

Innovative Approaches in Agricultural, Biological, and Life Sciences

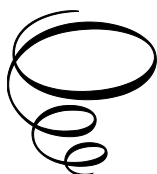
Innovative Approaches in Agricultural, Biological, and Life Sciences:

Research and Sustainability

Edited by

Monika Stojanova and Yalcin Kaya

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FOREWORD

In an era marked by unprecedented scientific advancement and global challenges, the role of interdisciplinary research has become more crucial than ever before. This special collection *Innovative Approaches in Agricultural, Biological, and Life Sciences: Advancing Research and Sustainability* gathers the most outstanding peer-reviewed papers presented at the VII International Agricultural, Biological and Life Sciences Conference (AGBIOL 2025), held in Istanbul, Turkey. It reflects the latest breakthroughs, innovative methodologies, and the growing interconnectedness of agriculture, biology, and life sciences, emphasizing how collaborative efforts across disciplines are vital to tackling some of humanity's most urgent issues.

Since its establishment in 2018, the AGBIOL conference has evolved into a premier international platform that brings together scientists, researchers, academics, and professionals from all over the world. The conference has grown impressively, drawing thousands of participants and hundreds of papers, showcasing a wide array of topics spanning agricultural engineering, biotechnology, environmental sciences, biomedical research, and beyond. This collection distills the essence of that growth, offering a carefully curated selection of cutting-edge research that embodies both scientific rigor and practical relevance.

One of the defining features of this collection is its multidisciplinary approach. The complex challenges we face today—climate change, food insecurity, biodiversity loss, environmental degradation—cannot be addressed within isolated scientific silos. Instead, they demand integrated perspectives that connect multiple fields of knowledge. This volume highlights the critical intersections between disciplines such as plant science, genetics, biochemistry, soil science, veterinary medicine, and bioengineering, illustrating how the integration of diverse expertise fosters innovative and sustainable solutions.

This interdisciplinarity is complemented by the global reach of the collection. Contributions come from researchers representing over 50 countries, bringing diverse ecological, cultural, and scientific viewpoints to

the forefront. This international dimension not only enriches the research but also underscores the universal nature of the challenges addressed. The varied methodologies employed—from experimental fieldwork and laboratory analyses to computational modeling and case studies—reflect the dynamic and multifaceted character of contemporary scientific inquiry.

Beyond its academic contribution, this special collection also offers significant practical value. Many studies present novel technological advancements and applied research with direct implications for improving agricultural productivity, enhancing ecosystem resilience, advancing animal and human health, and developing environmentally friendly biotechnologies. Consequently, this volume stands as a critical resource for a wide audience, including scientists, students, educators, policymakers, and industry stakeholders who seek evidence-based guidance to inform decisions and innovations in their respective fields.

Furthermore, the AGBIOL conference and this publication embody a strong commitment to sustainability and environmental responsibility. In alignment with the principles of green science and technology, efforts were made to minimize resource consumption, including the digital dissemination of conference materials and the promotion of eco-friendly practices throughout the event. This collection thus serves not only as a scientific compendium but also as a testament to the ethical imperatives guiding modern research and scholarly communication.

The importance of this volume extends to its role as a catalyst for future research and collaboration. By identifying emerging trends, knowledge gaps, and innovative methodologies, it encourages researchers to explore new frontiers and fosters a culture of continuous learning and discovery. It also strengthens the global scientific community by providing a platform for networking and idea exchange, which is essential for addressing complex problems that transcend geographic and disciplinary boundaries.

We anticipate that this collection will inspire readers across various domains. It offers valuable insights and practical knowledge for those involved in agriculture, biology, environmental science, biotechnology, and related disciplines. Whether one is a researcher seeking new directions, a student eager to learn about the latest developments, or a policymaker aiming to apply scientific findings to real-world challenges, this volume provides an indispensable resource.

Ultimately, this publication reflects the vision and mission of the AGBIOL conference – to be a bridge that connects scientists and practitioners worldwide, enabling them to share expertise, build collaborations, and contribute to sustainable and innovative solutions for global challenges. It captures the spirit of a global scientific community united by a common goal: to advance knowledge and technology in ways that support the health and well-being of both people and the planet.

We invite you to delve into this collection with curiosity and enthusiasm, to engage with its diverse research contributions, and to be inspired by the remarkable progress and potential of interdisciplinary science. Together, through shared knowledge and collaborative effort, we can continue to make meaningful strides toward a sustainable and prosperous future.

Editors

CHAPTER 24

TOXIC DIALOGUES: HERBICIDES, MICROBIAL VOICES, AND THE ECOSYSTEM'S RESPONSE

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Abstract: Herbicides, long heralded as precise tools in agricultural management, leave behind echoes that reverberate through the most intimate layers of ecological networks. This study explores how herbicidal interventions—especially those involving compounds like glyphosate—silently alter microbial communities that anchor essential ecosystem functions. These non-target effects begin at the microscopic scale, where shifts in soil microbiome composition interrupt vital processes such as nutrient cycling, rhizosphere signaling, and plant–soil feedback mechanisms.

Framed through a microbiome-centric lens, we present a synthesis of recent studies alongside conceptual models illustrating how herbicide residues serve not only as chemical stressors, but as agents that restructure the metabolic dialogues among microbes and their hosts. Alterations in microbial diversity and function affect plant vitality, reduce resilience to biotic and abiotic stresses, and cascade upward to influence animal performance, herbivory dynamics, and pollination success. As herbicides disrupt these finely tuned interdependencies, we observe potential tipping

points that may reshape ecosystem trajectories and even influence microbial and host evolution.

More than collateral damage, microbial responses to herbicidal exposure represent a silent rebellion—one with the power to mediate or magnify ecological instability. We advocate for integrative strategies that acknowledge microbiome health as a central criterion in agrochemical risk assessments. Understanding these subterranean symphonies is essential for mitigating the long-term consequences of anthropogenic disturbance and for crafting sustainable, microbe-conscious stewardship of ecosystems.

Keywords: microbiome, herbicides, soil microbial networks, environmental resilience, agrochemical impact, microbe-mediated risk

Introduction

Herbicides have revolutionized modern agriculture by enabling targeted and efficient weed control, contributing significantly to crop productivity and food security. Among these, glyphosate stands as one of the most extensively used broad-spectrum herbicides worldwide due to its effectiveness and non-selective inhibition of the 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) enzyme in the shikimate pathway (Duke and Powles, 2008). However, while glyphosate's primary mode of action is aimed at plants, this same biochemical pathway is present in many soil microorganisms, raising growing concerns about its unintended effects on non-target species (van Bruggen et al., 2018).

Soil microbial communities, particularly those inhabiting the rhizosphere, play a pivotal role in maintaining ecosystem functions. These communities mediate nutrient cycling, organic matter decomposition, and intricate plant–microbe interactions that influence plant growth, health, and resistance to environmental stressors (Berg et al., 2020). Disturbances to microbial composition and diversity—whether through direct toxicity or altered plant exudation patterns—can ripple through the entire ecosystem. Emerging evidence suggests that herbicide residues can suppress mycorrhizal colonization, shift bacterial community structures, and increase plant susceptibility to soil-borne pathogens (Zaller et al., 2014; Newman et al., 2016; Johal and Huber, 2009).

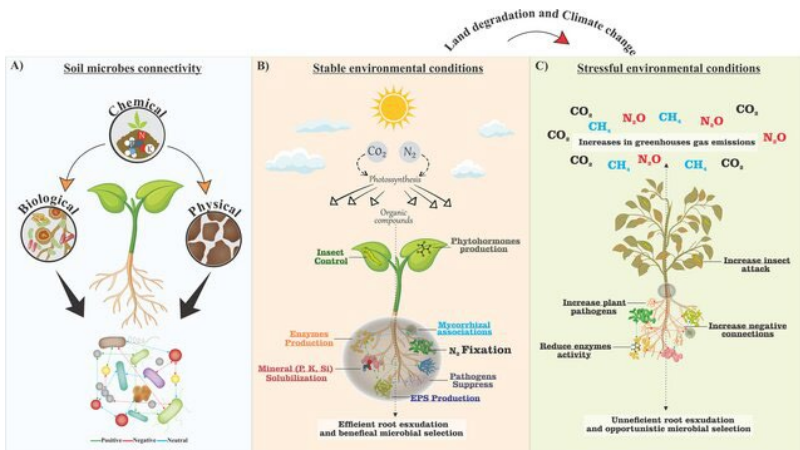


Figure 1. The intricate connections between soil biodiversity and plants. a These interactions are influenced, including chemical, physical, and biological variability. b In a stable ecosystem with no or low human disturbances, plants can effectively recruit their microbial communities, primarily facilitated through rhizosphere exudation and selection processes. This plant-soil biodiversity interactions catalyze multiple ecosystem processes such as enhanced enzyme activity, solubilization, nitrogen fixation, and disease suppressiveness. However, land degradation and ongoing climate changes disrupt these interactions, leading to an increased negative correlation among taxa. c As a result, plants become more vulnerable to harmful and opportunistic agents like insects and pathogens (from Pedrinho et al., 2024).

Importantly, these microbial alterations are not merely short-term or incidental. Herbicides may induce long-term restructuring of microbial networks, with implications for microbial evolution, functional redundancy, and overall soil resilience (Timmis et al., 2019). Furthermore, chronic exposure to glyphosate and similar compounds may drive microbial adaptation or resistance, potentially reducing the soil's capacity to buffer abiotic stressors such as drought or nutrient depletion (Schlatter et al., 2017).

Given the central role of the microbiome in agroecosystem stability, there is an urgent need to reconsider how herbicides are evaluated in terms of ecological risk. Traditional assessments focusing solely on crop yield or visible phytotoxicity fall short of capturing the subtle but profound consequences on microbial health. Integrating a microbiome-centric perspective into agrochemical regulation offers a more holistic

understanding of ecosystem sustainability and resilience (Mitter et al., 2019).

This paper synthesizes recent findings on the impact of herbicides—especially glyphosate—on soil microbial communities. It aims to elucidate the biochemical, ecological, and evolutionary consequences of microbial disruption, and to advocate for frameworks that prioritize microbial integrity as a cornerstone of sustainable agriculture.

Herbicides and their Legacy

Herbicides have revolutionized modern agriculture by enabling efficient weed control, reducing labor costs, and increasing crop yields. Since the introduction of synthetic herbicides like 2,4-D in the 1940s, over 270 active ingredients have been commercialized, shaping global farming practices and food systems (Mesnage et al, 2021; U.S. EPA, 2004). However, their legacy is complex—marked by ecological disruption, resistance evolution, and persistent residues in soil and water. Herbicides have played a central role in modern agricultural intensification, with compounds like glyphosate, atrazine, and 2,4-D becoming dominant tools in weed control (Duke and Powles, 2008). Glyphosate, in particular, has been praised for its broad-spectrum action and post-emergent use. However, its primary target—the shikimate pathway, absent in animals but present in most plants and microbes—raises significant concerns about non-target effects on microbial communities (van Bruggen et al., 2018). While herbicides were initially believed to degrade rapidly in soil, increasing evidence shows that residues persist and interact with complex biotic and abiotic soil components, affecting ecosystem function far beyond weed suppression (Silva et al., 2019). Herbicides such as glyphosate, atrazine, and dicamba have become staples in conventional farming due to their broad-spectrum activity and compatibility with genetically modified (GM) crops (Parven et al., 2024). Systemic and pre-emergence herbicides offer targeted control, reducing the need for repeated applications and mechanical weeding.

Despite their utility, herbicides pose significant risks, as soil degradation (long-term use alters microbial communities, reduces biodiversity, and impairs nutrient cycling), water contamination (runoff and leaching introduce herbicide residues into aquatic ecosystems, affecting non-target organisms like amphibians, fish, and invertebrates) and resistance development (overuse has led to herbicide-resistant weed populations,

complicating management and increasing chemical dependency (Mesnage and Antoniou, 2017).

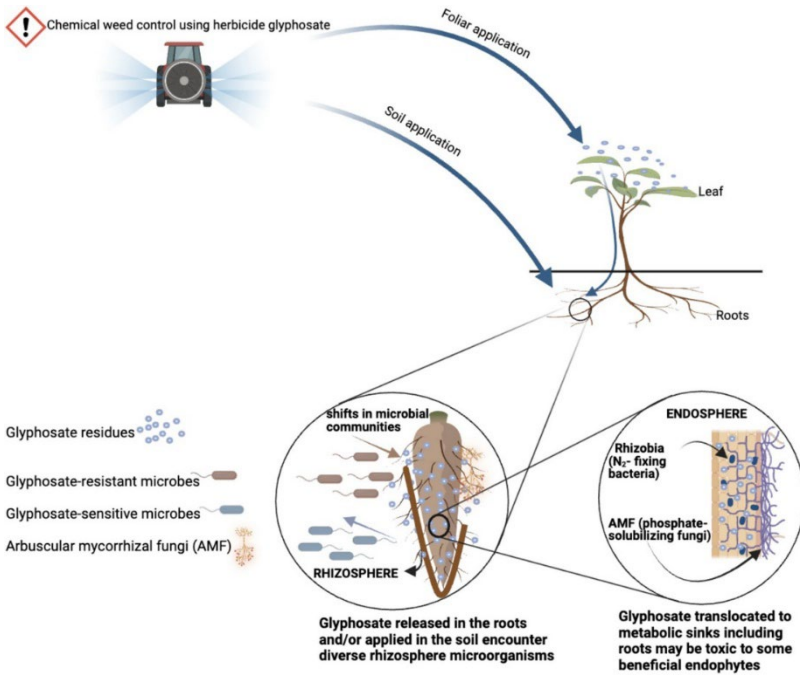


Figure 2. Possible interference of glyphosate with microbial communities in the rhizosphere and endosphere (from Sibalekile et al., 2025).

The Rhizosphere Microbiome: Keystone of Soil Health

The rhizosphere microbiome—microorganisms that inhabit the narrow zone surrounding plant roots—plays a foundational role in nutrient cycling, stress response, and plant immunity (Berg et al., 2020).

The specific functions of soil microbes can be divided into seven major groups (Berendsen et al., 2012; Cheng et al., 2022; Kumar et al., 2022):

- **Decomposition:** Microbes—bacteria and fungi—break down organic matter such as crop residues, insect carcasses, animal manure, and other organic materials in the soil. Microbes secrete enzymes that help break down complex organic compounds into

simpler forms, releasing nutrients that plants can use. Microbes contribute to humification as they break down organic compounds. Humification produces stable, mature organic compounds that increase the organic matter content of the soil. This offers additional benefits to crops, such as increased water-holding capacity, nutrient retention, and carbon sequestration.

- Nutrient cycling: Microbes are involved in the circulation of essential nutrients in the soil. They can “unlock” nutrients that are locked up in forms inaccessible to the plant and therefore promote the availability of nutrients for plant absorption. Nitrogen fixation (mineralization) is one example of how many beneficial soil microbes convert organic nutrients into inorganic forms that can be absorbed by plants. Soil microbes also unlock nutrients from inorganic “bound” forms.
- Soil structure and aggregation: Certain bacteria and fungi produce sticky substances such as polysaccharides that bind soil particles together, forming aggregates. Soil aggregates improve soil structure, porosity, and water-holding capacity, allowing for better root penetration and aeration.
- Disease suppression: Certain beneficial bacteria and fungi called biocontrol agents can suppress soil-borne pathogens and pests. Biocontrol agents suppress pathogens and pests through a variety of processes, including: producing antimicrobial compounds, consuming or parasitizing pests and pathogens, or outcompete pathogens for soil niches. The term "disease-suppressing soils" is often used to refer to fields that experience little or no impact from soil-borne diseases, even when the diseases are widespread throughout the surrounding region or minimal crop protection products are used. Microbial biocontrol agents are known to play a key role in the ability of disease-suppressing soils to mitigate the impacts of pathogens.
- Phytohormone Production: Some soil microbes can produce plant hormones in the soil, many of which are called "plant growth regulators" or PGRs. Hormones such as auxin, cytokinin, and gibberellin are known to support plant growth, yield, and stress tolerance when applied as foliar products. However, their routine application can be very expensive. Microbial hormone producers in the soil can also offer these benefits and have been found to support crop resistance to stressors such as drought and activate plant defense systems to ward off pathogens.

- Symbiotic relationships: Many plants form beneficial symbiotic relationships with soil microbes. Mycorrhizal fungi form associations with plant roots, extending their reach for water and nutrients in exchange for microbial “food” in the form of carbon produced by the plant through photosynthesis. Mutually beneficial bacteria, known as endophytes, live within plant tissues and promote plant growth by performing beneficial processes such as nitrogen fixation and carbon uptake through root exudates. This symbiotic relationship improves plant nutrient uptake, overall plant and soil health, and the efficiency of agricultural systems. However, common agricultural practices can disrupt these relationships, leading to a decline in beneficial microbes and increased dependence on agricultural inputs.
- Salinity regulation: Some microbes have adapted to survive in saline environments and possess mechanisms to tolerate high salt concentrations. They can actively colonize and thrive in saline soils where other organisms struggle. Salt exclusion is when certain microbes have mechanisms to exclude salts from their cells or actively limit their uptake. By excluding salts, microbes can ensure proper cellular function and growth in high salinity conditions. Salt metabolism is when certain microbes possess enzymes that can metabolize or break down specific types of salts. They can convert salts into less harmful forms or compounds that other organisms can use.

In short, balancing microbiome disruptions with practices that support plant-microbe symbiosis, such as cover crops and conservative tillage, is key to optimizing soil health processes and harnessing the benefits of soil microbes.

These microbial consortia are sensitive to external chemical inputs and serve as early indicators of soil disturbance (Kurenbach et al., 2021; Yang et al., 2023; El-Helow et al., 2024). Herbicides can alter:

- Microbial richness and evenness
- Community composition (e.g., shifts from *Proteobacteria* to *Actinobacteria*)
- Enzyme activity, such as dehydrogenase and phosphatase
- Plant-microbe communication, such as root exudate signaling

Soil microbial consortia—interactive communities of bacteria, fungi, archaea, and protists—are highly sensitive to herbicide exposure. Although

herbicides are designed to target weeds, their biochemical specificity often extends to non-target organisms, leading to unintended disruptions in soil microbial dynamics. Also, herbicides can disrupt microbial communities by following mechanisms (Kurenbach et al., 2021; Yang et al., 2023; El-Helow et al., 2024):

- **Enzyme inhibition:** Common herbicides like glyphosate inhibit the shikimate pathway, which is present in bacteria and fungi. This hampers the synthesis of vital aromatic amino acids such as tryptophan, tyrosine, and phenylalanine, affecting microbial growth and metabolism.
- **Loss of microbial diversity:** Herbicide exposure can shift community composition by reducing beneficial groups like nitrogen-fixing bacteria, phosphate-solubilizers, and symbiotic fungi. This undermines key soil functions like nutrient cycling and plant-microbe interactions.
- **Metabolic shifts and functional decline:** While some microbes adapt to herbicides, this often comes with altered metabolic activity or reduced efficiency in organic matter decomposition and other soil biochemical processes.
- **Antibiotic resistance proliferation:** Studies show that prolonged herbicide use can increase the abundance of antibiotic resistance genes (ARGs) and mobile genetic elements (MGEs), potentially facilitating the spread of resistant pathogens through horizontal gene transfer.

Adaptive Responses and Microbial Resistance

Repeated herbicide exposure can drive microbial adaptation, including degradation capability evolution (e.g., *Pseudomonas* acquiring glyphosate degradation genes), shift toward resistant or resilient taxa or horizontal gene transfer of resistance traits. While such adaptations may improve degradation efficiency, they may also alter microbial network interactions, affecting ecological balance (Rousidou et al., 2013). Microbial shifts may feed back into plant susceptibility, nutrient cycles, and carbon dynamics, especially under climate stress.

Microbes adapt to herbicides through several strategies, such as efflux pump activation, membrane modifications (like changes in membrane permeability help microbes limit herbicide uptake and increase resistance to antibiotics), stress response pathways (e.g. herbicide exposure triggers

oxidative stress, DNA damage, and SOS responses, which can lead to mutagenesis and horizontal gene transfer) and cross-resistance evolution (mutations that confer herbicide tolerance may also increase resistance to antibiotics, especially when stress pathways overlap) (Liao et al., 2021; Hill, 2017). These adaptive responses have cascading effects soil microbiome disruption, antimicrobial resistance and food chain contamination, like residual herbicides and resistant microbes can enter crops and livestock, posing risks to human health (Daram et al., 2021; Paul and Mandal, 2019).

Herbicide Effects on Ecosystem-Level Processes

While the rhizosphere is a well-studied hotspot of microbial activity, recent research reveals that microbial alterations extend far beyond root zones, influencing macroecological processes such as nutrient cycling, carbon sequestration, biodiversity patterns, and ecosystem resilience. These changes are not confined to local soil patches—they ripple across landscapes and biomes, shaping ecological trajectories at multiple scales (Wang and Zou, 2024; Mohanram and Kumar, 2019). Microbial communities in bulk soil, litter layers, and aquatic interfaces respond dynamically to environmental perturbations, including herbicide exposure, land-use change, and climate variability. These shifts can alter biogeochemical cycles, modulate greenhouse gas emissions and influence plant community assembly (Pantigoso et al, 2022; Ruuskanen et al., 2022).

Microbial alterations often involve cross-kingdom interactions, such as fungal networks facilitating bacterial dispersal or protists regulating microbial grazing. These interactions contribute to soil organic matter formation, trophic cascades and to habitat connectivity.

Beyond the rhizosphere, microbial alterations influence macroecological processes, such as carbon sequestration via changes in microbial respiration, nitrogen and phosphorus cycling and soil aggregation and erosion resistance. Several studies report that herbicide-induced microbial imbalance can decrease soil organic matter, reduce greenhouse gas buffering capacity, and lower crop resilience to drought and pests (Ghimire et al., 2020). These indirect impacts challenge the long-held belief in herbicide neutrality toward ecosystem services.

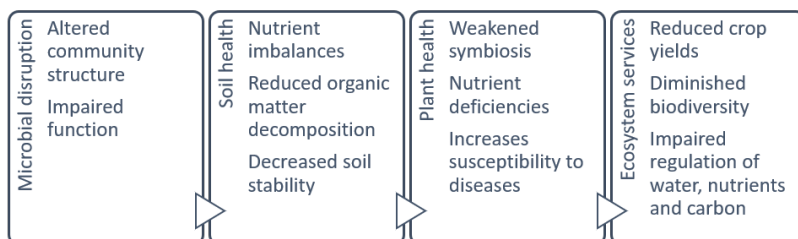


Figure 3. Ecosystem model showing cascading impacts of microbial disruption—soil health, plant health, insect interactions, and ecosystem services.

Herbicides have long been regarded as indispensable tools in modern agriculture—cost-effective, targeted, and efficient. Yet, their ecological footprint reaches far beyond weed suppression. Current herbicide risk assessment frameworks primarily focus on chemical persistence, toxicity to plants and animals, and residue levels in food and water. What remains largely overlooked is the impact of herbicides on the soil microbiome, a critical engine of nutrient cycling, plant health, and ecosystem stability (Sweeney et al., 2025; Kodikara et al., 2022).

Soil microbes—especially those in the rhizosphere—play foundational roles in maintaining agroecological functions. However, these organisms are almost entirely absent from conventional toxicological testing. Risk assessments typically rely on short-term, single-organism studies that fail to reflect the complexity and dynamism of microbial communities, which are deeply intertwined with numerous ecosystem services (Zhao et al., 2025; Wend et al., 2024).

An additional blind spot lies in microbial genetic mobility, where herbicide-induced stress can activate antibiotic resistance genes (ARGs) and mobile genetic elements (MGEs). This not only jeopardizes soil health but also raises concerns about public safety via the potential horizontal transfer of resistance traits to pathogenic microbes (EFSA, 2023; Liao et al., 2021).

Table 1. Gaps in Herbicide Risk Assessment.

Assessment Domain	Current Gaps
Soil Health	Focused mainly on chemical residues and physical structure
Non-target Effects	Limited consideration of microbial collateral damage
Temporal Dynamics	Assessed via static endpoints (e.g., residue half-life)
Bioindicator Integration	Rarely utilizes microbial indicators
Interaction Effects	Ignores chemical synergy or antagonism with microbial networks
Resistance Development	Focused on weed resistance only
Ecosystem Services Impact	Underrepresents microbial contributions to services
Standardized Protocols	Lacks harmonized microbial toxicity assays

Conclusions

Herbicides, while instrumental in modern agriculture, pose complex ecological challenges that extend far beyond weed control. Their influence on soil microbial consortia—especially in the rhizosphere—triggers cascading effects that alter nutrient cycles, suppress beneficial taxa, and potentially promote antibiotic resistance. These microbial disruptions reshape plant–soil interactions, reduce ecosystem resilience, and compromise vital services such as pollination, pest regulation, and carbon sequestration.

Conventional herbicide risk assessments often overlook these microbiome-mediated effects, focusing narrowly on chemical residues and plant toxicity endpoints. Integrating microbiome-centric metrics into regulatory frameworks—such as microbial diversity indices, functional group profiling, and gene transfer monitoring—offers a path toward more holistic ecological stewardship.

A microbiologically informed approach to weed management can help sustain soil health, foster agroecosystem stability, and safeguard public and environmental well-being. The microbial voice, long silent in regulatory discourse, must now become a guiding force in rethinking agricultural sustainability.

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