

RECRUITING MICROBIOMES FOR SUSTAINABLE AGRICULTURE: THE FOUNDATION OF THE NEXT AGRICULTURAL REVOLUTION <https://doi.org/10.63330/aurumpub.015-013>

Abraham Guerra¹, Nilo Ricardo Corrêa de Mello Júnior², Andrea Cecilia Romero Coronado³, Anderson Oswaldo Manares Romero⁴ and Hector Jose Valerio Ardon⁵

ABSTRACT

Conventional agriculture, while successful in boosting yields, has caused systemic soil degradation, threatening global food security. This chapter argues that the next agricultural revolution will be microbial, requiring a paradigm shift from a chemical-centric approach to one that actively recruits the soil microbiome. It begins by analyzing the physical, chemical, and biological decay resulting from industrial farming practices before framing soil as a living ecosystem, contrasting the properties of a healthy, biodiverse matrix with a degraded, dysfunctional one. The "bio-input toolkit"—a suite of microbial inoculants—is then presented as a key strategy for intervention, with an overview of its lab-to-field production pipeline. Ultimately, the chapter concludes that while bio-inputs serve as critical tools for intervention, the long-term goal is ecological integration through regenerative agriculture, fostering resilient, self-sustaining agroecosystems founded on a renewed partnership with the living soil.

Keywords: Soil degradation; Agricultural biotechnology; Soil; Biofertilizers; Bioinput; Fertilizer; Pesticides.

¹ Bachelor's Degree in Microbiology
São Paulo State University "Júlio de Mesquita Filho - Faculty of Agricultural and Veterinary Sciences
E-mail: abraham.guerra@unesp.br

² Master in Irrigated Horticulture
São Paulo State University "Júlio de Mesquita Filho - Faculty of Agricultural and Veterinary Sciences
E-mail: Nilo.jr@unesp.br

³ Bachelor's Degree in Microbiology
São Paulo State University "Júlio de Mesquita Filho - Faculty of Agricultural and Veterinary Sciences
E-mail: a.coronado@unesp.br

⁴ Bachelor's Degree in Microbiology
São Paulo State University "Júlio de Mesquita Filho - Faculty of Agricultural and Veterinary Sciences
E-mail: a.manares@unesp.br

⁵ Master in Agricultural Microbiology
São Paulo State University "Júlio de Mesquita Filho - Faculty of Agricultural and Veterinary Sciences
E-mail: hectorvalerio68@gmail.com



INTRODUCTION

The 20th century witnessed an unprecedented agricultural transformation. The green revolution, driven by advances in crop breeding, intensive use of agrochemicals, and mechanization, led to substantial increases in agricultural yields, contributing to global food security for a rapidly growing population and strengthening the economy (Pingali, 2012).

However, the achievements of conventional agriculture come with an environmental backdrop that cannot be ignored. Soil should be understood as a living and dynamic edaphic system, integrating the topsoil, subsoil, biota, groundwater, and atmosphere, maintaining essential physical, chemical, and biological exchanges for life (M Roper; V S R Gupta, 2007). This complex system regulates nutrient and energy cycles, structures habitats for countless organisms, and connects different ecological levels, forming the foundation of terrestrial ecosystems (Adão; Pádua; Sousa, 2025a; Dixon et al., 2022; Jiang et al., 2024; Mesele et al., 2025; Tarafdar, 2022).

Human activity, especially agriculture, intervenes in this system, modifying its structure, altering biogeochemical cycles, and influencing productivity. However, the primary function of soil is not to sustain agriculture but to maintain ecosystem balance and resilience, of which agricultural production is only one of its many expressions (Davis; Huggins; Reganold, 2023).

Soil plays an essential role in the geosphere, reinforced by its most abundant and active biological component: microorganisms, which constitute the biological engine of life. These communities form an integrated system that interacts with the physical and chemical environment of the soil, performing vital functions such as organic matter decomposition, nutrient cycling, and the formation of structures that support plant life (Creamer et al., 2022a; David C. Coleman, 2018). This network of organisms and their interactions, encompassing diversity, metabolism, communication, and ecological relationships, constitutes what is known as the soil microbiome (Hopkins; Dungait, 2010; Wang; Chi; Song, 2024a; Zhou et al., 2023).

While conventional agriculture focused primarily on managing the physical and chemical properties of soil, modern studies of the microbiome and soil biology show that soil fertility and resilience fundamentally depend on its biological components and the interactions they establish (Creamer et al., 2022b; Montgomery; Biklé, 2021a).

Historically, and in some cases still today, conventional agriculture neglected the environmental impact of unsustainable practices, with consequences that are now evident. Soil degradation, a crisis affecting approximately 33% of the planet's lands due to erosion, salinization, compaction, and contamination, directly threatens global food security (Bachman, 2015; Brown, 2015; Kopittke et al., 2025a).



This deterioration not only reduces the productive capacity of agricultural systems but also contaminates water bodies, contributes to climate change, and imposes high economic costs on both farmers and society. The loss of fertile soils and contamination of existing ones necessitates the use of new land for agriculture, which is increasingly limited due to urban expansion and land use for human settlements. In a context marked by interconnected global crises —climate change, biodiversity loss, and the challenge of feeding nearly 10 billion people by 2050(Lam, 2025)— the current agricultural paradigm proves unsustainable.

A new agricultural revolution is therefore required, one that is not based on intensive exploitation of resources but on collaboration with nature and the strengthening of ecological processes that sustain life. This chapter proposes that the next agricultural revolution will be microbial. It will involve a profound paradigm shift: moving from a focus solely on soil chemistry and productivity to a comprehensive understanding of its biology and interactions with the ecosystem.

The central strategy of this new era will be to actively recruit the soil microbiome, a vast invisible workforce composed of bacteria, fungi, and other microorganisms, to restore natural functions weakened or displaced by intensive and anthropocentric industrial practices. This recruitment goes beyond the mere application of inoculants; it encompasses a range of strategies, from targeted microbial interventions to ecological redesign of agricultural systems through regenerative practices, intelligent crop rotations, permanent soil cover, and reduced chemical inputs.

By partnering with these microscopic allies, we can rebuild agroecosystems that are not only productive but also resilient, self-regulating, and capable of sustaining life at multiple levels, from the microscale of soil to the global scale of ecosystems. In other words, this microbial revolution does not aim to dominate nature but to work with it, integrating scientific knowledge, technological innovation, and conscious agricultural practices to ensure adequate food production without compromising planetary health.

To support the proposal presented, this chapter is structured into four main sections. It begins with a diagnosis of the soil crisis, demonstrating how conventional agricultural practices such as the intensive use of chemical inputs, reliance on monocultures, high-yield crop varieties, and frequent tillage have progressively degraded soils. These practices have resulted in pollution, erosion, loss of organic carbon, a decline in microbial biodiversity, and substantial economic costs. The second section frames soil as a living ecosystem. It contrasts the complexity and resilience of healthy soils with the dysfunction of degraded systems, emphasizing the critical roles played by the soil microbiome, including nutrient cycling and natural pathogen suppression. Finally, the last section introduces the development and production of the bio-input toolkit, a set of microbial-based products designed to strategically restore essential soil functions. All interventions are framed within the broader paradigm of regenerative



agriculture, which prioritizes microbial recruitment and ecosystem resilience as the foundation for a productive, sustainable, and microbially driven agricultural future.

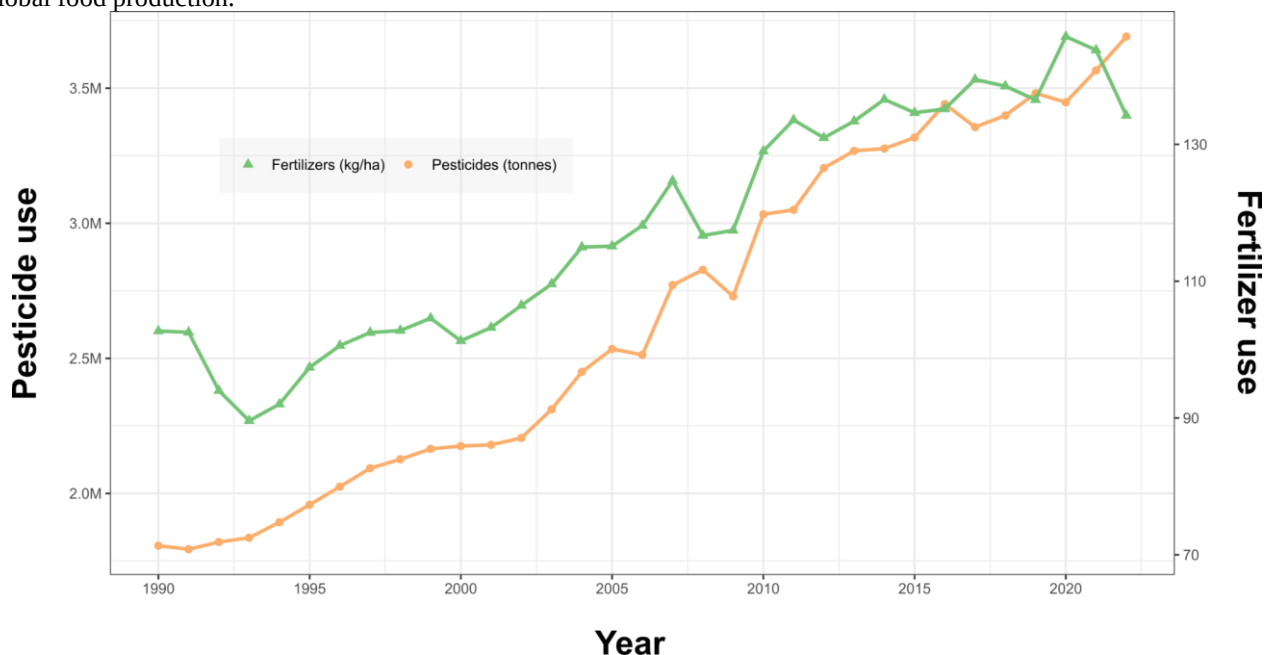
THE LEGACY OF CONVENTIONAL AGRICULTURE: A DEPLETED SOIL

The functional dynamics of conventional agriculture, which has dominated global food production for over half a century, is based on a set of practices involving intensive use of chemicals such as fertilizers, pesticides, and herbicides, a trend that has steadily increased over the last three decades (Fig. 1), heavy machinery, frequent and deep tillage, large-scale monocultures, high-yield varieties selected to maximize productivity but dependent on external inputs, intensive irrigation that alters water availability and promotes salinization, as well as production systems primarily oriented toward immediate yield, often disconnected from biodiversity conservation and the ecological balance of the soil (Angon et al., 2023; Belete; Yadete, 2023; Betancur-Corredor; Lang; Russell, 2022; Elkot et al., 2024; Karaca; Ince, 2023; Montgomery; Biklé, 2021b).

Although agriculture has accompanied humanity since its origins and has transformed over time, the high-yield model consolidated during the 20th century did not arise with the intention of degrading the soil. Rather, it emerged as a response to urgent needs such as hunger and economic growth. However, this productivist approach, designed from an anthropocentric perspective, proved short-sighted: it offered immediate benefits in terms of production but ignored the biological and microbiological processes that sustain soil fertility and resilience.

We now know that for decades negative effects have been accumulating, now expressed in pollution, loss of edaphic biodiversity, and progressive infertility. According to the FAO, 90% of the world's soils could be at risk of degradation by 2050 if these unsustainable practices persist. The magnitude of the problem is striking: approximately 24 billion tons of fertile soil are lost to erosion each year (Smith et al., 2024), equivalent to the disappearance of a football field of productive land every five seconds.

Figure 1. Global trends in fertilizer and pesticide use. Annual evolution of global fertilizer use (kg/ha) and pesticide use (tonnes) between 1990 and 2022. A general trend of consistent increase in the use of both agricultural inputs is observed throughout this period. This highlights the intensification of agricultural practices and the increasing reliance on external inputs in global food production.



This degradation is not an isolated phenomenon but a complex syndrome of interconnected physical, chemical, and biological deterioration. Intensive cultivation has caused the loss of 25–75% of soil organic carbon reserves, compromising nutrient cycling and water retention capacity (Lehtinen et al., 2014). Experimental studies suggest that microbial biodiversity and soil functionality can decrease significantly in monoculture systems compared to diversified systems (Bender; Wagg; Van der Heijden, 2016).

Soil alterations not only cause ecological damage but also have repercussions on agricultural productivity. Excessive nitrogen fertilization contributes to nitrous oxide (N_2O) emissions, a potent greenhouse gas (GONZALEZ-ESTRADA; Camacho Amador, 2017), while indiscriminate pesticide use alters the soil microbiome, affecting essential processes such as biological nitrogen fixation and natural pathogen suppression (Swaine et al., 2025). This erosion of soil health constitutes a critical threat to the long-term viability of food systems.

Rethinking soil as a living ecosystem and adopting regenerative, agroecological practices based on bioinputs is not an idealistic option but a necessary strategy to ensure food security, ecosystem resilience, and future climate stability.

THE THREE DIMENSIONS OF SOIL DEGRADATION: PHYSICAL, CHEMICAL, AND BIOLOGICAL DECAY

Soil degradation manifests as a multidimensional decline in its physical, chemical, and biological properties, a contrast clearly illustrated by the key indicators distinguishing healthy from degraded soil (Fig. 2).

Soil physical degradation is a complex process in which soil structure is compromised, affecting its capacity to support ecological, hydrological, and productive processes. At its core lies the destabilization of soil aggregates, formations that result from the interaction between mineral particles, organic matter such as humus and plant exudates, adsorbed water, and bioactive compounds produced by microorganisms. These aggregates act as the “cement” of the soil, providing cohesion, resistance to erosive forces, and a porous structure that regulates the flow of water, nutrients, and gases (Bedolla-Rivera et al., 2023a; Nunes; Karlen; Moorman, 2020; Weidhuner et al., 2021a, 2021b).

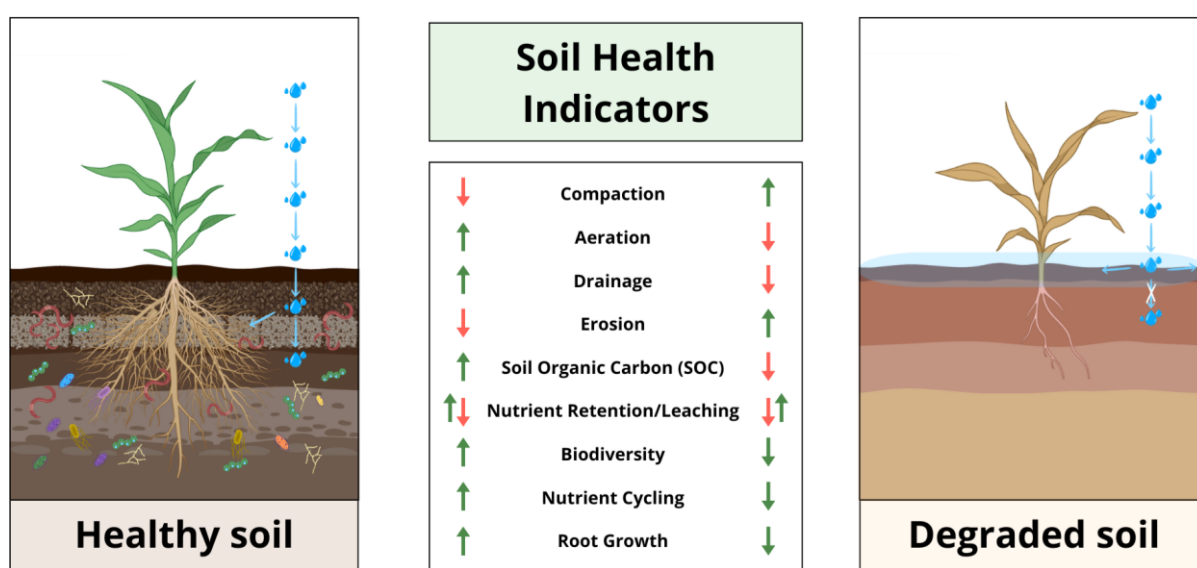
The soil microbiota plays a central role in this aggregation. Bacteria and fungi contribute to the formation and stabilization of aggregates through the decomposition of organic matter and the production of extracellular polymers that bind mineral particles. This microbial activity ensures structural integrity, promotes porosity, and facilitates efficient gas exchange, which is essential for root respiration and soil biochemical activity. The loss of this microbial community, as occurs under intensive tillage or exposure to agrochemicals, triggers a progressive weakening of aggregates, increasing compaction, restricting root growth, and reducing the soil’s capacity to retain water and oxygen (Frene; Pandey; Castrillo, 2024; Montgomery; Biklé, 2021c; Pandey; Bennett, 2024a; Weidhuner et al., 2021b).

From a physical perspective, aggregate degradation alters pore distribution, decreasing macropores that facilitate drainage and increasing micropores that hold water in a form largely unavailable to plants. This leads to denser soils, reduced infiltration, and higher susceptibility to water and wind erosion, where the fertile topsoil is quickly lost. The combination of compaction, lower water retention, and increased surface exposure also raises soil temperature and alters the rhizosphere microclimate, directly affecting biological activity and nutrient cycling (Bedolla-Rivera et al., 2023b; Correa et al., 2019; Frene; Pandey; Castrillo, 2024; Pandey; Bennett, 2024b).

Therefore, physical degradation is not an isolated phenomenon but a synergistic process in which the loss of aggregates and the decline of microbiota generate a vicious cycle: compacted soils reduce porosity and oxygenation, accelerating erosion and ultimately decreasing fertility. This process has direct consequences on agricultural productivity, soil water storage capacity, and the resilience of agroecosystems to droughts, intense rainfall, and climate change (Bedolla-Rivera et al., 2023b; Correa et al., 2019; Frene; Pandey; Castrillo, 2024; Pandey; Bennett, 2024a).

At a global scale, physical degradation is a critical factor in the loss of fertile soil, affecting large regions in the United States (32%), Africa (16%), China (31%), Europe (17%), and India (45%), posing a significant threat to food security and the sustainability of cropping systems (Borrelli et al., 2017; Guo; Hao; Liu, 2015; Lal, 2003; Singh et al., 2020; Tamene et al., 2017).

Figure 2. Soil health indicators between healthy and degraded soil. Fundamental contrast in the physical, chemical, and biological properties between a healthy agricultural soil and a degraded one. The central table details key soil health indicators, using arrows (↑ high/good, ↓ low/poor) to compare their levels in both scenarios: compaction, aeration, drainage, erosion, soil organic carbon (SOC), nutrient retention/leaching, biodiversity, nutrient cycling, and root growth. For the healthy soil, a porous structure with stable aggregates is observed, facilitating water infiltration and supporting a rich microbial community. Plant roots extend deeply, indicating good aeration and access to resources. In contrast, degraded soil exhibits a compacted structure and a crusted surface that impedes infiltration, leading to superficial water accumulation and runoff. Plant roots are shallow, and the soil shows a clear scarcity of microbial life.



The chemical degradation refers to the progressive deterioration of its internal balance, characterized by the loss of organic carbon reserves and the alteration of conditions that sustain fertility. Soil organic carbon (SOC), a key component of organic matter and the foundation of the soil's biological network, is reduced by intensive tillage, which accelerates its oxidation and microbial consumption (Bedolla-Rivera et al., 2023c; Córdova et al., 2025; Joshi et al., 2025; Muhammed et al., 2018; Toth et al., 2025). This decline not only decreases nutrient retention and structural stability but also increases CO₂ emissions, closely linked to climate change.

The recurrent use of synthetic fertilizers, particularly nitrogen-based ones, exacerbates this issue. At high doses, they induce acidification, alter micronutrient availability, and release toxic elements such as aluminum (Bedolla-Rivera et al., 2023d). Their low efficiency promotes nitrogen and phosphorus leaching into groundwater and surface water, triggering eutrophication and the deterioration of aquatic ecosystems (Bedolla-Rivera et al., 2023d; Montgomery; Biklé, 2021d).



This scenario directly impacts soil life: microbial and mycorrhizal communities are impoverished, while contaminants such as heavy metals and hydrocarbons, derived from industrial and atmospheric sources, disrupt processes like nitrogen fixation and microbial respiration (Angon et al., 2024; Bedolla-Rivera et al., 2023d). As a consequence, agroecosystems become less resilient to droughts, intense rainfall, and external pressures, forcing farmers to rely increasingly on external inputs, which raises costs and poses risks to food security.

In response, alternatives focused on SOC restoration and regenerative practices are gaining attention. Strategies such as crop rotation, the use of green manures, biochar, or microbial biofertilizers show promise in counteracting acidification, improving nutrient availability, and reducing contaminants. These approaches not only restore productive capacity but also pave the way toward more sustainable agricultural systems under growing climatic and social pressures.

The biological degradation is perhaps the most fundamental and damaging aspect, as it represents the loss of life in the soil. The combined pressures of monoculture, which provides a limited diet for soil organisms, intensive tillage that destroys their habitats, and the application of broad-spectrum pesticides and fungicides that directly eliminate them have decimated soil biodiversity (Bedolla-Rivera et al., 2023d; Tripathi et al., 2020). This includes a drastic reduction in the abundance and diversity of the entire soil food web, from microorganisms responsible for nutrient cycling to the large ecosystem engineers, such as earthworms (Hofer, 2022; Li; Wang; Shao, 2021; Liu et al., 2025; Tripathi et al., 2020).

Adding to this scenario is a critical collateral effect: physical and chemical degradation acts as a trigger for biological degradation, especially at the microbiological level. Compaction and erosion reduce pore space and oxygen availability, while the loss of organic carbon and intensive use of synthetic fertilizers at uncontrolled doses create a toxic environment that restricts microbial growth (Bellabarba et al., 2024; Longepierre et al., 2022). Acidification, accumulation of heavy metals, and the non-specificity of biocides directly alter the composition and functionality of the soil microbiota, limiting essential processes such as biological nitrogen fixation, decomposition of organic residues, and natural pathogen suppression (Alengebawy et al., 2021; Hussain et al., 2009).

This loss of biological functionality is the main cause of physical and chemical problems: without the living agents that build soil structure, stabilize aggregates, and naturally recycle nutrients, the entire system collapses. Moreover, a cascade of impacts occurs that compromises other levels of the soil food web, including protozoa, nematodes, microarthropods, and earthworms, weakening the resilience of agroecosystems to droughts, floods, or pests, and forcing an increasing dependence on external inputs, with far-reaching economic and ecological consequences (Yan et al., 2025).



QUANTIFYING THE ECONOMIC FALLOUT

The environmental damage caused by soil degradation has direct and escalating economic consequences, threatening both farm-level viability and regional economic health. The most immediate threat falls upon farmers themselves. As the innate fertility of the soil declines, growers are forced to compensate by applying ever-increasing quantities of expensive synthetic inputs to maintain yields (Panagos et al., 2018, 2024; Pimentel et al., 1995). This creates a dependency that erodes farm profitability (Tey; Brindal, 2015). A landmark study on U.S. corn agriculture revealed that fertilizer applied annually serves not to boost yields, but merely to compensate for the ongoing loss of soil fertility from degradation (Jang et al., 2021). This compensatory application costs U.S. corn farmers more than half a billion dollars every year (Jang et al., 2021; Panagos et al., 2018). The problem is compounded by the volatility and sharp increases in fertilizer prices, which have risen dramatically in recent years, placing even greater strain on farm budgets (Hernandez; Torero, 2013; Vos et al., 2025).

Beyond the farm gate, the societal costs of soil degradation are an order of magnitude larger. These off-farm externalities represent the costs that are not paid by the producer but are borne by the public at large (Kopittke et al., 2025b; Laamouri; Khattabi, 2025). The most significant of these is the environmental damage caused by nutrient runoff. Excess nitrogen and phosphorus from agricultural fields are the primary cause of the hypoxic "Dead Zone" in the Gulf of Mexico, an area depleted of oxygen and unable to support marine life, devastating commercial fisheries and coastal economies (Li et al., 2025; Restore the Mississippi River Delta, [S.d.]). The costs of water purification to remove nitrates from drinking water, the loss of recreational value in lakes and rivers plagued by algal blooms, and the damage to aquatic ecosystems are immense (Akinlawo, 2023; Amorim; Moura, 2021). This reveals that what is often considered efficient food production, when judged by short-term outputs or narrow economic indicators, is, in fact, heavily subsidized by the degradation of natural capital and the depletion of public resources.

MICROBIAL DRIVERS OF THE NUTRIENT CYCLE

Given the economic unsustainability of compensating for lost fertility with chemical inputs, it becomes crucial to understand the natural, self-sustaining alternative: the microbial engine that drives the nutrient cycle. In any natural ecosystem, nutrients are continuously cycled, moving from organic matter back into forms that plants can use. The soil microbiome is the primary engine of these biogeochemical cycles (Basu et al., 2021; Mohanty et al., 2021). Without this microbial machinery, essential nutrients would remain locked in unavailable forms, rendering the soil infertile.

One of the most critical of these functions is nitrogen fixation. The Earth's atmosphere is approximately 78% nitrogen gas (Zhang; Low; Xiong, 2025), but this form is inert and unusable by



plants. Certain specialized bacteria, known as diazotrophs, possess the unique ability to "fix" atmospheric nitrogen, converting it into plant-available ammonia (Chen et al., 2024a; Hu et al., 2023; Martinez-Feria et al., 2024). This biological process is the natural equivalent of the energy-intensive Haber-Bosch process used to create synthetic nitrogen fertilizers (Rouwenhorst et al., 2021). Nitrogen-fixing bacteria operate in two main ways: symbiotically, such as *Rhizobium* and *Bradyrhizobium* species that form nodules on the roots of legume plants (e.g., soybeans, peas), and as free-living organisms in the soil, such as *Rhizobia* and *Burkholderia* (Kiprotich et al., 2025; Mahmud et al., 2020; Mowafy et al., 2022). In the symbiotic relationship, the plant provides the bacteria with energy in the form of carbohydrates, and in return, the bacteria supply the plant with a steady source of nitrogen .

Equally important is phosphorus solubilization. Phosphorus is an essential nutrient for plant energy transfer and root development, but it is often the most limiting nutrient in agricultural soils because it is typically bound in insoluble mineral compounds or tied up in organic matter (Alewell et al., 2020; Khan et al., 2023). A diverse group of microorganisms, collectively known as phosphate-solubilizing microorganisms (PSMs), are capable of unlocking this unavailable phosphorus. Bacteria like *Pseudomonas* and *Bacillus*, and fungi such as *Aspergillus* and *Rhizopus* secrete organic acids that dissolve mineral phosphates and produce enzymes called phosphatases that mineralize organic phosphorus, releasing it into the soil solution where plant roots can absorb it (Bashir et al., 2024; Wang et al., 2023a).

Beyond nitrogen and phosphorus, the microbiome orchestrates the cycling of virtually all other essential nutrients. Microbes decompose complex organic matter, releasing potassium, sulfur, calcium, magnesium, and a host of micronutrients in plant-available ionic forms (Chen et al., 2024b; Wang; Chi; Song, 2024b) This constant process of microbial decomposition and mineralization is what constitutes natural soil fertility.

THE SOIL AS AN ECOSYSTEM: A TALE OF TWO FIELDS

To comprehend the shift toward a microbial-centric agriculture, it is essential to fundamentally reframe our concept of soil. Traditionally, the industrial agricultural model treated soil as a passive medium, merely a physical substrate for plant roots and chemical inputs. The ecological reality, however, is that soil is a dynamic, living system (Chen et al., 2024c; Minami, 2021). The difference between a vibrant, healthy agricultural soil and a depleted, degraded one lies in its ecological functionality and biological complexity. Understanding this contrast is key to embracing the “living soil” paradigm and rethinking agriculture from the ground up.



THE SOIL: A LIVING, DYNAMIC SYSTEM

The modern scientific understanding of soil is encapsulated in the definition of soil health as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans" (Fausak et al., 2024a; Lehmann et al., 2020a). This definition is transformative. It moves beyond simple measures of chemical fertility and recognizes that a healthy soil must perform a suite of complex, interconnected ecological functions.

According to the U.S. Department of Agriculture, a healthy soil ecosystem provides five essential and interconnected functions (Natural Resources Conservation Service, [S.d.]). Fundamentally, it regulates water by controlling whether rainfall infiltrates the ground to recharge aquifers or runs off the surface, causing erosion. This ability to manage water allows it to sustain a vast diversity of plant and animal life and provide the physical stability necessary to anchor roots and support human structures. Beyond this foundational role, the soil operates as a dynamic biochemical processor. Its mineral and microbial communities filter and buffer potential pollutants by degrading and detoxifying them. Simultaneously, this same biological engine drives the cycling of essential nutrients, transforming elements like carbon, nitrogen, and phosphorus to make them available for the entire ecosystem.

DEFINING PROPERTIES OF HEALTHY SOIL

A healthy, living soil is characterized by a synergistic interplay of its biological, chemical, and physical properties. While numerous indicators of soil health exist, their interconnected nature across multiple processes often complicates a single, clear-cut definition (Lehmann et al., 2020b). At its core, healthy soil is defined by its rich biodiversity, which can include billions of microorganisms such as bacteria, fungi, protozoa, and nematodes (Fausak et al., 2024b; Lehmann et al., 2020c). This microscopic community is complemented by a host of larger organisms, such as earthworms, ants, beetles and other invertebrates, which together form an intricate soil food web (Ahmed; Al-Mutairi, 2022a; Hajji et al., 2024; Menta; Remelli, 2020; Wilder et al., 2025; Wu et al., 2015). These organisms are not passive inhabitants; they are active ecosystem engineers. Earthworms and insects burrow through the soil, creating channels that improve aeration and water infiltration, while the vast networks of fungal hyphae bind soil particles together (Ahmed; Al-Mutairi, 2022b).

This biological activity is fueled by high organic matter. Soil organic matter (SOM) is the carbon-based material derived from the decomposition of plant and animal residues, and it is the foundation of the soil food web (De Vries et al., 2013). SOM acts as a slow-release reservoir of essential nutrients, improves the soil's capacity to hold onto water and nutrients (cation-exchange capacity), and provides the energy that drives the entire soil ecosystem (SCHNITZER, 1965; Solly et al., 2020).



The combination of high biodiversity and abundant organic matter creates a robust physical structure. This leads to the formation of soil aggregates, another critical indicator of health (Rillig; Muller; Lehmann, 2017). A well-aggregated soil has a crumbly texture and is filled with a network of interconnected pore spaces (Kravchenko et al., 2015; Yang et al., 2025a). This porosity is critical; it allows the soil to function like a sponge, rapidly absorbing rainwater and storing it for plants to use during dry periods (Lipiec et al., 2006; Menon et al., 2020; Robinson et al., 2022). This structure resists compaction and erosion, making the entire agricultural landscape more resilient to the extremes of drought and flood (Adão; Pádua; Sousa, 2025b; Yang et al., 2025b).

A thriving biological community, abundant organic matter, and a well-aggregated structure are mutually reinforced by—and in turn, support—a balanced pH, optimal nutrient levels, and a rich mineral composition, among numerous other factors (Lehmann et al., 2020d).

THE DEGRADED MATRIX: A SYSTEM IN COLLAPSE

In stark contrast, a degraded soil is a dysfunctional system where these vital properties have been deteriorated. The primary symptom of this dysfunction is a collapse of the soil's biological community. Decades of intensive tillage, monocropping, and agrochemical applications have decimated the soil's living community (Montgomery; Biklé, 2021e). The soil food web has collapsed, leading to a dramatic reduction in both the abundance and diversity of microorganisms, and a absence of visible life like earthworms (Bai et al., 2020; Montgomery; Biklé, 2021e; Wang et al., 2023b). With its biological engine stalled, the soil loses its capacity to perform essential functions like nutrient cycling and disease suppression.

This leads to a state of chemical imbalance. With low organic matter, the soil lost its natural fertility and nutrient-holding capacity (Bai et al., 2020; Montgomery; Biklé, 2021e). It becomes entirely dependent on external inputs of synthetic fertilizers to support crop growth. This often results in an overload of the primary macronutrients, nitrogen (N), phosphorus (P), and potassium (K), while becoming deficient in essential trace minerals that are no longer being cycled by microbial activity. The soil's pH can also become unbalanced, swinging to acidic or alkaline extremes that further lock up nutrient availability for plants (Barrow; Hartemink, 2023; Ferrarezi et al., 2022).

Loss of organic matter and biological activity leads to structural collapse: without the biological glues that form and maintain aggregates, soil becomes compacted and dense (James J. Hoorman; João Carlos de Moraes Sá; Randall Reeder, *[S.d.]*), eliminating pore spaces and severely restricting movement of air, water, and plant roots (Bodner et al., 2023; Dorau; Luster; Mansfeldt, 2018; Peng et al., 2024). Water can no longer infiltrate effectively; instead, it ponds on the surface or runs off, carrying away loose soil particles and valuable nutrients in a process of accelerated erosion (Ju et al., 2024; Peng et al., 2024).



The soil feels hard and solid to the touch, and plant roots struggle to penetrate the compacted layers, limiting their access to water and nutrients (Jobbágy et al., 2023; Ju et al., 2024). This degraded matrix is brittle and dysfunctional, highly vulnerable to environmental stresses, and incapable of sustaining productive agriculture without massive and continuous artificial life support.

ARCHITECTS OF PLANT HEALTH AND RESILIENCE

The soil microbiome's role extends far beyond that of a simple nutrient provider. It functions as a dynamic, interactive partner with plants, directly influencing their growth, health, and ability to withstand environmental stress. Many soil microbes, particularly those inhabiting the rhizosphere—the narrow zone of soil surrounding plant roots (Olanrewaju; Glick; Babalola, 2017a; Poria et al., 2022; Thepbandit; Athinuwat, 2024), are classified as plant growth-promoting bacteria (PGPB). These organisms enhance plant development through several mechanisms, one of the most important being the synthesis of phytohormones.

PGPB can produce auxins, which coordinate plant cell elongation and directional growth (Olanrewaju; Glick; Babalola, 2017b; Rolón-Cárdenas et al., 2022); gibberellins, which stimulate stem elongation and seed germination (Castro-Camba et al., 2022; Olanrewaju; Glick; Babalola, 2017c; Shtin; Dello Ioio; Del Bianco, 2022); and cytokinins, which regulate cell division and shoot formation (Akhtar et al., 2020; Giron et al., 2013; Olanrewaju; Glick; Babalola, 2017c; Wu et al., 2021).

These microbial-derived hormones act as key regulators in plant interactions with other organisms, including both beneficial microbes and insect herbivores. By supplementing the plant's own hormone production, PGPB can significantly boost overall growth, development, and adaptive responses to biotic and abiotic stress.

The microbiome also serves as the plant's first line of defense against disease, providing biotic stress resistance through a variety of biocontrol mechanisms (Ali; Tyagi; Bae, 2023; Du; Han; Tsuda, 2025). Beneficial microbes can outcompete pathogenic organisms for space and nutrients on the root surface, effectively crowding them out (Ali; Tyagi; Bae, 2023; Chakraborty, 2023). Much produce a potent arsenal of antimicrobial compounds, including antibiotics and antifungal enzymes, that directly inhibit or kill pathogens (Ali; Tyagi; Bae, 2023; Das et al., 2021; Roca; Monge-Olivares; Matilla, 2024; Shodmonova et al., 2025). Furthermore, the presence of certain beneficial microbes on the root can trigger a state of alertness in the plant's own immune system, a phenomenon known as Induced Systemic Resistance (ISR) (Pieterse et al., 2014). This primes the entire plant to respond more quickly and effectively to a future pathogen attack.

A healthy microbiome is crucial for conferring abiotic stress tolerance, enhancing the plant's resilience to environmental challenges like drought and salinity (Ali et al., 2023; Ullah et al., 2025a).



Among the most important microbial contributors are arbuscular mycorrhizal fungi (AMF), which form symbiotic associations with the roots of most crop plants. These fungi develop extensive networks of microscopic filaments (hyphae) that extend far beyond the reach of the roots themselves (Berruti et al., 2016; Ortiz et al., 2015a; Sagar et al., 2021; Ullah et al., 2025b). This hyphal network acts as a highly efficient extension of the root system, dramatically increasing the plant's ability to explore the soil and absorb water and immobile nutrients, thereby improving drought tolerance (Ortiz et al., 2015a; Ruiz-Lozano; Azcón, 1995). Other microbes can help plants tolerate salinity stress by producing osmo-protective compounds that enable plant cells to maintain water balance in high-salt environments. These include species such as *Bacillus* and *Pseudomonas*, among other (Goszcz et al., 2025; Ortiz et al., 2015b).

APPLIED MICROBIOLOGY: THE BIO-INPUT TOOLKIT

Recognizing the central role of the microbiome in soil health and plant productivity has catalyzed the development of a new class of agricultural technologies: microbial inoculants. Whether the so-called biofertilizers, biostimulants, or biopesticides, these products are formulations containing specific, living beneficial microorganisms. When applied to seeds, soil, or the plant itself, they act as a targeted intervention, reintroducing key microbial functions that have been lost in degraded agricultural systems. They represent a tangible way to deliver a concentrated dose of beneficial microbes directly where they are most needed, jump-starting the process of ecological restoration.

The creation of these products is a sophisticated, science-driven process that bridges microbiology, fermentation science, and agronomy.

SCALING UP BENEFICIAL MICROBES: THE BIO-INPUT DEVELOPMENT

The journey of a microbial inoculant from a promising microorganism in a petri dish to a commercial product on a farm shelf is a rigorous, multi-stage pipeline designed to ensure efficacy, safety, and stability (Fig. 3). This process transforms a biological concept into a reliable agricultural tool.

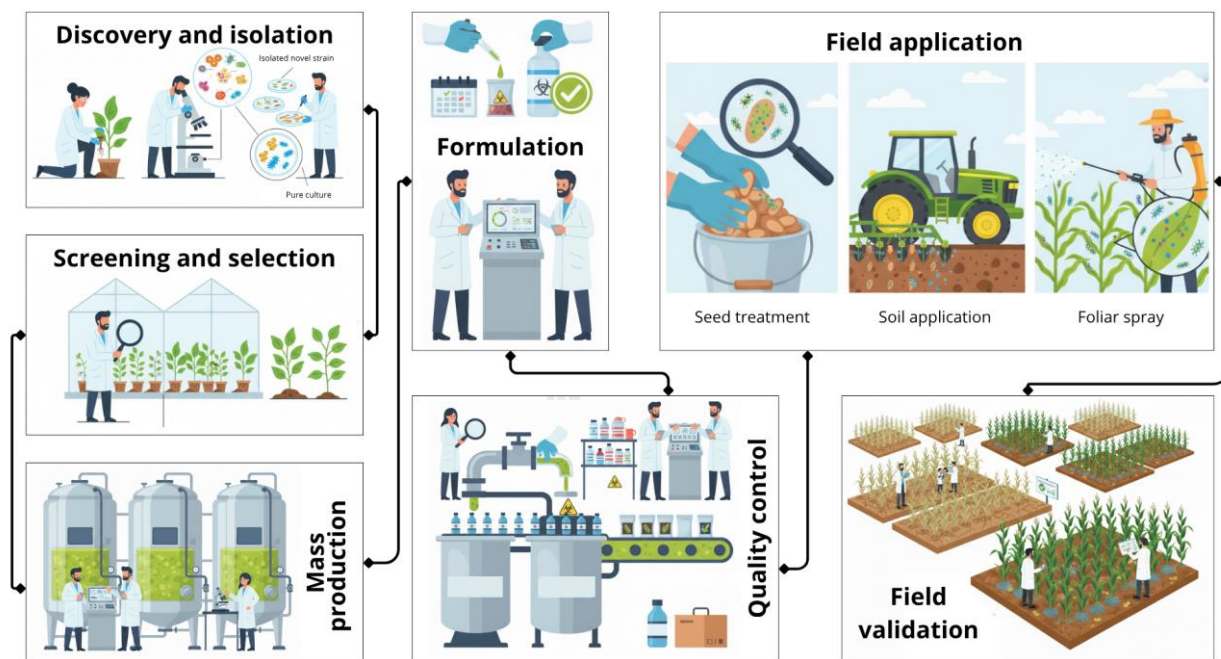
- **Discovery and isolation:** The process begins with bioprospecting. Scientists search for candidate microorganisms in diverse environments, such as the rhizospheres of healthy plants, pristine soils, water, or even plant tissues themselves. The goal is to isolate novel strains of bacteria or fungi that exhibit beneficial traits.
- **Screening and selection:** Thousands of isolated strains are then put through a rigorous screening process. In laboratory and greenhouse trials, they are tested for specific functions, such as the ability to fix nitrogen, solubilize phosphorus, produce growth hormones, or inhibit pathogens. Only the most effective strains are selected for further development.
- **Mass production (fermentation):** The selected strain is then grown to a massive scale. This



is typically done through liquid fermentation in large, sterile bioreactors (Dos Reis et al., 2024; Hernández-Álvarez et al., 2023; Yunus et al., 2022). The microbes are provided with a specific nutrient medium and grown under precisely controlled conditions (temperature, pH, oxygen) to achieve a very high population density, often in the billions of cells per milliliter (Dos Reis et al., 2024; Yunus et al., 2022).

- **Formulation:** The concentrated microbial culture is then formulated into a stable, easy-to-use product. This involves mixing the live microbes with a carrier material. Formulations can be liquid, often containing stabilizers and cell protectants to prolong shelf life, or solid, such as powders mixed with peat, clay, or biochar (Dos Reis et al., 2024; Figiel et al., 2025; Sharma, 2023; Sifton; Smith; Thomas, 2023; Yunus et al., 2022). The formulation is critical for protecting the microbes from environmental stress and ensuring their survival until they reach the field.
- **Quality control:** Throughout the process, strict quality control is essential. Each batch is tested to verify the concentration of the target microorganism, to ensure the product is free from contaminants, and to confirm its viability and shelf life (Figiel et al., 2025; Prisa; Fresco; Spagnuolo, 2023). This step is crucial for building farmer trust and ensuring consistent product performance.
- **Field application:** The final product is designed for easy application by the farmer. Common methods include seed treatment, where seeds are coated with the inoculant before planting, soil application, where the product is applied directly into the furrow during planting or broadcast over the field, or foliar spray, where a liquid formulation is sprayed onto the plant's leaves (Da Silva Medina; Rotondo; Rodríguez, 2024; Dzvene; Chiduza, 2024; Lawal; Babalola, 2014; Prisa; Fresco; Spagnuolo, 2023; Santos; Nogueira; Hungria, 2019).
- **Field validation:** Before full commercialization, the final formulated product undergoes extensive field trials across various geographical regions, soil types, and climatic conditions. These large-scale trials validate the product's effectiveness under real-world farming conditions and provide the data needed for regulatory approval and agronomic recommendations (Da Silva Medina; Rotondo; Rodríguez, 2024; Ibáñez et al., 2023; Maaz et al., 2025).

Figure 3. Schematic overview of the microbial bio-input production and application process, from lab to field. This flow diagram details the critical stages in the development of microbial bio-inputs for agriculture. The process begins with discovery and isolation, where scientists identify and cultivate beneficial microbial strains. This is followed by screening and selection through laboratory and greenhouse trials to identify the most effective strains. Selected strains then proceed to mass production in large-scale bioreactors, utilizing liquid fermentation to achieve high cell densities. Subsequently, formulation converts the concentrated microbial culture into stable, ready-to-use products (liquid or solid), using carrier materials and stabilizers. The quality control stage ensures the viability, purity, and concentration of microorganisms in each batch. Finally, bio-inputs are prepared for field application through methods such as seed treatment, direct soil application, or foliar spray, and their efficacy is rigorously validated in the field validation phase through controlled field trials under diverse conditions prior to commercialization.



CULTIVATING A MICROBIAL FUTURE

The arc of modern agriculture is bending back toward its biological roots. The industrial paradigm, with its reliance on chemical force, has pushed our agroecosystems to their breaking point, revealing a systemic failure that demands a systemic solution. This chapter has argued that the solution lies beneath our feet, within the complex, living world of the soil microbiome. The path forward for a sustainable, resilient, and productive agriculture is not to further intensify our chemical interventions but to learn how to recruit the vast, powerful, and efficient microbial workforce that has been driving planetary ecosystems throughout time.

This recruitment is a dual strategy, a journey from intervention to integration. In the depleted soils that are the legacy of industrial farming, targeted bio-inputs—the biofertilizers, biopesticides, and biostimulants of the burgeoning agricultural biologicals market—serve as essential tools for intervention. They are the ecological catalysts reintroducing critical functions and jump-starting the dormant biological engine of the soil. The rapid growth of the global bio-input market, driven by consumer demand,



regulatory pressure, and a growing recognition of their economic and environmental benefits, signals that this phase of the microbial revolution is already well underway.

Yet, these powerful tools are ultimately a means to a greater end. The long-term strategy, embodied by the principles of regenerative agriculture, is one of integration. By minimizing soil disturbance, keeping the soil covered, maximizing biodiversity, and maintaining living roots, we can create agroecosystems that are designed to be ideal habitats for microbial life. These practices shift the farmer's role from that of a chemical applicator to that of an ecosystem cultivator—one who focuses not on feeding the plant directly, but on feeding the soil life that, in turn, nurtures the plant. This approach creates a positive feedback loop of regeneration, where improving soil life leads to better soil structure, enhanced nutrient and water cycling, and greater resilience to pests, diseases, and climate shocks, ultimately building a farm that is self-sustaining and self-regulating. This transition from a chemical to a microbial future demands a concerted effort from all sectors.

The scientific community must accelerate its exploration of the soil frontier. We need deeper research into the efficacy of multi-strain microbial consortia, the complex chemical dialogues that govern plant-microbe interactions, and the development of next-generation bio-inputs. Crucially, this lab-based work must be complemented by more long-term, systems-level field trials that assess the synergistic effects of bio-inputs and regenerative practices over time.

Governments must create an enabling environment for this transition. This requires policies modeled on the success of nations like Brazil: sustained public investment in agricultural, the creation of streamlined, specific regulatory pathways for bio-inputs that recognize their unique biological nature, and the implementation of financial incentives—such as subsidies, tax credits, or robust carbon markets—that reward farmers for the public goods they provide when they adopt regenerative practices and build soil health. Policymakers must also recognize the profound national security and public health co-benefits of this shift, from enhanced food sovereignty to mitigating the crisis of antibiotic resistance.

The most fundamental shift must occur in the fields and in the minds of farmers, agronomists, and agricultural advisors. The transition requires moving beyond a mindset of isolated problems and silver-bullet solutions. It demands embracing complexity and adopting a new paradigm: to "feed the soil" with a diverse diet of carbon through plants, and in doing so, to empower the soil's own microbial workforce to do the heavy lifting of nutrient provision and plant protection.

Cultivating this microbial future is one of the great challenges and opportunities of the 21st century. It promises an agriculture that is not a source of environmental degradation but a powerful engine of ecological regeneration. It offers a pathway to producing abundant, nutritious food while simultaneously building soil, cleaning water, protecting biodiversity, and sequestering atmospheric



carbon. The foundation for this future is not a new chemical or a new machine, but a renewed partnership with the oldest and most powerful force in agriculture: the living soil.

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