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SOIL-BORNE DISEASES OF MEDICINAL PLANTS: HARNESSING HOST IMMUNITY AND MICROBIOMES FOR INTEGRATED DISEASE MANAGEMENT

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The Hidden Threat Beneath Medicinal Plants

Medicinal plants are increasingly important in healthcare, nutraceuticals, pharmaceuticals, and cosmetics. Their value depends not only on biomass but also on the accumulation of bioactive compounds such as alkaloids, withanolides, saponins, terpenoids, and phenolics. Many of these compounds are stored in roots, rhizomes, and tubers, which soil-borne pathogens attack. A root infection therefore reduces both the harvested yield and the quantity and quality of the raw drug. Soil-borne diseases are especially difficult to manage because pathogens survive for years in soil as chlamydospores, oospores, sclerotia, or in plant debris, and infect roots and the root–crown region well before symptoms appear above ground. By the time wilting or yellowing is noticed, the damage is often irreversible. Key pathogens include *Fusarium*, *Pythium*, *Phytophthora*, *Rhizoctonia*, *Macrophomina*, and *Ralstonia*, together with root-knot nematodes (*Meloidogyne spp.*). These pathogens cause wilt, root rot, collar rot, damping-off, and root-knot disease in crops such as ashwagandha, coleus, isabgol, safed musli, and roselle (Shreedevasena *et al.*, 2025). New threats continue to emerge; for example, *Fusarium proliferatum* was recently reported causing wilt and root rot of roselle in India (Shreedevasena *et al.*, 2026). Chemical fungicides offer limited and short-lived control of these pathogens. They also risk leaving residues in herbal products, a serious concern for export markets and pharmacopoeial quality standards. Continuous cultivation worsens the problem by promoting pathogen buildup and disrupting the soil's biological balance. As pathogens increase, beneficial bacteria, arbuscular mycorrhizal fungi, and antagonists such as *Trichoderma* decline, resulting in rhizosphere dysbiosis and greater disease risk.

Root Exudates and the Development of Rhizosphere Dysbiosis

Medicinal plants continuously release root exudates, including sugars, organic acids, amino acids, phenolic compounds, flavonoids, terpenoids, and other metabolites, which shape the plant's relationship with the soil. These compounds act as both food and signals for rhizosphere microorganisms, determining which microbes are attracted, which multiply, and which are suppressed. Under continuous cropping, some exudates accumulate as allelochemicals or autotoxic substances. Saponins, phenolic acids, and alkaloids from medicinal plants can inhibit root growth, disturb oxidative balance, and alter microbial community structure. This is a major cause of the "replant" or "continuous cropping obstacle" observed in perennial medicinal crops such as ginseng and *Rehmannia* (Quan *et al.*, 2026). Some phenolic acids can even stimulate Fusarium spore germination and growth while suppressing beneficial microbes. This creates a self-reinforcing cycle of chemical buildup, microbial imbalance, pathogen enrichment, and host damage. Disease development therefore results from complex interactions among plant metabolism, soil chemistry, microbial communities, and environmental factors such as temperature, moisture, and soil pH, not just pathogen presence.

Host Immunity as an Internal Plant Defense System

Medicinal plants possess advanced immune mechanisms to recognize and respond to invading microorganisms. Pattern-triggered immunity (PTI) begins when cell-surface pattern-recognition receptors detect conserved microbial molecules such as fungal chitin or bacterial flagellin. This recognition activates calcium influx, reactive oxygen species (ROS) production, MAP kinase cascades, and defense gene expression (Bigeard *et al.*, 2015). Successful pathogens deliver effectors that suppress PTI. In response, effector-triggered immunity (ETI) provides a stronger second layer through intracellular nucleotide-binding leucine-rich repeat (NLR) receptors that detect these effectors or their effects on host cells, often ending in localized cell death that confines the pathogen. These two layers are not independent; they mutually potentiate each other to produce robust resistance (Ngou *et al.*, 2021). ROS are key early defense signals that strengthen cell walls through lignin and callose deposition and activate further defenses, although prolonged oxidative stress can be harmful. Hormone networks then fine-tune the response. Salicylic acid mainly governs systemic acquired resistance against biotrophic pathogens, while jasmonic acid and ethylene regulate defense against necrotrophs and mediate induced systemic resistance (ISR) triggered by beneficial root microbes. Host immunity is closely linked to plant metabolism. Many specialized metabolites that define medicinal quality, such as withanolides and phenolic compounds, also act as antimicrobial defenses and rhizosphere signals. When attacked, plants can change their root exudation to recruit protective microbes, a strategy often described as a "cry for help." The recruited microbiome then primes immunity and helps maintain metabolic balance. Immunity, metabolism, and the rhizosphere microbiome therefore function as an integrated system.

Utilizing the Microbiome for Disease Suppression

The rhizosphere microbiome is a natural first line of defense against soil-borne diseases. Beneficial bacteria and fungi suppress pathogens through several complementary mechanisms. They compete for nutrients, iron (through siderophores), and colonization sites. They produce antimicrobial compounds such as lipopeptides from *Bacillus*, phenazines and 2,4-diacetylphloroglucinol from *Pseudomonas*, and cell-wall-degrading enzymes from *Trichoderma*, which also directly parasitizes pathogenic fungi. They also mobilize nutrients like phosphorus and stimulate plant defenses through ISR. Arbuscular mycorrhizal fungi further improve nutrient and water uptake and can enhance secondary metabolite accumulation. Microbiome composition is strongly influenced by host genotype and geography, and studies in ashwagandha show that disease-suppressive microbial communities differ by genotype and location (Bagul *et al.*, 2026). Current strategies are shifting from single biocontrol agents to synthetic microbial communities (SynComs), in which selected bacteria and fungi perform complementary functions. Such designed communities can combine pathogen suppression, plant growth promotion, nutrient acquisition, and immune stimulation. They are often more stable in the field than single strains. However, soil properties, native microbes, pathogen pressure, host genotype, and environmental factors all affect the success of microbial interventions. Inconsistent field performance, short formulation shelf life, and poor colonization remain practical barriers. Therefore, selecting strains native to the crop and region and verifying that they do not alter the bioactive profile of the harvested produce are essential.

Advancing Microbiome-Guided Integrated Disease Management

Managing soil-borne diseases in medicinal plants requires shifting from pathogen-focused control to an integrated, ecosystem-based approach. Practices such as crop rotation with non-host crops, organic amendments, green manuring, soil solarization, and biochar application help restore soil balance and reduce pathogen pressure. Beneficial microorganisms and synthetic microbial communities further support disease suppression and host immunity. For example, biochar can lower *Fusarium* levels and root-rot incidence while improving soil structure, water retention, and yield. Healthy, disease-free planting material, resistant or tolerant genotypes, and good drainage form the foundation on which these biological measures work best. Advanced tools such as amplicon and metagenomic microbiome profiling, multi-omics, network analysis, and machine learning help identify disease-suppressive microbes, predict disease risk from soil microbial signatures, and design tailored microbial consortia. The goal is to build a resilient plant–soil–microbiome system (Figure 1). In this system, healthy soil supports beneficial microbes; these microbes enhance host immunity, and robust plants limit pathogen establishment while

maintaining medicinal quality. Microbiome-guided integrated management offers a promising path for sustainable, residue-free medicinal plant production by uniting soil health, biological disease control, host immunity, and preservation of medicinal value.

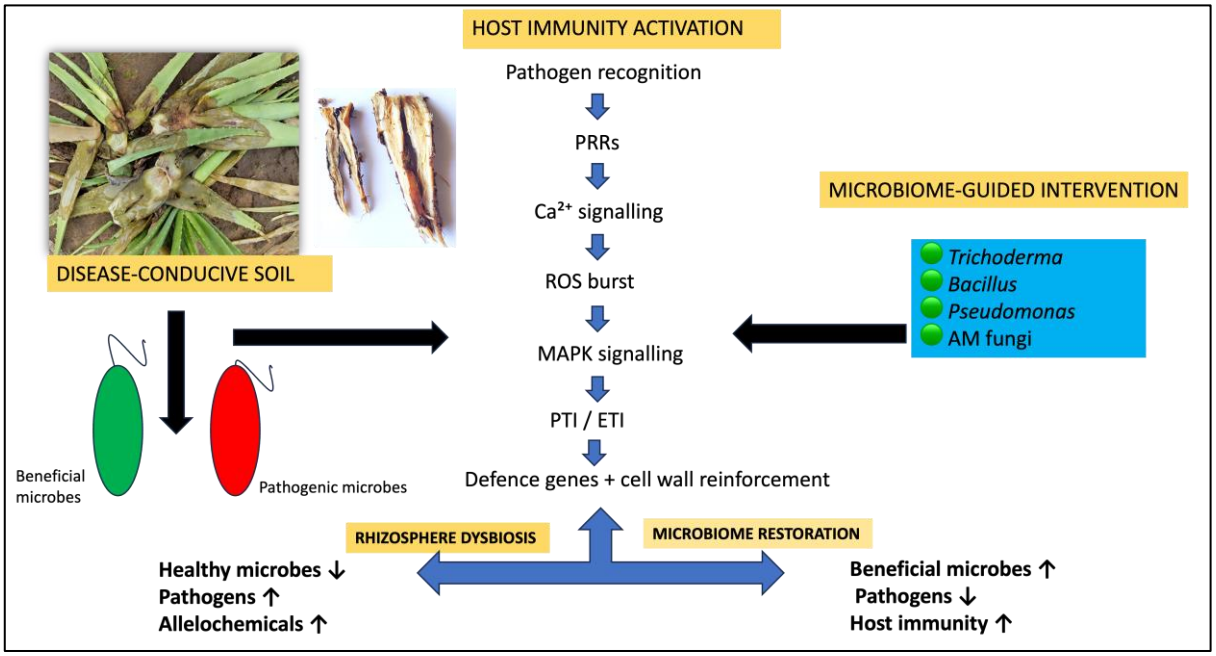


Fig. 1. Integrated framework of plant–soil–microbiome interactions governing soil-borne disease in medicinal plants.

The left panel depicts a diseased rhizosphere under continuous cropping. Soil-borne pathogens (*Fusarium*, *Pythium*, *Phytophthora*, *Rhizoctonia*, *Ralstonia*, and root-knot nematodes) persist as resting structures and infect roots and the root–crown region. Accumulated root exudates and autotoxic allelochemicals (saponins, phenolic acids, alkaloids) stimulate pathogens and suppress beneficial microbes, leading to rhizosphere dysbiosis, wilt, root rot, damping-off, and loss of yield and bioactive compounds. The central panel shows the host immune response. Cell-surface pattern-recognition receptors trigger pattern-triggered immunity (PTI) through Ca2+ influx, ROS burst, MAP kinase signaling, and defense gene expression, while intracellular NLR receptors activate effector-triggered immunity (ETI); the two layers potentiate each other and are regulated by salicylic acid, jasmonic acid, and ethylene. Altered root exudation recruits protective microbes ("cry for help"). The right panel represents a disease-suppressive rhizosphere achieved through microbiome-guided integrated disease management. Beneficial microbes and synthetic microbial communities (*Bacillus*, *Pseudomonas*, *Trichoderma*, arbuscular mycorrhizal fungi) suppress pathogens through competition, siderophores, antibiotics, and mycoparasitism, and they promote growth and induce systemic resistance. Crop rotation, organic amendments, and biochar restore soil health, while microbiome profiling, multi-omics, and machine learning guide targeted interventions. Arrows indicate the feedback loop in which healthy soil supports beneficial microbes, microbes strengthen host immunity, and robust plants limit pathogen establishment while preserving medicinal quality.

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