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Fostering the native microbiome: A superior alternative to microbial inoculation for sustainable soil health

Hassan Etesami†

Soil Science Department, University of Tehran, Tehran, Iran

†*Corresponding Author Email: hassanetesami@ut.ac.ir*

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ABSTRACT

Soil microbiome, the foundational engine of terrestrial ecosystems, is critical for global food security and environmental sustainability. For decades, agricultural science has pursued microbial inoculants as "silver bullet" solutions, yet this approach has yielded inconsistent results and failed to deliver the systemic resilience required for long-term soil health. This review synthesizes a growing body of evidence to argue that a paradigm shift is necessary: moving from a focus on inoculation to one of habitat managements. The central thesis posits that fostering the indigenous soil microbiome—by enhancing its organic matter, habitat complexity, and biodiversity—represents a more robust, resilient, and sustainable path forward. Evidence is presented demonstrating that management practices such as amending soil with organic matter, cover cropping, and practicing reduced tillage, enhance microbial diversity, functional redundancy, and self-regulation, and ultimately providing broader, more durable, and economically viable benefits than the introduction of single-strain microbes.

Keywords: Habitat management; Functional redundancy; Indigenous microbiota; Agricultural practices; Ecosystem resilience.

1. Introduction: a Paradigm Shift in Soil Microbiome Management

The soil microbiome, a complex assemblage of bacteria, archaea, fungi, protists, and viruses, constitutes the biological foundation of terrestrial ecosystems (Jiang et al., 2023; Rashid et al., 2021). These diverse communities drive essential processes that underpin soil health and agricultural productivity, including nutrient cycling, formation and stabilization of soil structure, suppression of plant pathogens, and thus direct promotion of plant growth (Etesami et al., 2023; Imran and Ortas, 2025). This intimate, co-evolved relationships between plants and their associated microbiota is best understood through the lens of the "plant-soil holobiont" concept, which frames the host and its microbial partners as a single, functional ecological unit (Müller et al., 2016; Vandenkoornhuyse et al., 2015). Safety and health of this holobiont is, therefore, inextricably linked to the diversity and functional capacity of the native soil microbiome. For decades, the primary strategy for harnessing microbial power in agriculture has been microbial inoculation—the deliberate introduction of specific, often isolated, beneficial strains into soil or onto seeds. The allure of this approach is strong, with roots in the successful use of *Rhizobium* inoculants for legumes and expanding to a broad range of Plant Growth-Promoting Rhizobacteria (PGPR) (Gou et al., 2022; Sangar and Singh, 2011). The theoretical appeal is clear: inoculants promise a targeted, specific, and commercially scalable solution to enhance crop performance, potentially reducing reliance on chemical inputs (de Andrade et al., 2023; Haskett et al., 2021).

However, a significant paradox has emerged between the promise of inoculation and its real-world performance (Figure 1). While microbial inoculants consistently demonstrate efficacy in controlled laboratory and greenhouse settings, their application in the field is plagued by inconsistent and often disappointing results (Ayala-Zepeda et al., 2024; Etesami, 2025; Khare and Arora, 2014). This "inoculation paradox" stems from several inherent limitations. Introduced strains frequently face establishment failure, struggling to survive, colonize, and compete within the resident, highly competitive soil microbial community (Čaušević et al., 2024; Etesami, 2025; Mawarda et al., 2022b). Furthermore, inoculant success is highly context-dependent, varying dramatically with soil type, pH, moisture, management history, and the incumbent microbiome, making generalizable success elusive (Adeniji et al., 2025; Etesami, 2025; Wakelin et al., 2008). Finally, the narrow focus on one or a few microbial functions overlooks the critical role of the broader, multi-trophic microbial network in delivering ecosystem services like long-term soil structure building and carbon sequestration (Bashan et al., 2016; Trabelsi and Mhamdi, 2013). Consequently, a paradigm shift is underway, moving from a philosophy of microbial *replacement* to one of microbial *empowerment*. This review synthesizes a growing body of evidence that

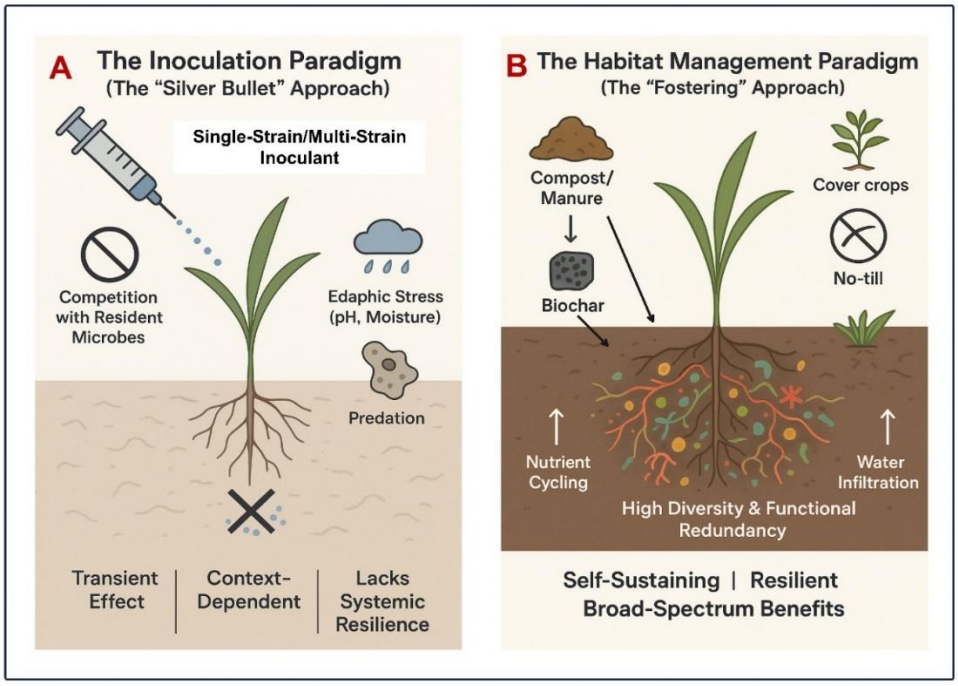

Figure 1. Contrasting paradigms for managing the soil microbiome. (A) The inoculation paradigm relies on introducing exogenous microbes, which often fail to establish due to biotic and abiotic barriers, resulting in transient and inconsistent benefits. (B) The habitat management paradigm fosters the indigenous microbiome through practices that enhance soil organic matter and habitat structure. This promotes a diverse, self-organizing, and resilient microbial network that delivers robust, multifunctional, and sustainable benefits for soil health and plant growth

proposes a superior alternative: managing soil habitat to foster the indigenous native microbiome. It is also argued that agricultural practices with enhancing soil organic matter, structure, and habitat complexity by application of organic amendments, cover cropping, reduced tillage, and techniques like reductive soil disinfestation (RSD)—create conditions for selectively enrich a diverse, resilient, and self-sustaining microbial community (Yin et al., 2025; Zhou et al., 2025b). This "soil-first" approach leverages the inherent "home-field advantage" of native microbes, which are pre-adapted to local conditions and integrated into existing ecological networks (Jiang et al., 2023). By increasing microbial diversity and network complexity, this strategy enhances functional redundancy and ecosystem stability, leading to more robust and sustainable improvements in soil health and plant productivity compared to the transient benefits often observed with inoculation (Li et al., 2024; Mbuthia et al., 2015). This review explores the scientific basis for this paradigm shift. The paper first details the critical ecological roles of soil microbiome and the concept of the plant-soil holobiont. It then critically examines the historical allure and inherent limitations of microbial inoculation. The core of the argument focuses on the mechanisms and compelling evidence supporting habitat management as a more effective strategy, highlighting its success in enhancing pathogen suppression, nutrient cycling, and plant growth. Finally, these insights are synthesized to argue that the future of sustainable agriculture lies not on introducing exogenous microbial "silver bullets," but to the powerful nurturing of the native microbial communities already exist in our soils.

2. Scientific Basis for Native Community Advantage

The superiority of fostering a native microbiome over targeted inoculation is grounded in fundamental ecological principles. Soil microbial communities are not random assemblages but are organized, self-regulating systems whose stability and functionality are governed by their diversity, internal interactions, and long-term adaptation to their environment.

2.1. Ecological principles governing soil microbiomes

The resilience and functionality of soil ecosystems are underpinned by three core ecological principles: the diversity-stability hypothesis, functional redundancy, and network complexity. The diversity-stability hypothesis posits that richer microbial communities are more resistant to and resilient from environmental stresses (Tardy et al., 2014). This "insurance effect" ensures that even if some taxa are suppressed by a stressor like drought or pollution, other, more tolerant species can maintain essential ecosystem processes (Wang et al., 2025). For instance, a

meta-analysis of 62 studies found that soils with higher microbial diversity exhibit 34-47% greater resistance to drought stress and 28-36% faster recovery following disturbance compared to low-diversity soils (Tardy et al., 2014; Wang et al., 2025). This buffering capacity is not merely a numbers game; it is often driven by specific keystone taxa—disproportionately influential species that can maintain specialized functions like nitrogen cycling or pollutant degradation under stress (Chao et al., 2024; Xun et al., 2021). However, the strength of this relationship is context-dependent, as soil properties like pH and organic carbon content can sometimes outweigh diversity as the primary determinant of functional stability (Jiang et al., 2020; Zhang et al., 2016).

Functional redundancy is the phenomenon where multiple microbial taxa perform similar ecological roles, ensuring that key processes persist even if some species are lost (Wertz et al., 2006; Yu and Whalen, 2020). This redundancy is high for broad functions like respiration but critically low for specialized processes such as the degradation of specific pollutants (Singh et al., 2014; Trivedi et al., 2019). In managed systems, agricultural intensification can erode this redundancy, increasing vulnerability to disturbance (Chen et al., 2022b). The persistence of function after diversity loss is facilitated by the presence of metabolically versatile generalist taxa, which enhance stability through network robustness, while specialists remain crucial for specific, high-value functions (Li et al., 2025b; Niu et al., 2025). Network complexity captures the architecture of synergistic and antagonistic interactions between microbes, including cross-feeding, quorum sensing, and competition (Wang et al., 2025; Xiao et al., 2024). Complex, modular co-occurrence networks are a stronger predictor of ecosystem multifunctionality than diversity alone and are fundamental to community stability (Chen et al., 2022a; Zhang et al., 2024). These networks are sensitive to environmental gradients; for instance, aridity and land-use intensification simplify network structure, reducing both complexity and ecosystem function (Dong et al., 2025; Idbella et al., 2025). Management practices that enhance this complexity, such as organic amendments and reduced tillage, are therefore critical for sustaining soil health (Luo et al., 2023b; Wen et al., 2025).

2.2. The native microbiome's inherent advantages

Beyond these general principles, native microbial communities possess specific, inherent advantages that are difficult for introduced inoculants to replicate. *Local adaptation* is a cornerstone of the native microbiome's efficacy. Through long-term co-evolution with the local plant community and soil environment, native microbes develop genetic, metabolic, and regulatory traits tailored to local conditions such as pH, moisture regimes, and organic matter quality (Brady and Farrer, 2024; Li et al., 2022). For example, microbial communities exhibit distinct life-history strategy shifts along aridity gradients, optimizing their function for survival and nutrient cycling under stress (Li et al., 2022). This adaptation is reflected in the enrichment of stress-responsive genes and shifts in key metabolic pathways for carbon and nitrogen cycling during ecosystem restoration, allowing the community to optimize resource use efficiency for the local environment (Liao et al., 2023; Lu et al., 2024; ur Rahman et al., 2025). *Pre-existing integration* refers to the native microbiome's embeddedness within the established soil ecological network. Native microbes are not isolated actors but are integral components of a complex food web, with well-established interactions with plants, fauna, and other microorganisms (Lavelle et al., 2016; Thakur and Geisen, 2019). This deep integration is orchestrated by keystone taxa that maintain network complexity and functional stability (Herren and McMahon, 2018; Jiao et al., 2022). The native community's history with local "ecosystem engineers," such as plant roots and earthworms, creates a biotically modulated environment that is primed for their success, facilitating stable nutrient cycling and ecosystem function (Williams et al., 2024). *Self-organization and regulation* enable native communities to maintain equilibrium and resist invasion. Through mechanisms like quorum sensing, biofilm formation, and the production of secondary metabolites, microbial populations coordinate their behavior and regulate community composition (Scherlach and Hertweck, 2020; Wu et al., 2024). This self-organization fosters a *home-field advantage*, where native synthetic communities (SynComs) consistently demonstrate superior root colonization and plant growth promotion compared to non-native commercial strains, as they are already compatible with the resident community's regulatory networks (Jiang et al., 2023; Velte et al., 2025). This inherent stability makes the native microbiome a resilient, self-sustaining resource that naturally resists displacement by introduced inoculants.

3. Challenges and Limitations of Microbial Inoculation

The promise of microbial inoculation is compelling, and it is important to acknowledge that certain inoculants—most notably *Rhizobium* spp. for legume crops and *Azospirillum* spp. for cereals—have demonstrated consistent field efficacy over decades of use, particularly when applied to nitrogen-deficient soils with compatible host genotypes (Bashan et al., 2014; de Andrade et al., 2023). These successes have rightly motivated continued research and commercialization. However, for the vast majority of non-symbiotic inoculants targeting functions such as phosphorus solubilization, pathogen suppression, or abiotic stress mitigation, the transition from controlled laboratory conditions to complex, heterogeneous field environments reveals a suite of formidable challenges that limit their reliability and scalability**.** These limitations often undermine the efficacy, reliability, and economic

viability of inoculation strategies, casting doubt on their scalability for widespread sustainable agriculture (Etesami, 2025). This section critically examines the primary barriers, including cultivation biases, establishment failures, context-dependency, and profound issues of scale and permanence.

3.1. The "misconception of cultivation" and biased selection

A foundational obstacle in microbial inoculation is the " misconception of cultivation"—the significant bias introduced by our reliance on standard laboratory techniques. Historically, it was estimated that over 99% of environmental microbes resist cultivation under standard laboratory conditions (Prakash et al., 2021). While modern methods like microfluidic platforms and *in situ* diffusion chambers have improved recovery rates (Alkayyali et al., 2021; Jung et al., 2022), a profound bias persists. These methods preferentially isolate fast-growing, copiotrophic taxa (e.g., Proteobacteria and *Bacillus*), while the slow-growing, oligotrophic, and interdependent members of the community remain largely inaccessible. This bias has a critical consequence: the systematic missing of *keystone taxa*. These are species that exert a disproportionate influence on community structure and ecosystem function, despite often being low in abundance (Herren and McMahon, 2018). Many keystone taxa are recalcitrant to cultivation because their growth depends on specific growth initiation factors—such as resuscitation-promoting factors (Rpfs) (Mukamolova et al., 1999) or siderophores provided by neighboring microbes (D'Onofrio et al., 2010)—or on complex ecological interactions that are nearly impossible to replicate *in vitro*. Consequently, inoculation programs are often built on a non-representative fraction of microbial diversity, lacking the very organisms that may be most critical for robust and stable soil function.

3.2. Barriers to establishment and survival

Even when a potentially beneficial microbe is successfully isolated and cultured, its introduction into soil is akin to releasing a domesticated animal into the wild; it must immediately face intense competition and environmental pressures. *Competition with the resident community.* The established native microbiome is a highly competitive environment. Inoculants often fail to secure a niche because resident microbes, already adapted to the local soil conditions, can outcompete them for resources and space (Mawarda et al., 2022a). Paradoxically, the inoculant itself can facilitate its own competitive loss by releasing metabolites that are exploited by the resident community, thereby strengthening its competitors (Čaušević et al., 2024). *Edaphic Factors.* Soil conditions such as pH, temperature, and moisture are major determinants of inoculant survival. For instance, the efficacy of *Azospirillum* in maize is optimal at 25–35°C but declines sharply at higher temperatures (dos Santos Lima et al., 2022). Similarly, acidic soils can severely reduce the survival and metabolic activity of inoculants like *Bacillus thuringiensis* (Mohammad et al., 2011). These abiotic stresses can render an otherwise potent inoculant completely ineffective. *Predation.* The soil food web presents a direct threat to introduced bacteria. Protozoan grazing and bacteriophage predation are major causes of inoculant mortality (Song et al., 2015; Zhang et al., 2014). Inoculants, often applied in a planktonic state, are particularly vulnerable to these predators, which can rapidly decimate their populations before they can establish in protective biofilms or microniches.

3.3. Context-dependency and lack of transferability

Perhaps the most significant practical challenge is the stark context-dependency of inoculant success. A formulation that demonstrates remarkable results in one soil type, climate, or crop system frequently fails in another (Ayala-Zepeda et al., 2024; O'Callaghan et al., 2022). This lack of transferability stems from the complex interplay of multiple factors: *Soil properties.* Soil pH, texture, and organic matter content directly influence inoculant survival and interact with the native community (Pabar et al., 2024). *Climate and management.* Temperature, rainfall patterns, and agricultural practices (e.g., organic *vs.* conventional tillage) create dynamic conditions that can either support or suppress the introduced microbes (Buscardo et al., 2024). *Crop genotype.* The plant host itself is a major driver, with different cultivars recruiting distinct rhizosphere communities through their root exudate profiles, further modulating inoculant performance (Bulgarelli et al., 2022). This inconsistency undermines farmer confidence and limits the commercial potential of "one-size-fits-all" microbial products, as their performance becomes unpredictable outside of narrowly defined contexts.

3.4. The problem of scale and permanence

Microbial inoculation faces two interconnected, grand challenges: the problem of physical scale and the problem of ecological permanence. *The logistical challenge of scale*. Inoculating vast agricultural landscapes is a monumental logistical and economic undertaking. While emerging technologies like drone-assisted application offer promise for precision delivery (Guebsi et al., 2024; Hernández-García et al., 2025), they come with high costs and regulatory hurdles (Ayamga et al., 2021). The feasibility of uniformly applying viable microbes across thousands of hectares, especially for smallholder farmers, remains a significant barrier. *The transient nature vs. self-sustaining communities*. Crucially, most inoculations are transient. Even successful introductions often result in a rapid boom-and-bust cycle, with inoculant populations declining to undetectable levels within a single growing season (Wang et al., 2021). This contrasts sharply with a well-functioning native microbiome, which is a self-

sustaining, resilient community capable of perpetuating itself through seasons. Achieving permanence—where an inoculant not only establishes but becomes a stable, functional member of the soil ecosystem—is the exception rather than the rule. Ecological processes like competition and assembly dictate that long-term persistence is not guaranteed by mere introduction (Klimasmith et al., 2024; Vandermaesen et al., 2024). In conclusion, the challenges of cultivation bias, establishment barriers, context-dependency, and transient efficacy reveal the inherent limitations of a simplistic "introduce and conquer" approach to soil microbiome management. These hurdles compel a paradigm shift away from reliance on external inoculation and towards strategies that nurture the resident microbial communities already adapted to local conditions—the focus of the subsequent sections.

4. The "Soil-First" Framework: Strategies to Foster the Native Microbiome

Given the profound challenges associated with microbial inoculation, a paradigm shift is warranted—from introducing exogenous microbes to nurturing the resident soil microbiome. This "Soil-First" framework posits that the most robust, resilient, and self-sustaining soil ecosystems are built by managing the environment to favor the establishment and function of beneficial native microbial communities. This section outlines three synergistic strategies: using organic amendments to build microbial wealth, leveraging plant power to engineer the rhizosphere, and modifying soil management to protect microbial habitats.

4.1. Organic amendments: The foundation of microbial wealth

Organic amendments are cornerstones of the Soil-First approach, serving a dual purpose: they provide a slow-release food source and create a favorable physical habitat, thereby stimulating the activity and diversity of indigenous soil microbes. *Compost and manure: inoculation and sustenance.* While compost and manure introduce exogenous microbes, their primary value lies in activating and sustaining the native soil-borne microbiota (Semenov et al., 2021). These amendments provide a complex mixture of organic carbon and nutrients that fuel microbial growth, leading to increased microbial biomass, enhanced enzymatic activities, and greater network complexity (Liu et al., 2022; Ren et al., 2019). Mature compost is particularly effective in suppressing soil-borne pathogens by enriching beneficial taxa like *Trichoderma* and *Bacillus*, with field studies reporting disease incidence reductions of 50-70% for *Fusarium* wilt and 40-60% for *Rhizoctonia solani* compared to unamended controls (Cao et al., 2018; Pugliese, 2021). Long-term (≥5 years) compost application increases total microbial biomass by 30-80% and microbial diversity (Shannon index) by 15-25% compared to synthetic fertilizer-only treatments (Liu et al., 2022; Ren et al., 2019). However, careful management is required, as excessive application can reduce microbial diversity, and raw manure can introduce antibiotic resistance genes (ARGs), though these often dissipate as native communities reassert dominance (Guo et al., 2023; Wang et al., 2020). *Biochar: a porous scaffold for microbial life.* Biochar, a carbon-rich porous material, functions as a long-lasting microbial habitat. Its intricate pore network offers refuge for microbes from predation and desiccation, while its ability to modulate soil pH and nutrient availability creates favorable micro-niches (Etesami et al., 2025; Palansooriya et al., 2019; Yang et al., 2022). This scaffold supports a more diverse and stable microbial community, enhancing functions like nutrient cycling (Yu et al., 2019). Furthermore, the co-application of biochar with manure or compost can synergistically improve soil aggregation and suppress ARGs by altering the conditions for horizontal gene transfer (Etesami et al., 2025; Fang et al., 2025; Qian et al., 2023). The benefits are highly dependent on biochar properties—such as pore size, which dictates whether aerobic or anaerobic microbes colonize it—and application rate, with moderate doses being optimal (Srocke et al., 2021; Xia et al., 2025).

4.2. Leveraging plant power: The rhizosphere as an engineering tool

Plants are active architects of their soil environment, primarily through root exudates. Strategic plant management can therefore be used to recruit and sustain specific beneficial microbial consortia. *Cover crops: Maintaining a living root foundation.* The presence of living roots is a continuous signal for microbial activity. Cover crops maintain this "rhizosphere pump," providing a steady stream of root exudates—sugars, organic acids, and secondary metabolites—that serve as the primary energy source for soil microbes (Olanrewaju et al., 2019). This continuous supply supports higher microbial diversity and activity, even outside the main crop season (Ghosh et al., 2024). The choice of cover crop species matters, as different plants release unique exudate profiles that selectively recruit distinct microbial taxa; for instance, legumes release flavonoids that favor nitrogen-fixing bacteria (Seitz et al., 2023). Cover crop incorporation has been shown to increase subsequent cash crop yields by 5-15% in low-input systems, with legume cover crops providing nitrogen equivalent to 50-100 kg ha^{-1} of synthetic N fertilizer (Ghosh et al., 2024; Seitz et al., 2023). Management, including termination method, also influences outcomes, with mechanical termination generally fostering more beneficial microbial communities than chemical methods (Centurión et al., 2022). *Crop diversity and rotation: shifting the exudate menu.* Monocultures lead to a simplified, often pathogenic, microbiome. In contrast, crop diversity and

rotation create a dynamically shifting landscape of root exudates, which selects for a more taxonomically and functionally diverse microbial community (Yang et al., 2023; Zhou et al., 2017). This diversity enhances the complexity and stability of microbial networks, which is a key driver of ecosystem multifunctionality, including nutrient cycling and disease suppression (Yang et al., 2023). Quantitatively, diversified crop rotations (3+ crop species) increase soil microbial alpha diversity by 10-20% and network edge density by 25-40% compared to monocultures, translating to a 15-30% reduction in synthetic fertilizer requirements (Yang et al., 2023; Zhou et al., 2017). Legume-based rotations are particularly powerful, enriching for nitrogen-fixing bacteria and fostering fungal networks that improve carbon sequestration (Meng et al., 2025; Yu et al., 2023). By breaking the continuous life cycle of host-specific pathogens, rotations are a cornerstone of natural disease management (Niu et al., 2017).

4.3. Modifying soil management to protect microbial habitats

The physical habitat of soil is critical for microbial survival. Practices that minimize disturbance and buffer environmental extremes are essential for maintaining a functional microbiome. *Reduced/no-Till: Preserving microbial infrastructure.* Intensive tillage is a major disruptor of soil structure, fragmenting the delicate hyphal networks of arbuscular mycorrhizal fungi (AMF) and other beneficial microbes. Reduced or no-till practices preserve this critical infrastructure, leading to higher microbial biomass, enhanced AMF colonization, and greater accumulation of fungal-derived organic compounds like glomalin-related soil protein (GRSP) (Curaqueo et al., 2011; Yang et al., 2024). This fungal-driven process is vital for forming stable soil aggregates and sequestering carbon (Dai et al., 2015). While a potential trade-off can be a temporary increase in certain pathogens, this is effectively mitigated by combining no-till with diversified crop rotations (Chen et al., 2024; Wang et al., 2020). *Water management: Avoiding abiotic stress.* Soil microbes are highly sensitive to moisture fluctuations. Drought enriches for stress-tolerant taxa like Actinomycetota, while waterlogging favors anaerobic organisms, often at the expense of overall diversity (Ebrahimi-Zarandi et al., 2023; Kundel et al., 2020; Zhang et al., 2025). Optimal water management, which avoids these extremes, is therefore crucial for maintaining a diverse and functional microbiome. Practices such as conservation tillage, which improves water infiltration and retention, and precision irrigation help buffer microbial communities against stress (Sharma et al., 2013). The integration of organic amendments like compost further enhances microbial resilience to drought and waterlogging, particularly in sandy soils (Amarasinghe et al., 2024; Siebielec et al., 2020). In conclusion, the "Soil-First" framework offers a synergistic and ecologically robust pathway to soil health. By combining organic amendments to build resources, strategic plantings to engineer the rhizosphere, and protective tillage and water management, we can cultivate a native microbiome that is resilient, self-sustaining, and capable of delivering the ecosystem services upon which sustainable agriculture depends.

5. Comparative Analysis: Native Enhancement Versus Inoculation

The preceding sections have detailed the challenges of microbial inoculation and the principles of the "Soil-First" framework. To crystallize this comparison, this section provides a direct, head-to-head analysis of the two paradigms across key ecological and practical metrics (Table 1). The evidence compellingly demonstrates that enhancing the native microbiome is a more robust, resilient, and sustainable strategy for long-term soil health than the introduction of exogenous microbial inoculants. The comparative analysis reveals a fundamental dichotomy. Microbial inoculation is a reductionist approach, attempting to engineer soil health by adding discrete, often non-resident parts. This strategy is hamstrung by the immense complexity of soil ecosystems, leading to inconsistent results and a lack of permanence. Its most appropriate application appears to be in highly specific, short-term scenarios, such as jump-starting processes in severely degraded soils where the native microbiome is absent, or in controlled environments like hydroponics. In contrast, native community enhancement is an ecological approach that works with the existing soil food web. By providing the right conditions—organic matter for food, habitat structure *via* biochar and reduced tillage, and diverse plant hosts through cover crops and rotations—we empower the native microbial community to self-organize into a resilient and multifunctional network. This strategy acknowledges that a healthy soil microbiome is not a simple sum of its parts, but a complex, adaptive system. Therefore, for the goal of widespread, sustainable soil health, fostering the native microbiome is not just a superior alternative to inoculation; it is a foundational principle. The future of sustainable land management lies not in introducing foreign microbes, but in nurturing the vast, ancient, and highly adapted microbial wealth already beneath our feet.

6. Synthesis and Future Perspectives

The evidence synthesized in this review compellingly argues for a fundamental paradigm shift in agricultural soil management: from a focus on introducing exogenous microbial inoculants to a strategy centered on fostering the native soil microbiome. The "Soil-First" framework, which enhances microbial habitat through organic amendments, cover cropping, and reduced disturbance, provides a more robust, resilient, and self-sustaining path

Table 1. A head-to-head comparison of soil management paradigms

Criterion	Microbial inoculation	Native community enhancement
Microbial diversity	Low. Typically introduces 1 to a few strains, resulting in minimal impact on overall alpha and beta diversity compared to environmental context (Li et al., 2024; Trabelsi and Mhamdi, 2013).	High. Supports thousands of microbial taxa, maintaining a broad phylogenetic and functional spectrum, including rare taxa critical for resilience (Li et al., 2024; Wang et al., 2023).
Functional redundancy & resilience	Low. Creates a "single point of failure." The loss or failure of the introduced strain can lead to a complete loss of the targeted function (Luo et al., 2023a).	High. Multiple taxa can perform similar functions, buffering the ecosystem against disturbance, species loss, and environmental fluctuations (Luo et al., 2023a; Schwartz et al., 2000).
Establishment & permanence	Often poor and transient. Inoculants are frequently outcompeted by the resident community, with effects dissipating after a single season or requiring repeated, costly applications (Čaušević et al., 2024; Papin et al., 2024; Wang et al., 2021).	Strong and self-sustaining. Managed native communities are already adapted, leading to stable establishment and long-term persistence without further intervention (Honjo et al., 2024; Middleton et al., 2015).
Context-dependency	High. Success is highly dependent on specific soil pH, moisture, temperature, and the composition of the resident microbiome. An inoculant that works in one system often fails in another (Bashan et al., 2014; Jiao et al., 2019).	Low. Leverages locally adapted communities that are already optimized for the prevailing conditions, making the strategy robust across a wider range of environments (Cleland et al., 2013; Jiang et al., 2023).
Ecosystem service scope	Narrow. Typically targets a single function (e.g., phosphorus solubilization, pathogen suppression). May even create trade-offs, such as boosting carbon sequestration at the expense of water retention (Hao et al., 2025; Zhou et al., 2025a).	Broad. Promotes simultaneous, multifunctional benefits, including enhanced carbon sequestration, soil aggregation, water retention, and nutrient cycling, driven by high network complexity (He et al., 2025; Maestre et al., 2012; Turner et al., 2022).
Network complexity	Reduces or simplifies microbial association networks, potentially increasing short-term stability through dominant strain effects but reducing functional interconnectivity (Li et al., 2024).	Increases complexity and robustness, fostering positive interactions and niche stability that underpin ecosystem multifunctionality and long-term resilience (Chen et al., 2022b; Wang et al., 2024).
Time scale of effectiveness	Short-term, rapid onset (days to weeks). Effects are typically transient, often dissipating within a single growing season unless reapplied. Requires repeated applications for sustained benefits (Wang et al., 2021; Papin et al., 2024).	Long-term, slower establishment (months to years). Benefits accrue gradually as soil organic matter and habitat structure improve. Once established, effects are self-sustaining and persistent across multiple seasons without reapplication (Luo et al., 2023b; Mbuthia et al., 2015).
Predictability / Controllability	Low to moderate predictability under field conditions. High variability in outcomes due to sensitivity to edaphic, climatic, and biotic factors. Greater theoretical controllability in controlled environments (e.g., greenhouses) but limited in open systems (Ayala-Zepeda et al., 2024; O'Callaghan et al., 2022).	Moderate to high predictability when best management practices are followed. Outcomes are more robust across environmental gradients due to reliance on locally adapted communities. Controllability is indirect, achieved through habitat manipulation rather than direct introduction, requiring adaptive management (Soto et al., 2021; Adeniji et al., 2024).
Integration & scalability	Technologically scalable but often requires sophisticated formulation and repeated application, limiting practicality for smallholders. Lacks integration with local knowledge (Bashan et al., 2014).	Scalable through participatory models and adaptive management. Integrates indigenous and local knowledge, enhancing social-ecological resilience and adoption (Hill et al., 2012; Lee and Chen, 2021).

to soil health. As we conclude, it is critical to synthesize these insights, acknowledge nuanced applications, identify key research gaps, and consider the implications for future research and agricultural policy.

6.1. Integrating approaches: A nuanced view

While the case for nurturing the indigenous microbiome is strong, a complete dismissal of microbial inoculants is neither practical nor scientifically justified. The key is to

recognize their specific, limited role within a broader ecological framework. Inoculants can function effectively as "starter cultures" in highly specific scenarios where the native microbiome is severely depleted or dysfunctional, such as in drastically degraded post-mining landscapes or heavily sterilized soils (Jia et al., 2025; Li et al., 2025a). In these contexts, introducing microbial consortia can jump-start essential processes like nutrient cycling and organic matter decomposition, creating a foundation for ecosystem recovery (Gutierrez et al., 2020; O'Callaghan et al., 2022). Furthermore, controlled environments like greenhouses and hydroponic systems offer a more predictable setting for inoculants, where environmental variables can be managed to favor their establishment (Arif et al., 2020). However, even in these successful applications, the inoculant is not the end goal but a temporary catalyst. The ultimate objective remains the transition to a diverse, self-regulating, and self-sustaining soil ecosystem (Adeniji et al., 2024). The most promising inoculants for facilitating this transition are not single-strain commercial products but synthetic microbial communities (SynComs) derived from and tailored to native soils, which have demonstrated a superior ability to integrate and persist (Delgado-Baquerizo, 2022; Velte et al., 2025). It is also worth noting that *Rhizobium* inoculants represent a special case of high success due to the intimate, co-evolved symbiosis with legumes that provides a strong selective niche for the introduced strain—a condition that is not generalizable to most other microbial functions (Lindström and Mousavi, 2020).

6.1.1. Acknowledging potential trade-offs of enhanced microbial complexity

While the 'Soil-First' framework predominantly favors the enrichment of beneficial microbial consortia, it is essential to acknowledge that increased microbial complexity and cross-feeding interactions may not invariably favor beneficial taxa. Under specific conditions, particularly those involving high nutrient inputs, altered redox conditions, or specific crop genotypes, habitat management practices could inadvertently promote undesirable or pathogenic microbial groups within the native community (Jimenez-Sanchez et al., 2015; Van Bruggen et al., 2015). For instance, long-term organic amendments have been associated with transient increases in potential human pathogens such as Escherichia coli or Salmonella spp., particularly when raw manure is applied without proper composting (Alegbeleye et al., 2018; Urra et al., 2019). Similarly, the enhanced network connectivity that underpins functional resilience could, in principle, facilitate the spread of quorum-sensing signals or mobile genetic elements among pathogenic populations, a phenomenon sometimes termed the 'dark side' of microbial connectivity (Raaijmakers and Mazzola, 2016; Zhu et al., 2019). The risk of such outcomes is context-dependent, influenced by factors such as amendment type (mature compost vs. raw manure), crop species, and the initial prevalence of pathogens**.** Importantly, a well-managed, diverse native microbiome typically exhibits competitive exclusion and resource preemption, which suppress rather than facilitate pathogen establishment (Mallon et al., 2015; Wei et al., 2015). Thus, while the potential for unintended consequences exists, the weight of evidence indicates that fostering native diversity remains a net-positive strategy. Nonetheless, future research should explicitly investigate the conditions under which habitat management might promote pathogenic groups and develop diagnostic frameworks to predict and mitigate such outcomes.

6.2. Key research gaps and future directions

Despite the growing body of evidence, several critical knowledge gaps must be addressed to refine and advance the "Soil-First" paradigm.

Identifying keystone taxa and their triggers: While we understand that keystone taxa disproportionately influence microbiome structure and function (Herren and McMahon, 2018; Xun et al., 2021), we lack a comprehensive catalog of these critical organisms in different agricultural soils and under various management regimes. Future research must pinpoint specific keystone taxa and, more importantly, identify the soil management practices that selectively enrich them. Understanding the "triggers"—such as specific root exudates from certain cover crops or the chemical composition of organic amendments—that activate their beneficial functions is a crucial next step (Chao et al., 2024).

Understanding microbial succession during management transitions: The shift from conventional, high-input agriculture to soil-health-focused management induces a succession in the soil microbial community. However, the patterns and drivers of this succession are not fully understood (Liu et al., 2022; Wen et al., 2025). Longitudinal studies tracking microbial community composition, network structure, and functional genes over multiple seasons are needed to predict the trajectory and timeline of soil health recovery. This knowledge would help farmers manage expectations and optimize their practices during the transition period.

Developing accessible diagnostic tools for soil microbiome health: For the "Soil-First" paradigm to be widely adopted, farmers need accessible, interpretable tools to diagnose the "health" of their soil microbiome. Current molecular techniques (e.g., high-throughput sequencing) are powerful for research but are often too complex, slow, and expensive for routine on-farm use (O'Callaghan et al., 2022). Future work should focus on developing simplified, cost-effective biomarkers or bioindicators—perhaps based on key enzymatic activities,

specific microbial taxa, or network properties—that can provide a reliable snapshot of soil biological status, enabling adaptive management (Adeniji et al., 2024).

6.3. Implications for policy and agricultural practice

The paradigm shift from microbial products to microbial habitat management has profound implications for how we support and practice agriculture.

Incentivizing soil-building practices: Agricultural policies must evolve beyond subsidizing chemical inputs and instead create financial incentives for farmers who adopt practices that build long-term soil health. Programs such as carbon farming credits, which reward practices like cover cropping and organic amendment application that sequester soil organic carbon, directly align with the goal of fostering a healthy native microbiome (Soto et al., 2021). Support for composting infrastructure and technical assistance for transitioning to reduced-tillage systems are also critical policy levers.

Shifting the agricultural narrative: For decades, the agricultural industry has promoted a "silver bullet" product-based approach. A fundamental shift in narrative is required, moving the farmer's role from a "product applier" to an "ecosystem manager." This involves education and extension services that emphasize understanding and managing the soil as a living ecosystem. Participatory models, such as Farmer Field Schools and co-creation projects where farmers and scientists collaboratively develop and test management strategies, have proven highly effective in fostering this understanding and ensuring that practices are context-specific and socially acceptable (Adeniji et al., 2024; Soto et al., 2021). In conclusion, while microbial inoculants have a niche role, the future of sustainable soil health lies in empowering the native microbiome. By focusing on building soil organic matter, maintaining living roots, and reducing physical and chemical disturbance, we can cultivate the inherent capacity of the soil to sustain its own fertility, suppress disease, and support productive agriculture for generations to come.

7. Conclusion

The evidence synthesized in this review overwhelmingly indicates that the most effective, resilient, and sustainable way to harness the power of the soil microbiome is not by introducing exogenous microbial players, but by systematically nurturing the immense functional potential of the native community. The decades-long pursuit of microbial inoculants as agricultural "silver bullets" has largely faltered on the hard rocks of ecological reality—establishment failure, context-dependency, and transient effects. In contrast, a management paradigm that prioritizes the soil habitat itself—through organic amendments, diversified plant systems, and reduced disturbance—unlocks the latent power of the indigenous microbiome. This approach leverages the native community's inherent advantages: local adaptation, deep integration into soil food webs, and a self-organizing capacity for resilience that no single-strain inoculant can match. This "Soil-First" paradigm represents more than just a technical shift in agricultural practice; it is a more profound alignment with fundamental ecological principles. It moves us from a philosophy of domination and simplistic intervention to one of stewardship and co-evolution with the soil ecosystem. By choosing to foster rather than replace, to empower rather than inoculate, we open a path to agricultural systems that are not merely productive in the short term, but are fundamentally resilient, regenerative, and capable of sustaining life for generations to come. The future of soil health lies not in a package from a factory, but in the vibrant, ancient world beneath our feet.

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