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Harnessing the rhizosphere microbiome for sustainable weed suppression in agroecosystems

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Abstract
The escalation of herbicide-resistant weeds presents a critical threat to global food security, necessitating a shift toward sustainable and eco-friendly agricultural practices. The rhizosphere—the dynamic interface where plant roots and soil microorganisms interact—holds immense, largely untapped potential for biological weed management. This review synthesizes current research at the intersection of plant botany and soil microbiology to explore how the rhizosphere microbiome can be harnessed to suppress weed emergence and growth. We examine the fundamental mechanisms driving these interactions, including microbe-mediated allelopathy, resource competition, and the action of host-specific deleterious rhizobacteria (DRB). By comparing the root exudate profiles and microbiome assembly of cultivated crops versus invasive weed species, we highlight how targeted microbial interventions can disrupt weed physiology while promoting crop resilience. Furthermore, the review addresses the practical challenges of translating these microbial dynamics from controlled laboratory conditions to field applications, emphasizing the need for stable bio-formulations and their compatibility with existing organic inputs like bio-fertilizers. Ultimately, Integration of microbiome-based bioherbicides into standard weed management programs offers a viable, sustainable pathway to reduce synthetic chemical reliance and restore soil health in intensive agroecosystems.

Keywords: Rhizosphere microbiome, sustainable weed management, Deleterious rhizobacteria (DRB)

1. Introduction

The heavy reliance on synthetic herbicides in modern agroecosystems has precipitated an ecological bottleneck, characterized by soil degradation, water contamination, and the rapid emergence of herbicide-resistant weed biotypes [1]. Understanding the precise intensity and distribution of these weed populations across specific regional districts is crucial for grasping the sheer scale of the agricultural threat. As mapping these aggressive plant species becomes a priority for agronomists, it is increasingly clear that pure chemical management is unsustainable. In response, agricultural science is pivoting toward biological and ecologically integrated management strategies. At the forefront of this shift is the rhizosphere, the narrow region of soil directly influenced by root secretions and associated soil microorganisms. The rhizosphere represents a highly competitive ecological battleground where crops and weeds vie for resources. Harnessing the native microbiomes within this zone offers a promising, sustainable pathway to suppress weed proliferation while simultaneously enhancing soil health and crop resilience [6]. This review explores the botanical and microbiological dynamics of the rhizosphere, detailing the mechanisms by which microbial communities can be leveraged as bio-herbicidal agents and out-competitors against invasive agricultural weeds.

2. The Botany-Microbiology Nexus: Root Exudates and Microbiome Assembly

The composition of the rhizosphere microbiome is not random; it is highly curated by the host plant through the release of root exudates. Botanically, these exudates—comprising sugars, organic acids, amino acids, and secondary metabolites—act as primary signaling molecules and carbon sources that recruit specific microbial taxa from the bulk soil. Crucially, weed species and cultivated crops exhibit distinct exudation profiles, leading to differential microbiome assembly. Invasive weeds often engineer their rhizosphere to recruit microbial communities that facilitate rapid nutrient acquisition and stress tolerance, giving them a competitive edge over crops [10]. Conversely, specific crop cultivars can be bred or managed to release exudates that attract microbes capable of antagonizing weed growth. Understanding this biochemical dialogue is essential for manipulating the soil microbiome to favor crop establishment over weed dominance.

3. Mechanisms of Microbial Weed Suppression

The suppression of weeds by rhizosphere microorganisms occurs through several overlapping biological mechanisms, ranging from direct pathogenesis to indirect ecological competition.

Microbe-Mediated Allelopathy

Allelopathy involves the release of biochemicals by one plant that influence the growth of another. However, these allelochemicals rarely act in a sterile environment. Soil microbes play a pivotal role in mediating allelopathy by either synthesizing their own phytotoxic compounds or bio-transforming inactive crop root exudates into highly toxic allelochemicals that inhibit weed seed germination and root elongation [14
].

Deleterious Rhizobacteria (DRB) and Pathogenic Fungi

DRB are a specialized subset of the microbiome that colonize plant roots and inhibit plant growth without causing visual symptoms of classical disease. Host-specific DRB targets the root systems of specific weed species, disrupting cellular functions through the overproduction of phytotoxins like hydrogen cyanide (HCN) or specific lipopeptides [9]. Similarly, soil-borne fungi can act as bioherbicides by penetrating weed seed coats, leading to seed decay before emergence.

Resource Competition and Niche Exclusion

A highly diverse and robust crop microbiome can physically and metabolically outcompete weed seedlings for limiting soil resources, particularly phosphorus and nitrogen. By dominating the ecological niches within the root zone, efficient microbial consortia effectively starve weed competitors [20].

Phytohormone Manipulation

Microbes significantly influence plant architecture by synthesizing or degrading phytohormones. For example, certain bacteria produce high levels of indole-3-acetic acid (IAA) which, while beneficial at low concentrations, becomes highly inhibitory to root development in weed seedlings at elevated levels [24]. Other microbes synthesize 1-aminocyclopropane-1-carboxylate (ACC) deaminase, altering ethylene levels and disrupting the normal growth trajectory of competitive weeds.

4. Translating Lab to Field

Formulation and Bio-efficacy the transition of weed-suppressing microbes from controlled laboratory conditions to variable agricultural fields remains a significant hurdle. Single strain isolates often fail in the field due to environmental stress and competition with indigenous soil microbiomes. The future lies in developing robust, multi-strain microbial consortia that exhibit functional redundancy. Furthermore, the formulation science behind these products is critical. Encapsulation techniques, the use of appropriate carrier materials, and the extension of shelf-life are required to maintain microbial viability [28]. It is also vital that these bioherbicidal formulations are compatible with standard organic farming practices, ensuring they do not negatively interact with locally produced bio-fertilizers or organic composts applied for plant nutrition.

5. Environmental Influences and Agronomic Practices

The efficacy of the rhizosphere microbiome in suppressing weeds is highly contingent upon abiotic soil factors. Soil pH, moisture content, temperature, and organic matter levels directly influence microbial survival and phytotoxin production [33]. Agronomic practices such as crop rotation, cover cropping, and reduced tillage also profoundly shape the microbiome. Integrating microbial weed suppression into existing Integrated Weed Management (IWM) framework requires an understanding of how seasonal variations and localized climate conditions dictate microbial behavior in the soil profile.

6. Challenges and Future Perspectives

Despite the high potential of microbiome-based weed suppression, commercialization is currently limited by regulatory hurdles, inconsistent field efficacy, and the high cost of production. Moving forward, the application of advanced multi-omics technologies (meta-genomics, meta-transcriptomics, and metabolomics) will be crucial for deciphering the complex plant-microbe dialogues that dictate weed suppression [37]. Additionally, the targeted use of CRISPR-Cas technologies to engineer hyper-efficient, highly specific DRB strains holds immense promise for the next generation of precision bioherbicides.

7. Conclusion

The rhizosphere microbiome represents a powerful, yet underutilized, tool for sustainable weed management in modern agroecosystems. By understanding the intricate botanical and microbiological interactions driven by root exudates, allelopathy, and resource competition, agricultural scientists can develop targeted biological interventions that suppress invasive weeds. Overcoming the translational challenges from the laboratory to field formulations will require continued interdisciplinary research. Ultimately, integrating microbiome management into standard agricultural practices offers a critical pathway toward reducing chemical herbicide dependency and fostering resilient, sustainable food production systems.

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