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Ish Prakash
Assistant Professor-Cum-Scientist, Rajendra Prasad Central Agricultural University, Pusa, Samastipur, Bihar, India

Kamsali Sukeswara Achari
Ph.D. Research Scholar, Department of Agronomy, ICAR-National Dairy Research Institute, Karnal, Haryana, India

Chetali Prakash Jawade
Ph.D. Research Scholar, Department of Plant Pathology, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India

Piyush Kumar
Ph.D Research Scholar, Department of Plant Pathology, FOA, Sher-e-Kashmir University of Agricultural Sciences and Technology, Shalimar, Srinagar, Jammu and Kashmir, India

Piyush Parihar
Ph.D Research Scholar, Department of Plant Pathology, FOA, Sher-e-Kashmir University of Agricultural Sciences and Technology, Shalimar, Srinagar, Jammu and Kashmir, India

Mohit Meena
M.Sc. (Ag.) Mycology & Plant Pathology, Department of Mycology and Plant Pathology, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh India

Kanika
B.sc. (Hons.) Agriculture, College of Agriculture, Agricultural University, Jodhpur, Rajasthan, India

Abhishek Malav
M.Sc. (Ag.) Agronomy, Department of Agronomy, Institutes of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh, India

Babburi Sai Maheswari
Ph.D Research Scholar, Department of Plant Pathology, FOA, Sher-e-Kashmir University of Agricultural Sciences and Technology, Shalimar, Srinagar, Jammu and Kashmir, India

Corresponding Author:
Piyush Kumar
Ph.D Research Scholar, Department of Plant Pathology, FOA, Wadoora, Sher-e-Kashmir University of Agricultural Sciences and Technology, Shalimar, Srinagar, Jammu and Kashmir, India

Soil microbiome dynamics: Implications for soil health and sustainable agriculture

Ish Prakash, Kamsali Sukeswara Achari, Chetali Prakash Jawade, Piyush Kumar, Piyush Parihar, Mohit Meena, Kanika, Abhishek Malav and Babburi Sai Maheswari

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Abstract
The soil microbiome is a complex and dynamic community of microorganisms essential for biogeochemical cycling, soil health, plant productivity and ecosystem stability. Advances in molecular biology, metagenomics, and bioinformatics have enhanced the understanding of microbial diversity, revealing key taxa such as nitrogen-fixing bacteria (*Rhizobium*, *Azospirillum*), phosphate-solubilizing microbes (*Pseudomonas*, *Bacillus*), and arbuscular mycorrhizal fungi (*Glomeromycota*), which contribute to nutrient acquisition, plant growth, and disease suppression. However, intensive agriculture, pollution, and climate change threaten microbial communities, disrupting ecosystem functions and degrading soil health. Comprehensive profiling of the soil microbiome has become crucial for assessing soil quality and guiding sustainable management practices. By identifying beneficial microbes and pathogens, microbiome analysis supports strategies to enhance soil fertility, reduce chemical inputs, and improve crop resilience. Integrating microbiome-based solutions with modern agricultural practices can enhance long-term soil sustainability and productivity. Future research should focus on harnessing microbial interactions and engineering microbial consortia to develop innovative, climate-resilient farming systems.

Keywords: Soil microbiome, metagenomics, *Glomeromycota*, intensive agriculture, consortia

Introduction

The agricultural sector faces many challenges, including climate change, soil degradation, and the growing demand for food due to an increasing global population. By 2050, the global population is projected to reach 9.7 billion, necessitating a 70% increase in food production to meet rising demands (Suman *et al*., 2022) [72]. Traditional farming methods, which rely heavily on chemical fertilizers and pesticides, have contributed to soil depletion, pollution, loss of biodiversity as well as increased susceptibility to diseases and environmental stresses (Hartmann *et al*., 2015) [30]. To overcome these issues, sustainable solutions are essential. One promising approach is harnessing the beneficial microbes found in soil and plants. The collective population of these beneficial microbial organisms, is referred to as the microbiota (Suman *et al*., 2022) [72]. These microorganisms play a crucial role in breaking down organic matter, making nutrients available to plants, improving soil structure, and protecting crops from diseases. Some microbes, such as nitrogen-fixing bacteria, enhance soil fertility by converting atmospheric nitrogen into a form that plants can absorb, reducing the need for synthetic fertilizers. Others help plants resist drought, pests, and other environmental stresses. With advancements in microbiome research, scientists can now better understand how these microbial communities' function and interact with plants. This knowledge allows for the development of biofertilizers, biopesticides, and other microbiome-based agricultural solutions that boost crop production while minimizing harm to the environment. By integrating these natural processes into modern farming, we can improve soil health, increase food security, and create a more sustainable agricultural system for future generations (Molino *et al*., 2021) [51].

Plants contain diverse microbial communities across different ecological niches, including the rhizosphere, rhizoplane, phylloplane, and endosphere, which can influence growth positively or negatively. While plant-microbe interactions have been extensively studied, their complexity remains largely unresolved. Harnessing soil microbiota offers a sustainable strategy to enhance crop resilience, improve soil health, and address challenges related to food security and environmental sustainability (Schlaeppi & Bulgarelli, 2015) [64].

What Is Soil Microbiome?

Microbiome is a community of indigenous microorganisms that exist within a specific host or environmental niche (Lederberg and McCray, 2001) [40]. These microbiomes are present across various ecosystems, including humans, animals, plants, soils, marine environments, and other natural habitats. The combination of microorganisms in each environment is unique, but soils are considered to host the most complex and diverse microbiome on our planet (Xiang *et al*., 2021) [29]. The microbial communities residing within the soil, collectively known as the soil microbiome.

Composition and Diversity of Soil Microbiome

The soil microbiome is a complex, highly dynamic ecosystem on the earth, with an estimated 10^9 to 10^{11} microbial cells per gram (Raynaud & Nunan, 2014) [61] consisting of diverse microbial taxa, each contributing to soil health and plant productivity. The soil microbiome is composed of a diverse range of microorganisms including bacteria, fungi, archaea, actinomycetes, protozoa and viruses, each with unique functional roles. A single gram of soil can contain over 50,000 microbial species (Bardgett & van der Putten, 2014; Fierer, 2017) [3, 23], making the soil microbiome the most genetically diverse biological community known. Despite its vast diversity, the soil microbiome remains largely unexplored, with less than 1% of its microbial inhabitants having been studied to date (Kendzior *et al*., 2022) [38].

Among these, bacteria dominate in terms of abundance, with key phyla such as *Proteobacteria*, *Actinobacteria*, and *Firmicutes* playing crucial roles in nutrient cycling. For instance, *Rhizobium* and *Bradyrhizobium* species form symbiotic relationships with leguminous plants, fixing atmospheric nitrogen into bioavailable forms (Kuypers *et al*., 2018) [39]. Similarly, phosphate-solubilizing bacteria like *Pseudomonas* and *Bacillus* enhance phosphorus availability by secreting organic acids that dissolve mineral-bound phosphates (Richardson & Simpson, 2011) [62].

Fungi, particularly mycorrhizal species (*Glomeromycota*), extend their hyphal networks into the soil, effectively acting as an extension of plant root systems. These fungi facilitate the uptake of water and nutrients, such as phosphorus and zinc, in exchange for plant-derived carbohydrates (Tedersoo *et al*., 2014) [74]. Beyond mutualistic fungi, saprophytic species (*Ascomycota*, *Basidiomycota*) are critical decomposers, breaking down complex organic matter into simpler compounds that enrich soil fertility.

Archaea, though less abundant, contribute significantly to nitrogen and carbon cycling. Ammonia-oxidizing archaea (*Thaumarchaeota*) drive nitrification, converting ammonia into nitrite, a key step in the nitrogen cycle (Offre *et al*., 2013) [56]. Additionally, methanogenic archaea in waterlogged soils produce methane, influencing greenhouse gas emissions (Conrad, 2007) [17].

Viruses and protozoa, often overlooked, regulate microbial populations through predation and infection. Bacteriophages (viruses that infect bacteria) modulate bacterial diversity, while protozoa control bacterial biomass by grazing, indirectly stimulating nutrient mineralization (Emerson *et al*., 2018) [21].

Actinomycetes are widely prevalent in soil ecosystems and play a crucial role in agricultural systems by contributing to the carbon cycle through both photosynthetic carbon fixation and the decomposition of organic matter. They are particularly effective in breaking down resistant compounds such as humus, facilitating nutrient recycling. As a dominant group of soil microorganisms, actinomycetes produce a range of hydrolytic enzymes that support the efficient degradation and turnover of organic materials in the environment.

Factors affecting soil microbiome diversity

The composition, diversity, and functional capacity of the soil microbiome are intricately linked to ecosystem processes and are influenced by soil physicochemical properties and anthropogenic activities. These factors collectively shape microbial community structure and regulate ecological functions within the soil environment (Fierer, 2017) [23]. Despite their significance, the soil microbiome is modulated by various biotic and abiotic factors, including plant species, microbial predators, and competitors, as well as soil pH, moisture content, texture, structure, nutrient availability, agricultural practices, climate conditions, plant diversity, land degradation, and deforestation (Islam *et al*., 2020) [32]. The structure of the soil microbiome is primarily governed by edaphic properties, which act as an ecological filter, influencing microbial diversity, community composition, and functional dynamics (De Gannes *et al*., 2015) [19]. Soil structure significantly impacts mesofauna communities, with micropores in clay particles providing protective microhabitats that facilitate growth while simultaneously limiting microbial predation, thereby shaping soil food web interactions. Although no single factor universally dictates microbiome composition (Fierer, 2017) [23], key soil properties such as moisture, pH, and texture serve as primary predictors of microbial diversity on a global scale (Brockett *et al*., 2012) [12], though their impact varies across microbial groups. For instance, soil moisture is a crucial factor of protist composition and microbial biomass (Mishra *et al*., 2023) [50] for maintaining their life and helps in their mobility in soil, dissolution of nutrients, and diffusion of gases (Young and Ritz, 2000) [82].

The soil microbiome is highly sensitive to contamination from heavy metals, microplastics, and pesticides. Heavy metals, introduced through fertilizers and industrial emissions, persist in soil without microbial degradation, disrupting biochemical processes and microbial balance (Boros-Lajszner *et al*., 2021) [11]. Microplastic accumulation alters microbial structure and function (Guo *et al*., 2020) [29], while pesticide residues, though understudied, can affect soil microbes, with 30-50% of applied pesticides accumulating in soils (Rodríguez-Eugenio, *et al*., 2018) [63].

Fungal Diversity	More Important	Bacterial Diversity
MAP pH MAT PET Fire from the last time Other variables: Under edaphic factors as soil carbon, CN ratio, P, K, Ca, Mg, Soil moisture, Potential of evapotranspiration	Less Important	pH N2 MAP PET NPP Soil moisture Other variables: Under edaphic factors as soil carbon, CN ratio, Ca, Mg, K, and under climatic/geographic factors as seasonality, latitude and fire from the last time.

Fig 1: Abiotic and biotic factors affecting soil bacterial and fungal communities (Bahram *et al*., 2018)

Impact of Agricultural Practices on Soil Microbial Communities

Modern agricultural systems have profoundly altered soil microbiomes. Intensive tillage, for example, disrupts fungal hyphal networks and reduces mycorrhizal associations, leading to decreased soil aggregation and increased erosion (Mbuthia *et al*., 2015) [46]. Conversely, conservation tillage and no-till farming preserve fungal biomass and enhance organic matter retention, promoting long-term soil health. The overuse of synthetic fertilizers has been shown to reduce microbial diversity by favouring fast-growing, copiotrophic bacteria over slower-growing oligotrophs that thrive in low-nutrient conditions (Geisseler & Scow, 2014) [27]. High nitrogen inputs can also suppress nitrogen-fixing bacteria, disrupting natural nutrient cycling processes (Zhou *et al*., 2016) [85]. Pesticides and herbicides, while effective in pest control, often have non-target effects on beneficial microbes. Glyphosate, for instance, has been found to inhibit the growth of *Pseudomonas* and *Bradyrhizobium*, reducing nitrogen fixation in legume crops (Zobiole *et al*., 2010) [86].

In contrast, organic farming practices such as compost application, cover cropping, and crop rotation enhance microbial diversity and activity. Organic amendments introduce a wide range of carbon substrates, supporting diverse microbial consortia involved in decomposition and nutrient cycling (Lori *et al*., 2017) [43].

Table 1: Impacts of sustainable management practices on the soil microbiome, soil processes, and ecological functions (Nadeu *et al*., 2023) [52]

Practice	Description of the impact
Crop rotations	Enhanced crop productivity, suppression of soil-borne pathogens, and decreased reliance on external agrochemical inputs.
Cover crop	Facilitate the release of root exudates, contribute to the stabilization of topsoil and suppression of weed growth, enhance carbon sequestration, and minimize nitrogen leaching losses.
Tillage	Incorporates crop residues into the soil while disrupting soil aggregates, leading to significant alterations in microbial diversity, structural integrity, and community composition.
No Tillage	Reduces the risk of soil erosion and improves the soil's capacity to retain moisture; however, it may inadvertently lead to a greater reliance on chemical pesticides and herbicides under certain management practices.
Microbial inoculants	Enhance root development and improve plant water absorption, while promoting carbon sequestration and lowering methane (CH_4) emissions. However, current understanding of the interactions between introduced microbial inoculants and indigenous soil microbial communities remains incomplete, and a significant disparity persists between laboratory findings and field-level outcomes.
Organic fertilizers	Stimulate the activation of specific microbial taxa and facilitate the introduction of external microbial strains into the soil ecosystem. These amendments ensure a prolonged release of essential nutrients, enhancing soil fertility over time. However, excessive application may negatively impact microbial diversity, particularly by reducing the overall abundance of beneficial bacterial populations.
Inorganic fertilizers	Excessive use may contribute to soil degradation, alterations in organic carbon levels, and shifts in soil pH. Such overapplication can disrupt the nutrient equilibrium within the soil matrix and negatively influence microbial ecology, often resulting in a decline in beneficial bacterial populations.
Pesticides	The toxicity of pesticides poses a significant threat to soil microorganisms. Their application can alter microbial communities by selectively promoting certain taxa while suppressing others, leading to an imbalance in the microbial ecosystem.
Mixed fertilizers	It has a beneficial effect on both crop productivity and the population of soil microorganisms.

Soil Microbiome and One Health

The concept of one Health establishes a fundamental connection between human, animal, and environmental health by recognizing their dynamic interactions within ecosystems. It emphasizes the necessity of multidisciplinary approaches to human, animal, and environmental health as essential for enhancing overall well-being. Originating from the fields of human and veterinary medicine, particularly in the context of antimicrobial resistance and infectious disease management, One Health has expanded its application to agrifood systems. As endorsed by the Food and Agriculture Organization (FAO), this perspective underscores the critical role of soil health in fostering broader benefits for human health (Kemper & Lal, 2017) [37]. The soil microbiome plays a crucial role in One Health; it impacts both the environment and human health indirectly and directly. The direct impact of this is on plant growth, promotion, plant pathogens, soil health and reducing climate change, while indirect impacts are on soil-borne pathogens, animal social behaviour, geophagia, dust and exposure, or antibiotic-resistant bacteria (Banerjee and van der Heijden, 2023) [2]. In addition to controlling soil functions, soil microbes also play a crucial role in enabling ecosystem services and terrestrial biodiversity. Further, soil microbes regulate the cycling of essential elements in soil and facilitate the uptake of these elements by plants, such as zinc and selenium, which are delivered by mycorrhizal fungi (Smith and Read, 2008) [70]. Carrara *et al*. (2023) [14] demonstrated that sustaining robust populations of beneficial soil fungi, specifically arbuscular mycorrhizal fungi, can enhance the concentration of an amino acid with antioxidant and anti-inflammatory properties across various plant species. Beneficial microbes contribute significantly to human health; however, the microbiome also presents potential risks. A reduction in microbial diversity can disrupt ecosystem stability, leading to an increased prevalence of pests and pathogens, thereby elevating the risk of disease emergence (Wall *et al*., 2015) [78]. Additionally, soil functions as a major reservoir for pathogenic microorganisms that impact humans, animals, and plants, with exposure to soil-borne pathogens accounting for hundreds of millions of infections annually (Singh *et al*., 2023) [69].

Soil Microbiome and their role in Sustainable Agriculture

1. Soil fertility and nutrient management

The Food and Agriculture Organization (FAO) recently defined the soil microbiome as a transformative element in food production and agricultural sustainability, emphasizing its crucial role in enhancing soil health, nutrient cycling, and ecosystem resilience (Kendzior *et al*., 2022) [38]. Microorganisms such as nitrogen-fixing bacteria (*Rhizobium*, *Azospirillum*) convert atmospheric nitrogen into plant-usable forms, while phosphorus-solubilizing bacteria (*Pseudomonas*, *Bacillus*) enhance phosphorus availability by breaking down insoluble compounds (Richardson & Simpson, 2011) [62]. Mycorrhizal fungi, particularly arbuscular mycorrhizal fungi (AMF), improve plant access to essential nutrients like phosphorus and micronutrients by extending root absorption capacity (Smith & Read, 2008). Decomposer microbes, including *Actinobacteria* and saprophytic fungi, break down organic matter, releasing nutrients in bioavailable forms and improving soil structure and water retention (Jansson & Prosser, 2013) [35]. Enhancing soil health enables farmers to improve crop productivity, reduce nutrient depletion, and mitigate soil erosion (Lynch, 2015) [45].

2. Reducing chemical inputs

The soil microbiome plays a vital role in minimizing the use of chemical inputs, including pesticides, herbicides, and fertilizers, by enhancing nutrient availability, promoting plant health, and naturally suppressing pests and diseases. Additionally, certain microbial species produce antibiotics and secondary metabolites that suppress soil-borne pathogens, reducing the dependency on chemical pesticides (Compant *et al*., 2010) [16]. Plant growth-promoting rhizobacteria (PGPR) and endophytic microbes enhance plant resilience to abiotic stressors like drought and salinity, further reducing the necessity for synthetic agrochemicals (Naylor & Coleman-Derr, 2018) [54]. By leveraging microbial-based solutions such as biofertilizers and biopesticides, farmers can transition toward more sustainable agricultural practices while maintaining productivity and soil health (Geisseler & Scow, 2014) [27]. Furthermore, by promoting the proliferation of beneficial microorganisms and understanding the factors regulating the soil microbiome, farmers can reduce their reliance on chemical inputs, leading to lower costs and minimizing adverse environmental impacts.

3. Disease management

The soil microbiome plays a crucial role in plant disease management by suppressing soil-borne pathogens, enhancing plant immunity, and promoting overall soil health. Beneficial microorganisms, including bacteria, fungi, and archaea, contribute to disease suppression through multiple mechanisms such as competition, antibiosis, and induced systemic resistance (ISR) (Berendsen *et al*., 2012) [9]. Soil microbiome helps manage diseases through microbial competition, where beneficial microbes outcompete harmful pathogens for nutrients and space, limiting their ability to establish and spread (Mendes *et al*., 2011) [48]. Antibiosis, the production of antimicrobial compounds by beneficial microbes, also plays a significant role in disease suppression. For example, species of *Bacillus* and *Pseudomonas* produce antibiotics and lytic enzymes that inhibit the growth of pathogens like *Fusarium* and *Phytophthora* (Raaijmakers & Mazzola, 2012) [60].

Another important mechanism is induced systemic resistance (ISR), where beneficial microbes stimulate plant defence responses, making them more resistant to future pathogen attacks. Certain plant growth-promoting rhizobacteria (PGPR), such as *Pseudomonas fluorescens*, and mycorrhizal fungi enhance the production of plant defence-related compounds, thereby strengthening resistance against diseases (Pieterse *et al*., 2014) [58]. Additionally, the soil microbiome contributes to disease suppressive soils, where microbial communities naturally prevent the establishment of plant pathogens. Long-term organic farming practices, crop rotation, and compost applications have been shown to enhance disease-suppressive microbial populations, reducing the need for chemical fungicides (Chapelle *et al*., 2016) [15].

Harnessing the soil microbiome for disease management presents a sustainable alternative to chemical pesticides, reducing environmental impact while promoting healthier crops. Future research on microbiome engineering and targeted microbial inoculants could further enhance biological disease control strategies in agriculture.

4. Precision agriculture

To maximize agricultural efficiency and minimize environmental consequences, precision farming can be synergistically combined with soil microbiome analysis. Understanding the structure and functional potential of microbial communities within the soil allows for site-specific agricultural interventions, enabling farmers to optimize nutrient management, enhance crop productivity, and reduce reliance on chemical inputs. This integrative approach fosters sustainable agricultural systems by improving soil health, promoting ecological balance, and mitigating environmental degradation (McPherson *et al*., 2018) [47].

Table 2: Essential contributions of soil microorganisms toward sustainable agriculture in different crops

Microbiome	Crop	Mechanism	References
Bacillus thuringiensis AZP2	Wheat	Enhancement of stress tolerance	Thies *et al*., 2006 [75]
Streptomyces, *Luteimonas*, and *Enterobacter* sp.	Tomato	The inoculants affect the structure of the bacteria and enhance the growth of the plant	Timmusk *et al*., 2014 [76]
Erwinia species and *P. chlororaphis* sp.	Coffee	Increase in the availability of insoluble phosphate to soluble phosphate in soil by increase in the production of organic acids	Bar On *et al*., 2018 [5]
Pseudomonas aeruginosa FP6 sp.	Chilli	The biosynthesis of siderophores to enhances iron availability	Lim and Kim, 2013 [41]
Mesorhizobium sp.	Bengal gram	Improve nutrient uptake efficiency and promote higher crop productivity	Tardif *et al*., 2016 [73]
Bacillus amyloliquefaciens 5113 and *Azospirillum brasilense* NO 40	Wheat	Enhance enzymatic activity under drought conditions to safeguard wheat against water stress	Yergeau *et al*., 2015 [81]
Pseudomonas syringae sp.	Kiwifruit	Influences the phyllosphere microbiome, leading to a reduction in microbial diversity	Barelli *et al*., 2020 [4]
Rhizoctonia solani sp.	Lettuce	Increases the diversity of Gammaproteobacteria	Purahong *et al*., 2018 [59]

Table 3: Functions performed by soil microbiome

Microorganism	Illustrative Member/s	Functional Group	Main Functions	References
N_2- fixing bacteria	Rhizobium	Nitrogen fixation	Converting atmospheric nitrogen (N_2) into biologically available forms, such as amides and ammonium ions (NH_4^+)	Lladó *et al*., 2017 [42]
Eukaryote	Protists	Bio-indicators	Energy transfer within ecosystems by functioning as primary consumers, feeding on bacteria, fungi, and other small eukaryotes in the food web.	Bates *et al*., 2013 [6]
Fungi and bacteria	Mycorrhizal Fungi, β-proteobacteria	Decomposers	Nutrient retention, Synthesis and decomposition of Soil Organic Matter, Emissions of greenhouse gases such as CO_2 and CH_4, facilitating carbon sequestration	Jansson & Hofmockel, 2019; Johns, 2017 [87, 36]
Archaea	Ammonia oxidizing archaea Crenarchaeote	Soil nitrifiers, Nutrient Transformers	Soil nitrification, Ammonia oxidation and Nitrification	Islam *et al*., 2020 [32]
Mesofauna	Collembola, Enchytraeids	Soil invertebrates	Decomposition of organic matter, development of soil structure, and carbon cycling	Mishra and Singh, 2020 [49]

Advanced Tool Kits for Unveiling the Black Box of Soil

Conventional methods such as Denaturing Gradient Gel Electrophoresis (DGGE), Terminal Restriction Fragment Length Polymorphism (T-RFLP), Phospholipid Fatty Acid Analysis (PLFA), and Amplified Ribosomal DNA Restriction Analysis (ARISA) have traditionally been used to study soil microbial communities and their dynamics. While these techniques provide foundational insights, they offer limited understanding of microbial interactions and functions within the soil ecosystem (Bell-Dereske *et al*., 2017) [7]. The advent of advanced molecular and sequencing technologies has significantly enhanced the resolution and depth of microbial analysis (Dubey *et al*., 2019) [20]. Modern omics approaches—including genomics, metagenomics, metatranscriptomics, metaproteomics, and metabolomics—now enable detailed exploration of microbial diversity, functional potential, and host-microbe interactions. Among these, metagenomics is particularly powerful, allowing detection of both culturable and unculturable microbes with high specificity. The integration of these tools with next-generation sequencing offers a more robust, precise, and environmentally sustainable approach to studying soil microbiomes and their ecological roles (Biswas and Sarkar, 2018) [10].

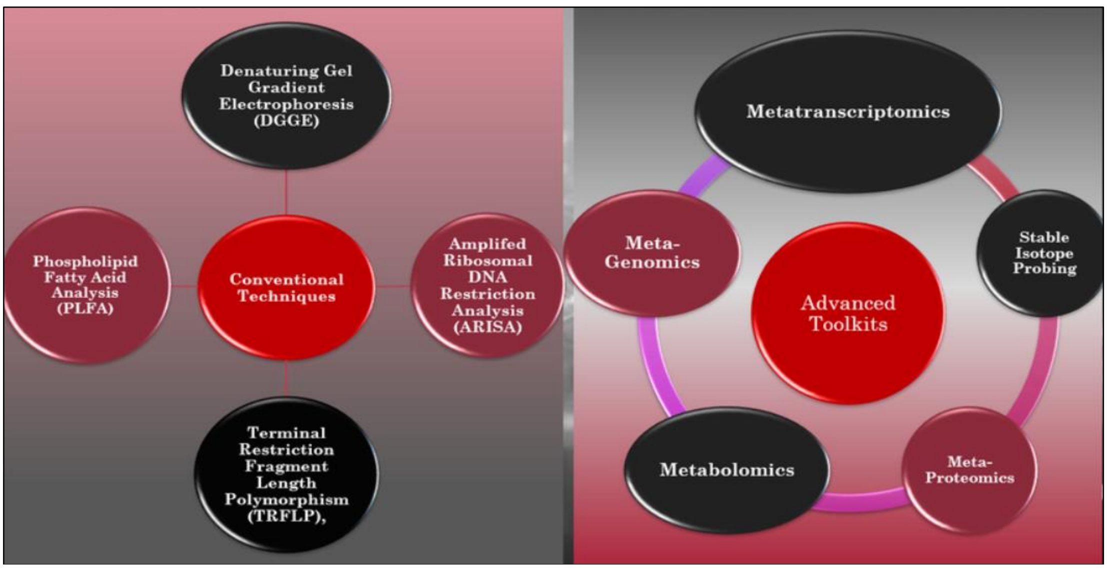

Fig 1: Techniques for unveiling the black box of soil (Shah *et al*., 2022) [67]

The term 'Omics' encompasses a suite of molecular approaches aimed at quantifying biologically significant molecules to decode the structure, function, and physiological mechanisms of diverse organisms in their natural environments (Feng, 2013) [22]. These approaches collectively generate integrated data on gene expression, protein synthesis, and metabolite production, offering a comprehensive understanding of microbial activity within the soil ecosystem (Dubey *et al*., 2019) [20]. Omics-based methodologies have introduced a transformative phase in soil science, particularly in exploring the functional dynamics of microbial communities. However, synthesizing multiple omics datasets into coherent ecological interpretations remains challenging due to the complex and heterogeneous nature of soil microbiomes (Jansson and Hofmockel, 2018) [87].

Amplicon sequencing, though useful in revealing microbial composition, often yields variable results due to factors like primer bias, sequencing depth, or extraction methods (Zaheer *et al*., 2018) [83]. Advanced tools such as stable isotope probing now enable the identification of functionally active microbes involved in key soil processes (Zhang *et al*., 2018) [84]. Soil metagenomics, which relies on DNA extraction and clone library construction, has significantly enhanced the discovery of novel genes and biomolecules from uncultured soil microorganisms (Coughlan *et al*., 2018) [18]. While 16S rRNA gene amplification has provided insights into microbial taxonomy, it offers limited information on functional capabilities (Fierer *et al*., 2012) [24]. Shotgun metagenomics addresses this gap by capturing both structural and functional diversity but may underrepresent rare taxa and is computationally intensive (Wooley *et al*., 2010) [80].

Metatranscriptomics improves upon this by identifying actively expressed genes and their microbial sources, although challenges like rRNA contamination and sequencing requirements persist (Wolf, 2013) [79]. Metaproteomics contributes to understanding translational profiles but is currently constrained by low-throughput technology (Callister *et al*., 2018) [13]. Soil metabolomics offers detailed snapshots of nutrient cycling and metabolite fluxes, though interpretation is hindered by incomplete reference databases (Heaven and Benheim, 2016) [31] Together, these omics tools are unlocking new dimensions in microbial ecology, enabling deeper insights into gene distributions, functional traits, and microbial adaptability across various ecosystems (Nesme *et al*., 2016) [55].

Challenges

Despite significant advancements, challenges remain in harnessing soil microbiomes for sustainable agriculture. One major challenge is the inherent complexity and variability of soil microbial communities across different soil types and environmental conditions, limiting the development of universal microbiome-based solutions (Fierer, 2017) [23]. Moreover, soil microbe-plant interactions are highly context-dependent (Hartmann *et al*., 2015) [30]. Inconsistency of microbial inoculants, as their effectiveness can be influenced by abiotic factors such as soil pH, moisture, and temperature fluctuations (Philippot *et al*., 2013) [57]. Furthermore, the lack of standardized methodologies for microbiome characterization and application limits the reproducibility and scalability of microbiome-driven agricultural practices (Bender *et al*., 2016) [8]. Climate change further complicates soil microbiome management, as rising temperatures and erratic precipitation patterns alter microbial composition and function, potentially disrupting soil nutrient cycles (Singh *et al*., 2020) [49].

Future research to address these challenges

Future research should focus on developing targeted microbial interventions, improving microbiome stability under climate stress, and integrating microbiome data with digital farming tools. Further research is needed to refine microbial species definitions, as the predominant focus on bacteria may lead to misinterpretations of microbiome functions in ecosystems (Geisen, 2021) [26]. Advances in soil DNA/RNA markers have improved microbial identification (Harkes, 2020) [88], yet genomic data remains limited in predicting microbial processes. A function-driven approach, selecting tests based on target processes, could enhance methodological tools for microbiome monitoring, including digital innovations (Fierer *et al*., 2021) [25]. A deeper understanding of soil microbiome contributions to soil functions, nutrient cycling, and plant protection can significantly enhance the sustainability of agricultural systems (Sergaki *et al*., 2018) [66]. Further research is required to elucidate the impact of pesticide mixtures on soil microbial communities (Geissen *et al*., 2021) [28]. Additionally, studies on the interactions between crop diversity, organic fertilizers, and biocontrol strategies are essential to understand their effects on both specific microbial taxa and overall community dynamics in relation to soil health. Policymakers must also support microbiome-based approaches through regulatory frameworks and incentives for farmers to adopt sustainable soil management practices (Schlatter *et al*., 2015) [65]. With continued advancements in microbiome research and biotechnological innovations, soil microbiome engineering holds significant promise for enhancing global food security while mitigating environmental degradation.

Conclusion

The soil microbiome plays a crucial role in maintaining soil health and promoting sustainable agriculture by influencing nutrient cycling, soil structure, and plant resilience. Understanding microbial dynamics enables better soil management strategies, reducing reliance on chemical inputs while enhancing soil fertility and crop productivity. Agricultural practices such as crop rotation, organic amendments, and reduced tillage can positively shape microbial communities, fostering beneficial interactions. Climate change and intensive farming pose challenges, but harnessing microbial potential can mitigate negative impacts. Future research should focus on microbial interactions, soil biodiversity, and innovative biotechnological applications. By prioritizing soil microbiome health, we can ensure long-term agricultural sustainability and ecosystem balance.

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