanoparticles (AgNPs) have demonstrated better catalytic effectiveness among metallic NPs [26]. High antibacterial and catalytic activity are also demonstrated by biosynthesized Ag/Fe3O4 composites and fungal-synthesized NPs (e.g., Fusarium spp.) [30,32].

Mechanistically, these NPs cause cell lysis by disrupting microbial membranes, generating reactive oxygen species (ROS), and promoting electron transfer [17,33]. Proteins, terpenoids, and flavonoids were shown to be functional biomolecules that capped and stabilized the NP surfaces during synthesis, according to FTIR and TEM analyzes [1].

3. Dual Function in Agriculture: Growth Promotion and Disease Prevention :

Research Hub International Journal

MAPNPs function as biopesticides and nano-biofertilizers in addition to detoxifying surroundings. AgNPs and ZnONPs have considerably lessened the severity of diseases caused by pathogens such as Penicillium, Ralstonia, and Fusarium [5,29]. ZnONPs prevented P. expansum from developing conidiophores, whereas Ag-Cu-TiO_2 NPs together reduced many plant diseases [29].

While reducing lipid peroxidation, foliar treatments of AuNPs and SeNPs enhanced nitrogen metabolism, antioxidant responses, and seed quality [10,11]. However, the significance of dose optimization is highlighted by phytotoxic effects at greater NP concentrations [21].

4. PGPR and Soil Health Restoration :

Working Together Plant growth-promoting rhizobacteria (PGPRs) including Azotobacter, Pseudomonas, and Bacillus have been demonstrated to work in concert with MAPNPs to improve soil enzymatic activity, lower oxidative stress, and increase crop yields [37, 38].

While NPs improve nutritional bioavailability and stress tolerance, PGPRs contribute through IAA generation, siderophore release, and enzyme synthesis [6,9].

For example, MAPNPs produced from Streptomyces suppressed infections such as Aspergillus and Penicillium and increased wheat growth by 33% [20]. Additionally, ZnO and CuO NPs produced by microbiological means had strong antibacterial activity and encouraged the development of advantageous biofilms.

5. Evaluation of Conventional Technologies :

MAPNPs provide improved efficiency, tailored distribution, and less environmental impact as compared to traditional cleanup and fertilizing techniques. While ensuring steady nutrient release, nano-enabled delivery methods minimize pesticide runoff and fertilizer loss [24, 28]. Under both biotic and abiotic stress situations, improved nutrient usage efficiency (NUE) and yield improvements have been demonstrated by nano-fertilizers such as nano-ZnO and nano-Fe [21].

However, restrictions such biosafety issues, regulatory loopholes, and nanoparticle aggregation continue to be crucial [31]. It is necessary to look into their long-term effects on the ecosystem further.

Graphical Concept :

Research Hub International Journal

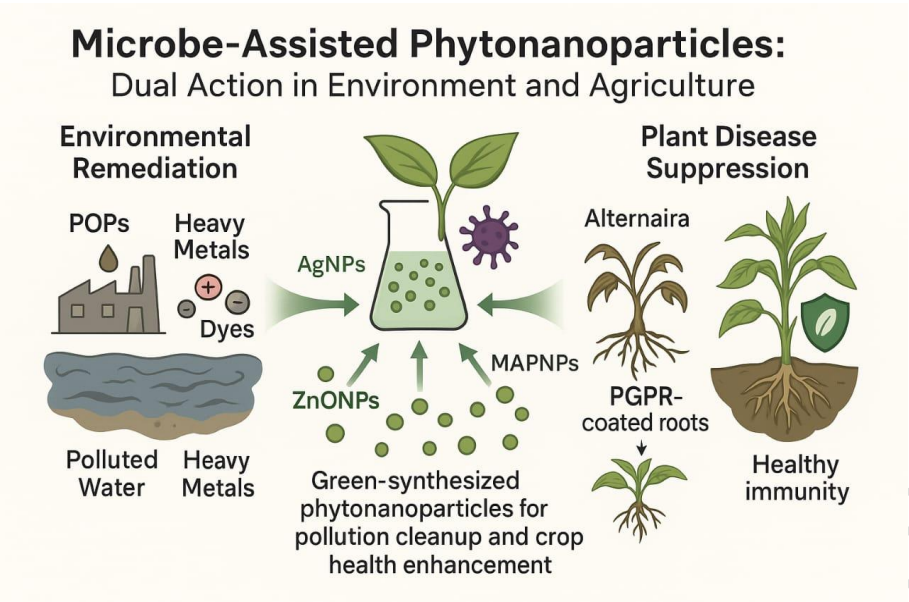


Figure : Green-synthesized phytonanoparticles for pollution cleanup and crop health enhancement

Visual Elements:

Left Side (Environmental Remediation):

Polluted water/soil with labels: "POPs", "Heavy Metals", "Dyes"

Arrows pointing to green-synthesized nanoparticles degrading these pollutants

Nanoparticles labeled with "AgNPs", "ZnONPs", etc.

Icons: oil drop, factory discharge, metal ions

Right Side (Plant Disease Suppression):

Crops affected by pathogens (Fusarium, Alternaria) → treated with MAPNPs

Visual of PGPR-coated roots + NPs boosting plant growth

Healthy plants showing higher yield & immunity (icon: shield + leaf)

Center (Synthesis Core):

Beaker showing plant leaf + microbe → forming nanoparticles (green dots)

Arrows radiating out to both sides (showing dual action)

Conclusion from Discussion :

Microbe-assisted phytonanoparticles are a sustainable and versatile solution to two problems: managing plant diseases and detoxifying the environment. Their dual-action mechanisms, green synthesis, and compatibility with bioinoculants such as PGPRs make them essential instruments in remediation sciences and sustainable agriculture. To guaranty effectiveness without sacrificing the environment, field-scale deployment must be controlled

by strict safety, dose calibration, and regulatory compliance.

Applications and Case Studies :

Phytonanoparticles produced by microbial and plant-assisted processes have become multipurpose agents with a wide range of uses in industry, agriculture, medicine, and environmental cleanup. The case studies that follow demonstrate the various uses and actual success stories of these nanomaterials:

1. Detoxification of the Environment :

Degradation of Pollutants and Dyes :

Under UV-visible light, biosynthesized silver nanoparticles (AgNPs) produced from Ulva lactuca, Azadirachta indica, and Zanthoxylum armatum effectively degraded methyl orange and other azo dyes, attaining >85% decolorization effectiveness [10,32]. Similarly, in just 20 minutes, 94.5% of methylene blue was broken down by neem-based phytonanoparticles [14].

Adsorption of Heavy Metals :

While fungal nanoparticles promoted the biosorption of lead and cadmium ions from contaminated soils, silver nanoparticles produced from Piliostigma thonningii demonstrated notable heavy metal adsorption in simulated wastewater [14,16].

Catalysis in the Transformation of Organic Pollutants Ag/α-Al_2O_3 nanocatalysts showed strong catalytic activity in ethylene epoxidation, and biosynthesized Ag–Au NPs degraded malachite green dye by more than 90% [26].

Insecticidal and Antiviral Applications :

Silica nanoparticles achieved 100% mortality against stored grain pests [24], while Bacillus-synthesized AgNPs were found effective against Bean Yellow Mosaic Virus (Case Study 1).

2. Suppression of Plant Diseases :

Antibacterial and Antifungal Properties :

While ZnO and TiO_2 nanoparticles made with lemon extract prevented Dickeya dadantii, the cause of sweet potato root rot, mycosynthesized AgNPs from Curvularia species inhibited plant pathogenic fungus (Ali et al., 2020). Additionally, AgNPs made from Fusarium solani shown broad-spectrum antibiotic activity against Staphylococcus aureus, Candida, and Cryptococcus [30].

Management of Fusarium Wilt :

While Pseudomonas fluorescens and Sinorhizobium fredii with chitinase activity were

linked to the biocontrol of Fusarium udum [37], AgNPs successfully suppressed Fusarium wilt in chickpeas [31].

3. Improvement of Agriculture :

Soil Health and Nanofertilizers While foliar application of Zn and Fe nanofertilizers enhanced the yield of Cicer arietinum by 34% [6], phosphatic nanofertilizers boosted the yield of soybean seeds by 20% [33]. In dry circumstances, Pseudomonas taiwanensis and nano-gypsum increased soil microbial diversity and nutrient availability [6].

Priming Seeds and Promoting Growth :

Carbon nanotube (CNT) and copper nanoparticles boosted seedling vigor; tomato plants treated with CNTs had twice as many flowers and fruits as controls [11,24].

Stress Tolerance in Abiotic Environments :

CuNPs seed priming increased drought tolerance in maize [11], whereas Azospirillum lipoferum and Bacillus coagulans in conjunction with ZnO-NPs reduced salt stress in wheat by boosting antioxidative enzymes [38].

4. Applications in Food and Medicine :

Food Preservation & Packaging :

To improve antibacterial qualities and shelf life, ZnO-NPs have been used into biodegradable packaging materials. Fruit preservation after harvest has also made use of bioactive-loaded nanoemulsions and nanoliposomes [21].

Potential in Biomedicine :

Phytonanoparticles had cytotoxic effects against HeLa cell lines (ICβ₀: 15–50 µg/mL), suggesting that they might be used as cancer treatments [35]. Gold and silver nanoparticles have been employed as antibacterial agents in wound dressings, for medication administration, and for imaging [18].

5. Sophisticated Intelligent Applications :

Biosensors and Nanosensors :

Integrated into spinach leaves, functionalized carbon nanotubes served as environmental toxin autosamplers (Li & Yan, 2020). The big cardamom chirke virus may be seen with the unaided eye thanks to lateral flow immunoassays utilizing gold nanoparticles [29].

Light-Induced Catalysis and Photothermal Therapy :

Gold nanoparticles facilitated the photodegradation of contaminants and transformed

Research Hub International Journal

absorbed light into localized heat for photothermal cancer treatment [23].

Conclusion from the Case Studies :

The transforming potential of microbe-assisted phytonanoparticles is illustrated by these case studies. They are positioned as next-generation green catalysts and sustainable solutions for addressing global issues in agriculture, health, and pollution management because of their dual activity, which targets environmental detoxification and suppresses phytopathogens.

Challenges and Future Directions :

Current Challenges :

A number of significant obstacles prevent the widespread use of microbe-assisted phytonanoparticles (MAPNPs), despite their remarkable dual-action potential in both environmental detoxification and plant disease suppression:

1. Ecological Hazards and Toxicological Uncertainties :

Even though MAPNPs are thought to be environmentally favorable, toxicity is still a big worry. The soil microbiota, aquatic ecosystems, and even human health may be at danger due to their tiny size, high reactivity, and capacity to bioaccumulate [4,18,30]. Detailed risk evaluations are necessary for interactions with non-target species, especially in rhizospheres and aquatic bodies [5,23].

2. Insufficient Field-Scale Information :

The majority of results are limited to greenhouse or laboratory environments. In a variety of agroclimatic settings, field experiments are rare and frequently lack replication [6,31,38]. This makes it more difficult to convert encouraging lab-scale results into scalable environmental or agricultural solutions.

3. Stability, Aggregation & Delivery Challenges :

Difficulties with Stability, Aggregation, and Delivery Consistency and effectiveness are impacted by stability problems such aggregation, fast oxidation, and uneven nanoparticle dispersion [18,26]. Furthermore, their functional accuracy is limited by the absence of regulated delivery methods designed for particular plant species or soil conditions [16,24].

4. Gaps in Standardization, Regulation, and Commercialization :

Standardized procedures for the biosynthesis, characterization, and use of MAPNPs are conspicuously lacking. Furthermore, there is no agreement on acceptable levels, safety testing, and labeling because regulatory frameworks are still developing [7,32,33]. Despite clear promise, these deficiencies make commercialization challenging [9].

Research Hub International Journal

5. Biosynthesis's Biological Complexity :

Because of extract complexity and biological heterogeneity, it is still difficult to identify and isolate the specific microbial enzymes or phytochemicals involved in nanoparticle reduction and stabilization [27, 37]. Compared to chemical synthesis, microbial synthesis frequently has slower kinetics and batch-to-batch variability [8].

6. Lack of Information on the Long-Term Environmental Future :

Insufficient research has been done on the long-term persistence, degradation behavior, and post-application consequences of MAPNPs in soil and aquatic settings [14,28]. This makes it more difficult to use risk mitigation techniques for secondary pollution, phytotoxicity, or bioaccumulation.

Future Directions :

Future research must be diverse and integrative, concentrating on the following areas in order to fully realize the promise of MAPNPs:

1. Agro-Waste-Based Green and Sustainable Synthesis :

Using endophytes and biomass from agricultural waste as precursors for the production of nanoparticles might save costs and increase sustainability [10,22]. This is consistent with the ideas of the circular bioeconomy.

2. AI-Powered Monitoring and Field-Level Validation :

Actionable information on NP efficacy, crop response, and environmental safety may be obtained by multi-location experiments and real-time monitoring with AI-integrated nanosensors [25,31]. This combination will be extremely beneficial to precision agriculture.

3. Adaptable and Focused Delivery Systems :

Enhancing bioavailability and reducing environmental impact might be achieved by developing nanoparticle formulations encapsulated in biopolymers or chitosan for crop-specific targeting and controlled release [5,21].

4. Metabolomics and Omics-Assisted Mechanistic Understanding :

Pathways controlling disease resistance and detoxification can be uncovered using genomic, transcriptomic, and metabolomic characterization of microbial strains and plant responses to MAPNPs [16,20,36]. This may aid in the creation of nanobiostimulants in the future.

5. Models for Risk Assessment and Regulatory Changes :

There is an immediate need for a consistent worldwide framework for assessing

Research Hub International Journal

MAPNP hazards, including microbiological toxicity, fate analysis, and dose-response modeling [8,17]. As technology develops, these models must also be updated.

6. Public Awareness and Multidisciplinary Cooperation :

To get MAPNPs from the bench to the field, communication across microbiology, nanotechnology, environmental science, and politics is essential. Programs for stakeholder participation and awareness must clarify the role of nanotechnology in environmental and food security [26, 29].

By resolving these issues and making calculated investments in the suggested future paths, MAPNPs have the potential to become revolutionary instruments in environmental management and sustainable agriculture, fusing nanotechnological accuracy with ecological safety.

Conclusion :

A potent fusion of green chemistry, microbiology, and nanotechnology, microbe-assisted phytonanoparticles (MAPNPs) provide a sustainable, dual-action approach to plant disease suppression and environmental detoxification. In terms of pollutant degradation, biocontrol activity, and catalytic potential, these phytonanoparticles, which are biosynthesized utilizing plant extracts and microbial enzymes, are not only safe for the environment but frequently just as effective as their chemically produced counterparts [1,10,26].

Because of their intrinsic bioactivity, nanoscale size, and large surface area, MAPNPs have a unique multifunctionality that allows for applications ranging from heavy metal immobilization to pathogen inactivation and crop growth stimulation [16,20,38]. They have great potential to reduce synthetic chemical inputs, improve nutrient usage efficiency, and increase resistance against biotic and abiotic challenges through their synergistic interaction with PGPR, rhizospheric microorganisms, and host plants [6,25,37].

However, care and critical analysis are essential in addition to their promise. Prior to commercialization, a thorough understanding of MAPNPs' toxicological behavior, long-term environmental destiny, and biosafety is required. Field-level validation, mechanistic research, and the creation of international regulatory frameworks are required to address problems such as nanoparticle accumulation in soil and water, disturbance of native microbial communities, and variability in bioactivity [11,18,30].

Bio-based NMs must go through stringent risk assessments, standardization procedures, and eco-toxicological evaluations before being widely used in agriculture, as several studies have shown [8,23,32]. For optimal effectiveness, the mechanism of nanoparticle distribution, formulation stability, and compatibility with native soil-plant systems must also be precisely tailored [5,24,29].

In the future, MAPNPs will be integrated with AI-driven diagnostics, smart delivery platforms, and precision agriculture to enable site-specific intervention with minimal ecological impact [21,31]. The creation of tailored, crop-specific, and scalable formulations

Research Hub International Journal

may be made easier by developments in metabolomics, enzyme profiling, and biogenic nanofabrication [27, 36].

Essentially, MAPNPs are now catalysts of the now rather than a notion of the future. These nanoscale bio-tools have the potential to revolutionize sustainable agriculture and environmental remediation through multidisciplinary cooperation, strict safety inspections, and eco-innovative approaches. In order to guarantee that MAPNPs become a staple in the worldwide pursuit of sustainability and food security, the route forward necessitates striking a balance between scientific innovation, ecological responsibility, and regulatory monitoring [17,22,35].

References :

- Ahmed, S., Saifullah, Ahmad, M., Swami, B. L., & Ikram, S. (2016). Green synthesis of silver nanoparticles using Azadirachta indica aqueous leaf extract. Journal of Radiation Research and Applied Sciences, 9(1), 1–7. https://doi.org/10.1016/j.jrras.2015.06.006
- Abdel-Aziz, S.M., Prasad, R., Hamed, A.A. and Abdelraof, M., 2018. Fungal nanoparticles: A novel tool for a green biotechnology? In: R. Prasad, ed. Fungal Nanobionics: Principles and Applications. Singapore: Springer, pp.61–83. https://doi.org/10.1007/978-981-10-8666-3_3
- Amini, S.M. (2019) 'Preparation of antimicrobial metallic nanoparticles with bioactive compounds', Materials Science & Engineering C, vol. 103, pp. 109809. doi: 10.1016/j.msec.2019.109809
- Ahmed, B., Ameen, F., Rizvi, A., Ali, K., Sonbol, H., Zaidi, A., Khan, M. S., & Musarrat, J. (2020). Destruction of cell topography, morphology, membrane, inhibition of respiration, biofilm formation, and bioactive molecule production by nanoparticles of Ag, ZnO, CuO, TiO_2, and Al_2O_3 toward beneficial soil bacteria. ACS Omega, 5(14), 7861–7876. https://doi.org/10.1021/acsomega.9b04084
- Ali, M.A., Ahmed, T., Wu, W., Hossain, A., Hafeez, R., Masum, M.M.I., Wang, Y., An, Q., Sun, G., & Li, B. (2020). Advancements in Plant and Microbe-Based Synthesis of Metallic Nanoparticles and Their Antimicrobial Activity against Plant Pathogens. Nanomaterials, 10(6), 1146. https://doi.org/10.3390/nano10061146
- Akhtar, N., Ilyas, N., Meraj, T. A., Pour-Aboughadareh, A., Sayyed, R. Z., Mashwani, Z.-u.-R., & Poczai, P. (2022). Improvement of plant responses by nanobiofertilizer: A step towards sustainable agriculture. Nanomaterials, 12(6), 965. https://doi.org/10.3390/nano12060965
- Alsaiari, N. S., Alzahrani, F. M., Amari, A., Osman, H., Harharah, H. N., Elboughdiri, N., & Tahoon, M. A. (2023). Plant and microbial approaches as green methods for the synthesis of nanomaterials: Synthesis, applications, and future perspectives. Molecules, 28(1), 463. https://doi.org/10.3390/molecules28010463
- Ahmed, T., Luo, J., Noman, M., Ijaz, M., Wang, X., Masood, H. A., Manzoor, N., Wang, Y., & Li, B. (2023). Microbe-mediated nanoparticle intervention for the management of plant diseases. Crop Health, 1(3). https://doi.org/10.1007/s44297-023-00006-9

Research Hub International Journal

- Basu, A., Prasad, P., Das, S. N., Kalam, S., Sayyed, R. Z., Reddy, M. S., & El Enshasy, H. (2021). Plant Growth Promoting Rhizobacteria (PGPR) as Green Bioinoculants: Recent Developments, Constraints, and Prospects. Sustainability, 13(3), 1140. https://doi.org/10.3390/su13031140
- Bhandari, G., Dhasmana, A., Chaudhary, P., Gupta, S., Gangola, S., Gupta, A., Rustagi, S., Shende, S.S., Rajput, V.D., Minkina, T., et al. (2023). A Perspective Review on Green Nanotechnology in Agro-Ecosystems: Opportunities for Sustainable Agricultural Practices & Environmental Remediation. Agriculture, 13(3), 668. https://doi.org/10.3390/agriculture13030668
- Balusamy, S. R., Joshi, A. S., Perumalsamy, H., Mijakovic, I., & Singh, P. (2023). Advancing sustainable agriculture: A critical review of smart and eco-friendly nanomaterial applications. Journal of Nanobiotechnology, 21, 372. https://doi.org/10.1186/s12951-023-02135-3
- Elemike, E.E., Uzoh, I.M., Onwudiwe, D.C. and Babalola, O.O., 2019. The role of nanotechnology in the fortification of plant nutrients and improvement of crop production. Applied Sciences, 9(3), p.499. https://doi.org/10.3390/app9030499
- Grasso, G., Zane, D. and Dragone, R., 2020. Microbial nanotechnology: Challenges and prospects for green biocatalytic synthesis of nanoscale materials for sensoristic and biomedical applications. Nanomaterials, 10(1), p.11. [online] Available at: https://doi.org/10.3390/nano10010011
- Gole, A., John, D., Krishnamoorthy, K., Wagh, N. S., Lakkakula, J., Khan, M. S., Odeibat, H. A. M., Tarique, M., & Islam, M. R. (2022). Role of Phytonanotechnology in the Removal of Water Contamination. Journal of Nanomaterials, 2022, Article ID 7957007, 19 pages. https://doi.org/10.1155/2022/7957007
- Hassan, S. E.-D., Salem, S. S., Fouda, A., Awad, M. A., El-Gamal, M. S., & Abdo, A. M. (2018). New approach for antimicrobial activity and bio-control of various pathogens by biosynthesized copper nanoparticles using endophytic actinomycetes. Journal of Radiation Research and Applied Sciences, 1–9. https://doi.org/10.1016/j.jrras.2018.05.003
- Halim, M. A., Rahman, M. M., Megharaj, M., & Naidu, R. (2020). Cadmium Immobilization in the Rhizosphere and Plant Cellular Detoxification: Role of Plant-Growth-Promoting Rhizobacteria as a Sustainable Solution. Journal of Agricultural and Food Chemistry. https://doi.org/10.1021/acs.jafc.0c04579
- Harish, V., Tewari, D., Gaur, M., Yadav, A.B., Swaroop, S., Bechelany, M., & Barhoum, A. (2022). Review on Nanoparticles and Nanostructured Materials: Bioimaging, Biosensing, Drug Delivery, Tissue Engineering, Antimicrobial, and Agro-Food Applications. Nanomaterials, 12(3), 457. https://doi.org/10.3390/nano12030457
- Iravani, S. (2011). Green synthesis of metal nanoparticles using plants. Green Chemistry, 13(10), 2638–2650. https://doi.org/10.1039/c1gc15386b
- Jasim, B., Jimtha, C. J., Jyothis, M., & Radhakrishnan, E. K. (2013). Plant growth promoting potential of endophytic bacteria isolated from Piper nigrum. Plant Growth Regulation. https://doi.org/10.1007/s10725-013-9802-y
- Jog, R., Pandya, M., Nareshkumar, G., & Rajkumar, S. (2014). Mechanism of phosphate solubilization and antifungal activity of Streptomyces spp. isolated from wheat roots and rhizosphere and their application in improving plant growth.

Research Hub International Journal

Microbiology, 160(4), 778–788. https://doi.org/10.1099/mic.0.074146-0

- Jiang, M., Song, Y., Kanwar, M. K., Ahammed, G. J., Shao, S., & Zhou, J. (2021). Phytonanotechnology applications in modern agriculture. Journal of Nanobiotechnology, 19(1), 430. https://doi.org/10.1186/s12951-021-01176-w
- Kharissova, O. V., Kharisov, B. I., Oliva González, C. M., Méndez, Y. P., & López, I. (2019). Greener synthesis of chemical compounds and materials. Royal Society Open Science, 6(11), 191378. https://doi.org/10.1098/rsos.191378
- Khan, I., Saeed, K., & Khan, I. (2019). Nanoparticles: Properties, applications and toxicities. Arabian Journal of Chemistry, 12(7), 908–931. https://doi.org/10.1016/j.arabjc.2017.05.011
- Kumari, R., Suman, K., Karmakar, S., Mishra, V., Lakra, S. G., Saurav, G. K., & Mahto, B. K. (2023). Regulation and safety measures for nanotechnology-based agri-products. Frontiers in Genome Editing, 5, 1200987. https://doi.org/10.3389/fgeed.2023.1200987
- Li, C., & Yan, B. (2020). Opportunities and challenges of phyto-nanotechnology. Environmental Science: Nano. Royal Society of Chemistry. https://doi.org/10.1039/d0en00729c
- Nasrollahzadeh, M., Mahmoudi-Gom Yek, S., Motahharifar, N., & Ghafori Gorab, M. (2019). Recent Developments in the Plant-Mediated Green Synthesis of Ag-Based Nanoparticles for Environmental and Catalytic Applications. The Chemical Record, 19(1), pp.1–45. doi:10.1002/tcr.201800202
- Ovais, M. et al. (2018). Role of plant phytochemicals and microbial enzymes in biosynthesis of metallic nanoparticles. Applied Microbiology and Biotechnology, https://doi.org/10.1007/s00253-018-9146-7
- Prakash, P., & Chandran, S. S. (2023). Nano-Phytoremediation of Heavy Metals from Soil: A Critical Review. Pollutants, 3(3), 360–380. https://doi.org/10.3390/pollutants3030025
- Rajwade, J. M., Chikte, R. G., & Paknikar, K. M. (2020). Nanomaterials: New weapons in a crusade against phytopathogens. Applied Microbiology and Biotechnology, 104, 1433–1446. https://doi.org/10.1007/s00253-019-10334-y
- Rai, M., Bonde, S., Golinska, P., Trzcińska-Wencel, J., Gade, A., Abd-Elsalam, K. A., Shende, S., Gaikwad, S., & Ingle, A. P. (2021). Fusarium as a Novel Fungus for the Synthesis of Nanoparticles: Mechanism and Applications. Journal of Fungi, 7(2), 139. https://doi.org/10.3390/jof7020139
- Ray, M. K., Mishra, A. K., Mohanta, Y. K., Mahanta, S., Chakrabartty, I., Kungwani, N. A., Avula, S. K., Panda, J., & Pudake, R. N. (2023). Nanotechnology as a promising tool against phytopathogens: A futuristic approach to agriculture. Agriculture, 13(9), 1856. https://doi.org/10.3390/agriculture13091856
- Singh, J., Dutta, T., Kim, K.-H., Rawat, M., Samddar, P., & Kumar, P. (2018). 'Green' synthesis of metals and their oxide nanoparticles: applications for environmental remediation. Journal of Nanobiotechnology, 16(1), 84. https://doi.org/10.1186/s12951-018-0408-4
- Salem SS. (2023). A mini review on green nanotechnology and its development in biological effects. Archives of Microbiology, 205:128. https://doi.org/10.1007/s00203-023-03467-2

Research Hub International Journal

- Saraswat, P., Singh, S., Prasad, M., Misra, R., Rajput, V.D. and Ranjan, R., 2023. Applications of bio-based nanomaterials in environment and agriculture: A review on recent progresses. Hybrid Advances, 4, p.100097. [online] Available at: https://doi.org/10.1016/j.hybadv.2023.100097
- Thatyana, M., Dube, N. P., Kemboi, D., Manicum, A.-L. E., Mokgalaka-Fleischmann, N. S., & Tembu, J. V. (2023). Advances in phytonanotechnology: A plant-mediated green synthesis of metal nanoparticles using Phyllanthus plant extracts and their antimicrobial and anticancer applications. Nanomaterials, 13(19), 2616. https://doi.org/10.3390/nano13192616
- Vaidyanathan, R., Kalishwaralal, K., Gopalram, S., & Gurunathan, S. (2009). Nanosilver—The burgeoning therapeutic molecule and its green synthesis. Biotechnology Advances, 27(6), 924–937. https://doi.org/10.1016/j.biotechadv.2009.08.001
- Vejan, P., Abdullah, R., Khadiran, T., Ismail, S., & Boyce, A. N. (2016). Role of Plant Growth Promoting Rhizobacteria in Agricultural Sustainability—A Review. Molecules, 21(5), 573. https://doi.org/10.3390/molecules21050573
- Verma, K. K., Joshi, A., Song, X.-P., Singh, S., Kumari, A., Arora, J., Singh, S. K., Solanki, M. K., Seth, C. S., & Li, Y.-R. (2024). Synergistic interactions of nanoparticles and plant growth promoting rhizobacteria enhancing soil-plant systems: a multigenerational perspective. Frontiers in Plant Science, 15, 1376214. https://doi.org/10.3389/fpls.2024.1376214

Research Hub International Journal