**Plant-Soil Interactions: Implications for Sustainable Crop Production - A Review**

**Abstract**

Plant-soil interactions are crucial to the establishment of crop productivity, soil well-being, and environmental stewardship. These interactions involve intricate biological, chemical, and physical processes that determine nutrient cycling, soil structure, and plant growth. Better understanding of these interactions is critical in the development of sustainable crop production strategies that maximize use of resources, improve soil fertility, and minimize environmental effects. This review explores the complex interactions between plant-soil relations, with particular focus on the functions of soil microbiomes, nutrient cycling, and sustainable agricultural management. It also assesses the effects of these interactions on crop yields, environmental well-being, and climatic resilience.

**Introduction**

Agriculture forms the foundation of human society based on the highly dynamic and intricate interactions between soils and plants (Hurni, et al., 2015). These interactions strongly influence nutrient supply, soil structure, plant growth, and general crop health (Khan et al., 2023). Sustainable crop production is based on a thorough appreciation of these complex processes to maximize productivity while preserving soil health and environmental stability (Shah, and Wu, 2019). Advances in soil science over the last few decades have shown how microbial communities, nutrient cycling, and root-soil interactions are essential to attain sustainable agriculture (Das et al., 2022). This review discusses these key areas and their connotations for long-term agricultural sustainability.

Soil is a finite and irreplaceable natural resource that plays a fundamental role in sustaining human life (Bhattacharyya et al., 2015). Over the past several decades, the global intensification of agricultural practices driven by the growing demand for food has significantly contributed to soil degradation on a large scale (Kopittke et al., 2019). This deterioration has led to a decline in soil fertility, reduced capacity for water retention, depletion of organic carbon, loss of biodiversity, and the disruption of essential nutrient cycling processes (Lal, 2015).

The health and productivity of soil are profoundly influenced by intricate interactions among plants, soil components, and microorganisms (Kumar, and Verma, 2019). Soil microorganisms, which include bacteria, fungi, and other microscopic life forms, engage in countless interactions with one another and with plant roots (Xing et al., 2025). These interactions support a wide array of biological processes that are critical for maintaining ecological balance and sustainability within the soil environment (Srivastava et al., 2023).

Plant microbe interactions can have both beneficial and harmful effects on plant development (Schirawski, and Perlin, 2018). When microbial activity negatively impacts plant growth, it is considered antagonistic or detrimental (Wang et al., 2022). Conversely, when microbial associations enhance plant survival, improve nutrient uptake, and boost crop yields, the relationship is viewed as synergistic or beneficial (Das, et al., 2022). A harmonious and balanced relationship between soil microorganisms and plant systems is essential for maintaining and improving soil health (Ortiz, and Sansinenea, 2022).

In response to increasing concerns about environmental degradation and the urgent need to restore soil quality, there has been a growing recognition of the critical role soil microorganisms play in agricultural and ecological systems (Timmis, and Ramos, 2021). This heightened awareness has encouraged the adoption of organic amendments such as compost, green manure, and animal waste as sustainable alternatives to synthetic chemical fertilizers (Bremaghani, 2024). The addition of organic matter not only mitigates soil degradation but also enriches microbial diversity, enhances soil structure, and supports long-term agricultural productivity (Bhattacharyya, et al., 2022).

**Microbial interactions**

**Beneficial nematodes *Bacteriovorous Fungivorous Omnivorous***

***Predatory nematodes***

**Plant Growth Promoting Rhizobacteria (PGPR)**

***Rhizobium Azospirillum Bacillus Pseudomonas Serratia Stenotrophomonas Streptomyces***

**Beneficial soil microfauna**

**Cyanobacteria**

**Mycorrhizal**

**associations**

**Soil health**

**Plant growth promotion (photosynthesis, yield, resistance to pathogens) Biological fertilizers**

**Bio-control agents Restoration of waste lands Soil bioremediation**

**Stability and productivity of desert soil**

**Sustainable agriculture and environment**

(Source, M. Tahat et al., 2020)

**Figure 1**: A conceptual theme demonstrating the role of beneficial soil microbes and their interactions for the development of sustainable agriculture and environment (modified from Singh et al., 2011).

**Plant Interspecific Competition**

Development of the root system is important in overall plant growth, especially when crop species are cultivated together (Vacheron et al., 2013). Such interactions are necessary to understand how plants uptake nutrients in mixed cropping systems (Homulle et al., 2022). Though significant, there is no extensive comparative research on root distribution patterns among intercropped species, primarily because of the difficulty and expense of carrying out such a study under field conditions (Wang et al., 2018).

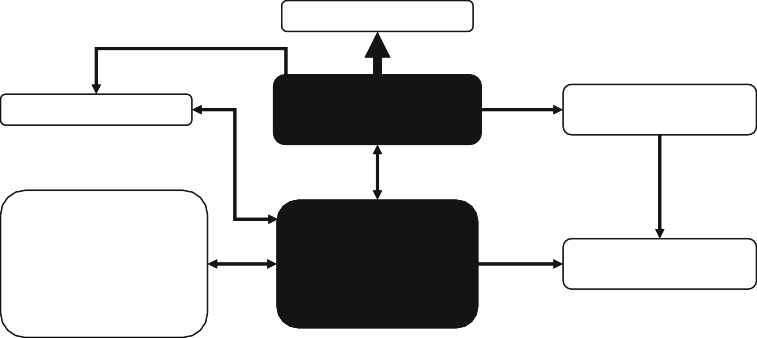
When higher yields are found in intercropping systems, they are usually due to more effective and complementary use of accessible resources an effect largely induced by underground root interactions and facilitation mechanisms (Homulle et al., 2022).

Facilitative plant-plant and plant-associated microorganism interactions generally favor reciprocal growth, compared to competitive interactions that can repress one or more species (Hassani, et al., 2018). These positive root interactions can occur directly by adaptive modifications in root structure or indirectly by mechanisms like nitrogen transfer from legumes to non-legumes, utilization of common mycorrhizal networks, and rhizosphere-mediated mobilization of nutrients (Dahiya et al., 2021). The latter encompasses exudation of amino acids, enzyme secretion, acidification of the soil, and biofumigation (Hanschen et al., 2020).

These facilitative mechanisms are particularly effective under conditions of low nutrients, where plant reactions can dramatically modify the character and consequences of interspecific competition.

**1. Plant-Soil Interactions**

Plant-soil interactions are complex and take place at multiple scales, ranging from molecular and microbial association in the rhizosphere to large ecological processes (Zhuang, et al., 2024). They affect soil fertility, crop yields, and environmental sustainability (Chaudhary et al., 2023). It is important to understand the mechanisms underlying such interactions to develop sustainable agriculture that can promote productivity while limiting ecological footprints (Brooker et al., 2021). This section addresses the dynamics of soil microbiomes, nutrient cycling, and soil structure and how they play roles in facilitating sustainable crop production (Hartmann, and Six, 2023).



Crop production

Soil structural dynamics

**Plant communities**

* Diverse litter
* Multiple root networks

Plant inter-specific competition

**Nutrient cycling**

* N-fixation
* OM turnover
* Nutrient mobilisation
* Nutrient transfer
* Decomposition
* Niche complementarity

**Microbial communities**

Root associated

* N-fixers
* Mycorrhiza
* PGPR

Free-living

Disease, pest and weed suppression

**(Source,** **Ehrmann, and Ritz, 2014).**

Figure 2: *Interactions within the plant–soil system in multiple cropping systems. Components are denoted in black boxes and processes in white boxes. The diagram illustrates how, in multiple-crop arrangements, root systems can directly and indirectly modify their environment through rhizosphere processes to promote mutually beneficial traits.*

**1.1 Rhizosphere Dynamics and Soil Microbiome**

Rhizosphere, a limited soil zone controlled directly by secretions from plant roots and accompanying soil microbes, is a dynamic hot spot in which interactions between soil and plant are strongest (Pathan et al., 2020). Bacteria, fungi, and archaea coexist here and survive on available nutrients, creating symbiotic association with the root system of a plant (Odelade, and Babalola, 2019). Positive microbes like mycorrhizal fungi and nitrogen-fixing bacteria contribute to improved nutrient uptake in the form of increased availability of key elements like phosphorus and nitrogen (Liu-Xu et al., 2024). They also release growth hormones, inhibit soil-borne diseases, and enhance stress tolerance in plants (Abdelaziz et al., 2023). It is essential to appreciate the ecological roles played by these microbial populations in order to harness their benefits in sustainable agriculture (Ali, and Xie, 2020). Practices like reduced tillage, cover cropping, and crop rotation can encourage positive rhizosphere microbial populations, ultimately leading to improved soil health and crop productivity (Jiang et al., 2022).

**Belowground Microbial Occurrence and Interactions**

Microorganisms are widely distributed on plant surfaces as well as in the surrounding soil. Plants actively recruit these microbes from their environment, which acts as a natural reservoir for microbial diversity (Hardoim et al., 2015). The root microbiome can be passed on through two main routes: horizontal and vertical transfer. Most microbial communities associated with plant roots are acquired horizontally, meaning they are sourced directly from the soil. These soils typically host a wide range of bacterial groups such as *Acidobacteria*, *Bacteroidetes*, *Proteobacteria*, *Planctomycetes*, and *Actinobacteria* (Fierer, 2017). Vertical transmission, on the other hand, occurs through seeds, allowing microbes to move from one generation to the next and aiding in early plant development (Hardoim et al., 2012).

Plant roots create distinct ecological zones in the soil niches that encourage microbial colonization not only in the rhizosphere and roots but, to a limited extent, even in aboveground plant parts (Hartmann et al., 2009). The rhizosphere, which refers to the thin layer of soil surrounding the roots, is particularly rich in microbial activity and considered one of the most complex and dynamic habitats for microbes (Hiltner, 1904). In an investigation using the terminal restriction fragment length polymorphism (T-RFLP) method, researchers found that the rhizosphere harbored a denser and more diverse microbial population compared to bulk soil, especially in large-scale wheat cultivation systems (Donn et al., 2015).

The rhizosphere, the plant root-influenced zone of the soil, harbors complex microbial communities that engage with plants (Terrazas et al., 2016). Positive microbes facilitate nutrient uptake, stimulate growth, and defend against pathogens.

**Aboveground Plant Microbiota**

Various aboveground plant tissues including vegetative foliage, leaves, and floral structures create unique niches that support diverse populations of both endophytic (internal) and epiphytic (surface) microorganisms (Kumar, et al., 2017). However, significant ecological differences exist between the bacterial communities inhabiting the endosphere (the internal plant environment where microbes reside, potentially with or without causing harm) and the phyllosphere (the aerial plant surfaces colonized by microbes) Dong, et al., 2019).

The plant's xylem plays a key role in the systematic distribution of endophytes to different internal compartments such as stems, leaves, and fruits (Compant et al., 2010). Nonetheless, studies have also shown that microbes can gain entry through aerial parts like flowers and fruits (Compant et al., 2011).

Each plant compartment tends to host a distinct endophytic community, influenced by how the plant allocates its internal resources. Meanwhile, the phyllospheric bacterial populations often originate from the soil, with their movement and colonization influenced by plant traits and environmental factors (Vorholt, 2012; Wallace et al., 2018).

**Table 1.** Relevant examples of abiotic factors modulating the rhizosphere microbiome in different places of study

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Abiotic modulating factor** | **Plant rhizosphere/ type of soil** | **Microbiome**  **profiling technique** | **Modulated or found taxa, general features** | **Place of study** | **Reference** |
| K, C, Ca | McMurdo Dry Valleys soils | Denaturing Gradient Gel Electrophoresis (DGGE), Terminal Restriction Frag- ment Length Polymorphism (T-RFLP) and 16S rRNA  gene clone library construc- tion | *Proteobacteria*, *Actinobacteria* and *Firmicutes* were dominant in all hori- zons. *Acidobacteria*, *Actinobacteria*, *Bacteroidetes* and *Gammaproteobac- teria* were mainly found in permafrost interface | Antarctica | Stomeo *et al*., 2012 |
| pH, C | Cacti rhizosphere (*Carnegiea gigantea* and *Pachycereus pringlei*) and bulk soil | Multiplexed pyrosequen- cing of the16S rRNA genes | Family *Desulfurococcaceae* was corre- lated with carbon and several classes of the phylum *Acidobacteria* with pH | Sonoran desert, AZ, USA | Andrew *et al*., 2012 |
| Soil water content, C | Rice and tomato/ Yolo silt loam soil | Phospholipid Fatty Acid  (PLFA) profiles | Species not detected. Soil water content and organic carbon availability are major determinants of the general microbial community composition | California, USA | Drenovsky *et al*., 2004 |
| DOM (Dissolved organic matter) | Tropical rain forest soil | Libraries of small-subunit ribo- somal RNA genes (SSU rRNA) | *Gammaproteobacteria* and *Firmicutes* groups were increased while *Acidobac- teria* were reduced | Costa Rica | Cleveland *et al*., 2007 |
| Agricultural prac- tices disturbances (Intense grazing, seasonal drought and fire) | Desert grassland | Carbon substrate utilization patterns in Biolog plates. Soil enzyme activity. | Species not specified. Fire and summer drought reduced soil microbial sub- strate utilization and enzyme activities. Winter drought, increased soil microbi- al diversity and activity. | Chihuahua, Mexico | Liu *et al*., 2000 |
| Temperature | Acid mine drainage  (AMD) biofilms | FISH and Tandem Mass Tag (TMT)-based pro- teomics | *Leptospirillum* group III decreased with increasing temperature | Richmond Mine, CA, USA | Mosier *et al*., 2015 |
| Temperature, atmos- pheric CO**2**  and precipitation | Captina silt loam soil | Ribosomal DNA quantita- tive PCR (qPCR) | The relative abundance of *Proteobac- teria* was greater in the wet soil. *Acido- bacteria* abundance was greater in dry treatments. Fungal abundance increased in warm treatments | National Ecological Research Park, Oak Ridge, TN, USA | Castro *et al*., 2010 |
| Type of soil | Maize, sugarcane and Morrow Plots  /three agricultural and boreal forest soils | DNA pyrosequencing | The most abundant bacterial groups in all four soils were the *Bacteroidetes*, *Betaproteobacteria* and *Alphaproteobac- teria*. Forest soil is a rich phylum but less diverse of Archaeal species compared to the three agricultural soils | Brazil, USA (Florida, Illinois) and Canada | Roesch *et al*., 2007 |
| pH | Typic Paleudalf soil | qPCR and bar-coded pyrosequencing | Relative abundance and diversity of bacteria were positively related to pH. The abundance of fungi was unaffected or weakly modulated by pH | Hoosfield acid strip (Rotham- sted Research, UK) | Rousk *et al*., 2010 |
| Soil moisture, pH, electrical conductiv- ity, soil organic mat- ter, major nutrients and ions. | McMurdo Dry Valleys soils | Pyrosequencing of the 16S rRNA gene | *Acidobacteria* and *Actinobacteria* were prevalent at the organic carbon rich, mesic and low elevation sites, while *Firmicutes* and *Proteobacteria* were dominant at the high elevation, low moisture and biomass sites | Taylor and Wright Valleys (Antarctica) | Van Horn *et al*., 2013 |
| pH | Multiple soil types | T-RFLP | Bacterial diversity was higher in neutral soils and lower in acidic soils, higly correlated with soil pH | North and South America | Fierer & Jackson, 2006 |
| Moisture | Herbaceous species and pasture/Grass- land | T-RFLP | Moisture had a comparatively higher impact on bacterial community, on fungal community soil N and C had a stronger effect | Scotland, UK | Singh *et al*., 2009 |
| Phosphorus fertilization | Alfalfa/ loamy clay soil | DGGE and PLFA | The application of fertilizer was asso- ciated with shifts in the composition of fungal and bacterial communities without affecting their richness | Saskatchewan, Canada | Beaure- gard *et al*., 2010 |
| CO**2** and temperature | Rice/ tropical soil | Measurement of microbial biomass-C and soil enzyme activities | Elevated CO**2** significantly increased the mean microbial biomass carbon (MBC) content and soil enzyme activi- ties and temperature | India | Das *et al*., 2011 |

(Source, Pizano et al., 2017)

**1.2 Nutrient Cycling and Soil Fertility**

Nutrient cycling is an essential process that sustains soil fertility and ensures sustainable crop production (Tully, and Ryals, 2017). Plants take up necessary nutrients from the soil, such as nitrogen, phosphorus, potassium, and trace elements, which are essential for development and growth (Shrivastav et al., 2020). Organic matter deposits nutrients back into the soil following plant senescence and decomposition, creating a perpetual cycle (Nair et al., 2021). Microorganisms in the soil, like bacteria, fungi, and actinomycetes, are essential in decomposing organic residues, mineralizing nutrients, and making them accessible for plant absorption (Javed et al 2021). Biological nitrogen fixation, nitrification, and decomposition are essential microbial processes that increase nutrient availability (Kafeel et al., 2023). Crop rotation, green manuring, and the application of compost and biofertilizers can improve nutrient cycling, minimize chemical fertilizer use, and promote soil health (Jiang, et al., 2022). Efficient nutrient management practices are necessary to enhance crop productivity, soil fertility, and environmental sustainability (M. Tahat, et al., 2020). Plants are involved in nutrient cycling through the uptake of soil nutrients and return of organic matter (Nair et al., 2021). Organic matter is broken down by soil microorganisms, releasing plant-available nutrients (Biswas, and Kole, 2018).

**1.3 Soil Structure and Water Dynamics**

Soil structure and water dynamics play a significant role in sustainable crop production, affecting root growth, nutrient supply, and soil health (Xing, et al., 2025). Plant roots physically change soil structure through the creation of pore space, which allows water to enter, become aerated, and penetrate by roots (Sharma, and Kumar, 2023). Root exudates like sugars, amino acids, and organic acids stabilize soil aggregates and increase microbial activity, which limits soil erosion and increases soil stability (Ma et al., 2022). Water-holding capacity, drainage, and compaction susceptibility are influenced by soil texture and structure (Abdallah et al., 2021). Improved soil structure can be achieved with practices like reduced tillage, cover cropping, and organic amendments, and also by increasing water retention and improving drought and soil degradation resilience (Wittwer, et al., 2023). Effective soil management promotes maximum water availability, surface runoff reduction, and soil erosion reduction, promoting productive and sustainable cropping systems (Martínez-Mena et al., 2020). Plant roots structure soil by providing pore space for water infiltration and retention. Root exudates bind soil aggregates, lowering erosion (Bodner et al., 2021).

**Plant, soil, and microbial interactions**

Soil microbes impart tremendous strength to crop plant growth and development against the soil-born pathogens in agriculture. First, the plant excretes some root excreted exudates in the soil and root interface that facilitates the migration of soil microorganisms towards the root hairs. Further, the rhizosphere then facilitates filtering inhabiting endophytic microbes; occasionally, some multi-diverse microbes migrate into the host plant and become transient endophytic microbes (Hu et al., 2020).

Pathogens migrate towards the rhizoplane of the host plant. After the migration into the respective location, some microbes colonize and invade the roots of plants and other microbes go to the aerial part of the roots by reducing the population density of microbes (Compant et al., 2010). Some microorganisms occurring in soil greatly benefit their host for their development and growth, whereas in some cases, some microbes play a beneficial or harmful role for the host plant (Raaijmakers et al., 2008). Certain soil-borne bacteria, including PGPB (plant growth-promoting bacteria) and PGPR, play a crucial role in plant growth, yield improvement, pathogen and environmental stress resistance, etc. (Lugtenberg and Kamilova, 2009).

**Plant-Microbiome Beneficial Interactions**

For over a century, the rhizosphere the zone surrounding plant roots has been recognized as a dynamic microenvironment populated by diverse microorganisms that significantly influence plant growth and health. The composition and activity of the rhizosphere are largely shaped by root exudates, which are secondary metabolites released by plants. These compounds, including carbohydrates, organic acids, amino acids, and vitamins, serve as chemical signals and nutrient sources, attracting and sustaining microbial communities (Bertin et al., 2003; Bais et al., 2006).

Some specific exudates, such as phenolic compounds and flavonoids, are known to selectively attract rhizobia a diverse group of nitrogen-fixing bacteria comprising genera like *Rhizobium*, *Bradyrhizobium*, *Sinorhizobium*, *Mesorhizobium*, and *Allorhizobium* (Hernández-Salmerón et al., 2013). The essential role of rhizospheric microorganisms in supporting plant functions is well-documented. These interactions range from providing moderate assistance to being vital for plant survival under challenging environmental conditions.

Microbial communities in the rhizosphere support plants through multiple mechanisms: enhancing growth (Lugtenberg & Kamilova, 2009), establishing symbiotic relationships (Koch et al., 2010), facilitating nutrient acquisition via nitrogen fixation (Gage, 2004); Raymond et al., 2004) and phosphate solubilization (Vassilev et al., 2006), degrading soil pollutants, and suppressing plant pathogens through biocontrol (Compant et al., 2005; Zhuang et al., 2007).

A variety of abiotic factors such as soil type, pH, temperature, water content, salinity, and nutrient availability influence the structure and functional dynamics of the rhizosphere microbiome (Abdul Rahman et al., 2021). These environmental factors directly and indirectly control microbial colonization, activity, and root-plant interactions (Chagas et al., 2018). Soil pH, for instance, may influence the dominance of bacterial versus fungal communities, while water content influences oxygen levels and microbial respiration (Yang et al., 2019). Nutrient gradients, fueled by both root exudation and external supplies (e.g., fertilizers), further favor microbial taxa possessing particular metabolic capacities (Canarini, et al., 2019). Combined, these abiotic factors constitute a selective environment that modulates establishment and function of beneficial plant-microbe associations (Pizano et al., 2017).

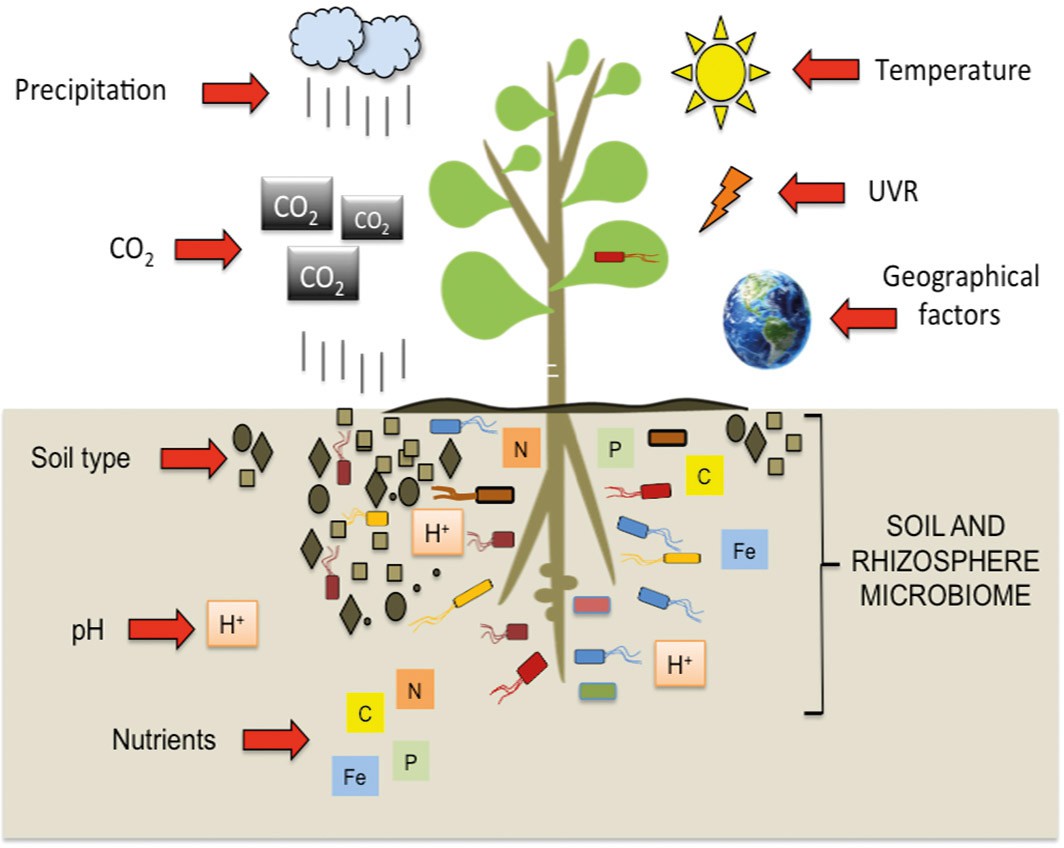


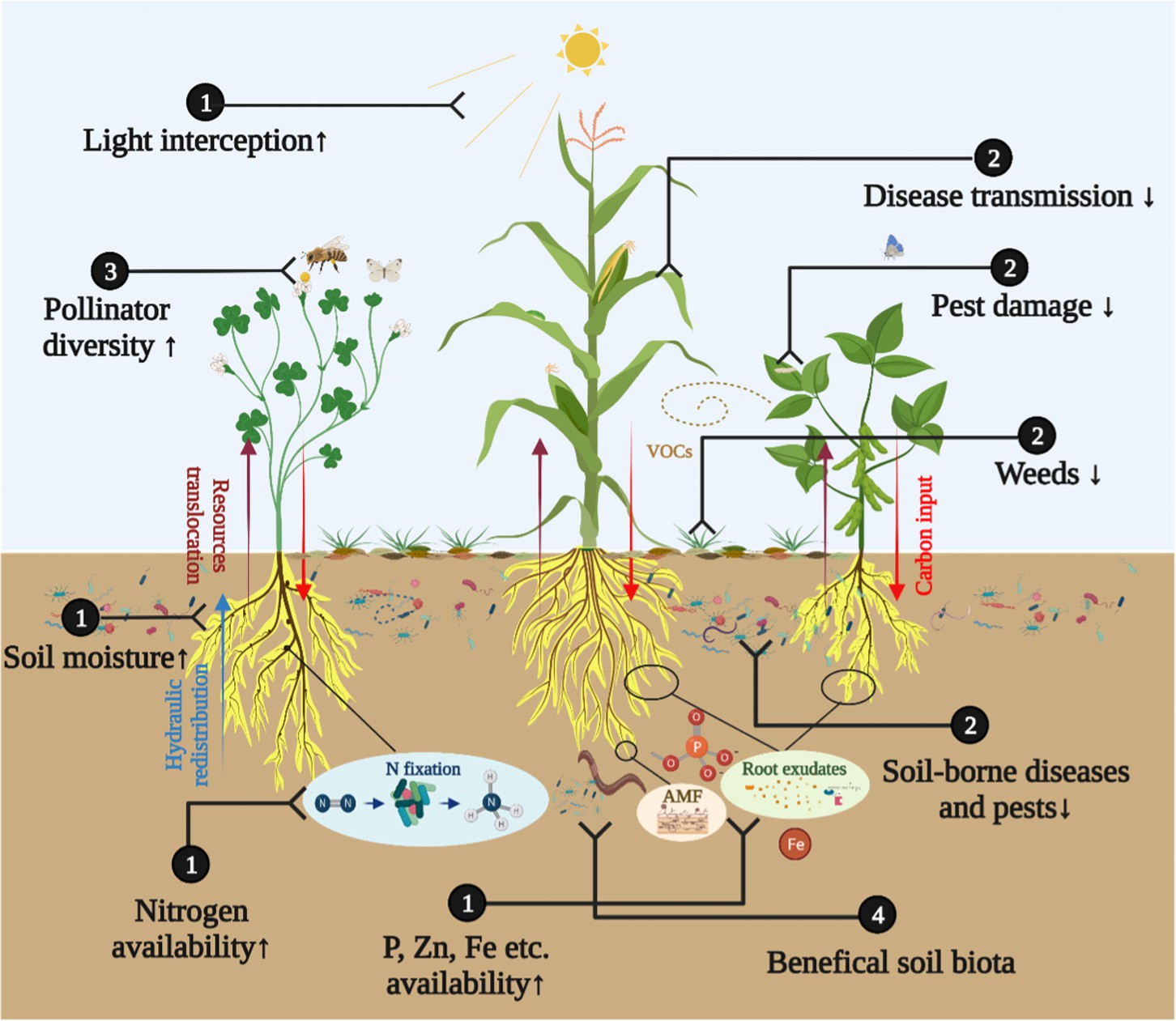
Figure 3. Abiotic Factors Regulating the Soil and Rhizosphere Microbiome.

(Source, Pizano et al., 2017)

**2. Implications for Sustainable Crop Production**

The implications of plant-soil interactions on sustainable crop production are significant, impacting soil health, nutrient management, and environmental stress resistance (Wang, et al., 2024). These interactions form the basis of sustainable agriculture, allowing for the creation of farming practices that increase productivity while maintaining soil quality (Rehman et al., 2022). Through understanding and optimizing these interactions, farmers can minimize reliance on chemical inputs, increase soil biodiversity, and maintain long-term productivity (Brooker et al., 2021). This section discusses the key areas where plant-soil interactions affect sustainable agriculture, including soil health management, integrated nutrient management, and climate resilience (Das et al., 2022).

Crop interactions in diverse or intercropped systems can generate lasting biological, chemical, and physical legacies in the soil and surrounding environment (Wang et al., 2021). These legacies are shaped by the functional traits of the neighboring crops, such as root architecture, exudate profiles, nutrient uptake strategies, and resistance to pathogens or pests (Jing et al., 2022). Interactions may influence rhizosphere microbial communities, alter nutrient cycling dynamics, suppress soil-borne diseases, or modify soil structure (Niu, et al., 2020). Such effects can persist beyond the immediate cropping season, impacting the growth, resilience, and productivity of subsequent crops (Altieri, et al., 2015). Understanding these complex interactions and their ecological footprints can aid in designing sustainable cropping systems that harness natural synergies for improved soil health and crop performance (Xing et al., 2025).

[](Image%20of%20&INS%20id=)

(Source, Jing et al., 2022)

**Figure 4 - Crop and soil Interactions**

**2.1 Soil Health Management**

Soil health management is a pillar of sustainable agriculture that aims to preserve and improve soil biological, chemical, and physical properties (Usharani, et al., 2019). Healthy soils underpin crop productivity, resilience, and ecosystem services, creating a sustainable basis for food security (Rehman et al., 2022). The efficient soil health management measures include crop rotation, cover cropping, conservation tillage, and organic amendments (Farmaha, et al., 2022). The mentioned measures improve the structure of soil, enhance organic matter levels, increase water storage capacity, and advance beneficial microbial functioning (Lal, 2020). Combine livestock, agroforestry, and agroecological approaches to further improve soil health through increased biodiversity and nutrient cycling (Fahad, et al., 2022). Management of long-term soil health can help climate change adaptation, avoid soil degradation, and promote sustainable production of crops (Lal, 2012). Prioritization of regenerative farming practices can rehabilitate degraded soils, increase carbon sequestration, and enhance ecosystem resilience (McCauley, and Barlow, 2023). Crop rotation, cover cropping, and organic amendments promote soil health by improving biological activity and the availability of nutrients (Mishra et al., 2024).

**2.2 Integrated Nutrient Management**

Integrated Nutrient Management (INM) is an integrated soil fertility management that is achieved through the integration of organic, inorganic, and biological inputs to maximize the availability of nutrients and reduce its adverse effects on the environment (Selim, 2020). INM seeks to promote sustainable crop production through enhanced soil fertility, increased nutrient use efficiency, and decreased reliance on synthetic fertilizers (Wu, and Ma, 2015). The system includes the use of organic manures, compost, green manures, biofertilizers, and selective application of chemical fertilizers as per soil and crop needs. This integrated practice not only helps in effective supply of nutrients but also enhances the structure of soil, microbial health, and sustainability of soil in the long term (Verma et al., 2019). Adoption of INM will help increase the yield of crops, decrease the degradation of soil, and achieve sustainable agriculture by maintaining ecological equilibrium and environmental protection (Shah, and Wu, 2019). Successful INM practices involve soil analysis, site-specific nutrient management, and incorporation of crop residues and organic amendments into cropping systems. Blending organic and inorganic fertilizers maximizes the availability of nutrients while reducing the environmental footprint (Panta, and Parajulee, 2021).

**2.3 Climate Resilience and Adaptation**

Climate resilience and adaptation are key to sustainable crop production, especially under growing climate variability and extreme weather conditions (Srivastav et al., 2021). Plant-soil interactions contribute notably to crop resilience against environmental stress factors like drought, heat, and soil erosion (Wang, et al., 2025). Soils with high microbial populations and organic matter improve water holding capacity, soil structure, and nutrient levels, which facilitate crops to cope with phases of water stress and scarcity (Lal, 2020). Adaptive management practices such as agroforestry, cover cropping, conservation agriculture, and organic amendments have the potential to improve soil resilience, lower greenhouse gas emissions, and enhance carbon sequestration (Sauer, et al., 2021). Additionally, breeding and biotechnological efforts to develop climate-resilient crop varieties coupled with sustainable soil management practices have the potential to reduce the negative effects of climate change (Munawar, et al., 2020). All these measures are crucial for preserving agricultural productivity and food security in a changing climate (Fonta et al., 2011). Healthy soils buffer crops from climate stressors, such as drought, extreme temperatures, and soil erosion (Lal, 2012).

**3. Challenges and Future Opportunities**

Plant-soil interactions are crucial for sustainable crop production but have some challenges that need to be overcome in order to unlock their full potential. The main challenges are:

**Soil Degradation:** Unsustainable and intensive agriculture practices such as monocropping, overgrazing, land mismanagement, and excessive application of chemical fertilizers and pesticides cause soil erosion, compaction, salinization, loss of soil organic matter, and nutrient depletion. Such processes lower soil fertility, impair water infiltration, and reduce soil structure, which makes soils susceptible to erosion and climate variability.

**Soil Loss of Biodiversity:** The reduction of soil microbial diversity as a result of practices like monocropping, overuse of chemical fertilizers and pesticides, and land degradation breaks the balance of healthy soil organisms. This reduction in microbial diversity undermines soil health by degrading nutrient cycling, soil structure, and pest and disease resistance. Balanced and healthy soil microbiomes play a critical role in soil fertility, plant growth, and ecosystem resilience. Encouraging biodiversity using crop rotation, cover crops, organic amendments, and minimal chemical application will restore soil health and guarantee sustainable farm productivity.

**Climate Change:** Irregular weather conditions, extended droughts, flooding, and erratic temperatures interfere with plant-soil interaction, impacting crop productivity. Climate change changes the soil moisture content, increases soil erosion, and alters nutrient cycling patterns, resulting in decreased soil fertility and productivity. Extreme weather conditions can lead to crop loss, soil erosion, and pest and disease infestation. Adaptation strategies like conservation agriculture, agroforestry, soil carbon sequestration, and climate-resilient crops are critical to counteract these effects. Best Management Practices for soil and water management can improve resilience so that sustainable production of crops takes place despite climate change.

**Restricted Adoption of Sustainable Practices:** A combination of reasons, including insufficient extension services, lack of farmer awareness, insufficient policy support, and financial constraints, typically results in restricted adoption of sustainable soil management practices. Insufficient access to resources, economic incentives, and suitable technologies also hinder extensive adoption of sustainable practices. The lack of suitable policy environments and institutional backing also makes scaling up sustainable agricultural practices difficult. Addressing these constraints necessitates specialized publicity campaigns, policy changes, capacity development programs, and financial assistance to induce farmers to adopt sustainable practices for sustainable soil health and productivity.

**Knowledge Gaps:** The intricacy of soil microbial processes and their interactions with roots is still not well understood, which restricts the use of plant-soil interactions effectively in sustainable agriculture. This knowledge gap prevents the enhancement of microbial functions for nutrient cycling, disease suppression, and stress tolerance. The dearth of scientific studies on region-specific microbial communities, the influence of environmental parameters, and long-term consequences of management practices on soil microbiomes poses challenges to the translation of scientific information into actionable solutions. Closing these gaps involves interdisciplinary studies, sophisticated molecular tools, and field testing to create context-specific, scalable, and efficient soil management practices for sustainable crop production.

**Future Prospects**

To address these limitations and maximize sustainable crop yields, future research and development should have the following priority areas:

**Innovative Cropping Systems:** Create adaptive and resilient cropping systems that foster positive plant-soil interactions, bring together cover crops, crop rotation, and agroforestry systems to maximize biodiversity, soil health, and productivity.

**Advanced Technology Solutions:** Harness precision agriculture equipment, such as soil sensors, artificial intelligence, machine learning, and remote sensing technologies, to monitor soil health in real time, apply site-specific nutrient management, and make predictive decisions.

**Regenerative Agriculture:** Encourage regenerative agriculture practices like agroecology, conservation agriculture, permaculture, and organic farming to regenerate soil fertility, build organic matter, and sequester carbon.

**Microbial Inoculants and Biofertilizers:** Promote increased development and deployment of microbial inoculants, biofertilizers, and biostimulants for enhancing nutrient cycling, soil quality, and crop yields.

**Policy and Institutional Support:** Intensify policies, incentives, and institutional structures for promoting sustainable soil management, availing finances, and providing farmer-focused training and education.

**Interdisciplinary Research and Innovation:** Support interdisciplinary partnerships among agronomists, soil experts, ecologists, and technologists to promote innovative approaches towards sustainable agriculture.

These efforts can facilitate the successful utilization of plant-soil interactions, opening the door to sustainable, resilient, and productive agricultural systems in the context of climate change and global food security threats.

Overcoming these challenges and utilizing plant-soil interactions can open the door to sustainable, resilient, and productive agricultural systems.

Challenges pose include soil erosion, biodiversity loss, and climate change. Research should be aimed at the development of robust cropping systems enhancing sustainable plant-soil relationships.

**Conclusion**

Ultimately, sustainable crop production is rooted in the maximization of plant-soil relationships. Future farming systems must prioritize soil health, effective nutrient cycling, improved resistance to environmental stresses, and the incorporation of regenerative and climate-smart practices to achieve long-term productivity, environmental sustainability, and global food security.

**COMPETING INTERESTS DISCLAIMER:**

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

**Reference**

Abdallah, A. M., Jat, H. S., Choudhary, M., Abdelaty, E. F., Sharma, P. C., & Jat, M. L. (2021). Conservation agriculture effects on soil water holding capacity and water-saving varied with management practices and agroecological conditions: A Review. *Agronomy*, *11*(9), 1681.

Abdelaziz, A. M., Hashem, A. H., El-Sayyad, G. S., El-Wakil, D. A., Selim, S., Alkhalifah, D. H., & Attia, M. S. (2023). Biocontrol of soil borne diseases by plant growth promoting rhizobacteria. *Tropical Plant Pathology*, *48*(2), 105-127.

Abdul Rahman, N. S. N., Abdul Hamid, N. W., & Nadarajah, K. (2021). Effects of abiotic stress on soil microbiome. *International Journal of Molecular Sciences*, *22*(16), 9036.

Ali, S., & Xie, L. (2020). Plant growth promoting and stress mitigating abilities of soil born microorganisms. *Recent Patents on Food, Nutrition & Agriculture*, *11*(2), 96-104.

Altieri, M. A., Nicholls, C. I., Henao, A., & Lana, M. A. (2015). Agroecology and the design of climate change-resilient farming systems. *Agronomy for sustainable development*, *35*(3), 869-890.

Andrew, D.R., Fitak, R.R., Munguia-Vega, A., Racolta, A., Martinson, V.G., & Dontsova, K. (2012). Abiotic factors shape microbial diversity in Sonoran desert soils. *Applied and Environmental Microbiology*, 78, 7527–7537.

Bais, H. P., Weir, T. L., Perry, L. G., Gilroy, S., & Vivanco, J. M. (2006). The role of root exudates in rhizosphere interactions with plants and other organisms. *Annual Review of Plant Biology*, 57, 233–266.

Beauregard, M.S., Hamel, C., & St-Arnaud, M. (2010). Long-term phosphorus fertilization impacts soil fungal and bacterial diversity but not AM fungal community in Alfalfa. *Microbial Ecology,* 59, 379–389.

Bertin, C., Yang, X., & Weston, L. A. (2003). The role of root exudates and allelochemicals in the rhizosphere. *Plant and Soil*, 256, 67–83.

Bhattacharyya, S. S., Ros, G. H., Furtak, K., Iqbal, H. M., & Parra-Saldívar, R. (2022). Soil carbon sequestration–An interplay between soil microbial community and soil organic matter dynamics. *Science of the Total Environment*, *815*, 152928.

Bhattacharyya, T. A. P. A. S., & Pal, D. K. (2015). The soil: A natural resource. *Soil Science: An Introduction; Rattan, RK, Katyal, JC, Dwivedi, BS, Sarkar, AK, Tapas Bhattacharyya, JC, Tarafdar, SK, Eds*, 1-19.

Biswas, T., & Kole, S. C. (2018). Soil organic matter and microbial role in plant productivity and soil fertility. In *Advances in Soil Microbiology: Recent Trends and Future Prospects: Volume 2: Soil-Microbe-Plant Interaction* (pp. 219-238).

Bodner, G., Mentler, A., & Keiblinger, K. (2021). Plant roots for sustainable soil structure management in cropping systems. *The root systems in sustainable agricultural intensification*, 45-90.

Bremaghani, A. (2024). Utilization of organic waste in compost fertilizer production: implications for sustainable agriculture and nutrient management. *Law and Economics*, *18*(2), 86-98.

Brooker, R. W., George, T. S., Homulle, Z., Karley, A. J., Newton, A. C., Pakeman, R. J., & Schöb, C. (2021). Facilitation and biodiversity–ecosystem function relationships in crop production systems and their role in sustainable farming. *Journal of Ecology*, *109*(5), 2054-2067.

Canarini, A., Kaiser, C., Merchant, A., Richter, A., & Wanek, W. (2019). Root exudation of primary metabolites: mechanisms and their roles in plant responses to environmental stimuli. *Frontiers in plant science*, *10*, 157.

Castro, H.F., Classen, A.T., Austin, E.E., Norby, R.J., & Schadt, C.W. (2010). Soil microbial community responses to multiple experimental climate change drivers. *Applied and Environmental Microbiology,* *76*, 999–1007.

Chagas, F. O., de Cassia Pessotti, R., Caraballo-Rodríguez, A. M., & Pupo, M. T. (2018). Chemical signaling involved in plant–microbe interactions. *Chemical Society Reviews*, *47*(5), 1652-1704.

Chaudhary, S., Sindhu, S. S., Dhanker, R., & Kumari, A. (2023). Microbes-mediated sulphur cycling in soil: Impact on soil fertility, crop production and environmental sustainability. *Microbiological Research*, *271*, 127340.

Cleveland, C.C., Nemergut, D.R., Schmidt, S.K., & Townsend, A.R. (2007). Increases in soil respiration following labile carbon additions linked to rapid shifts in soil microbial community composition. *Biogeochemistry*, 82, 229–240.

Compant, S., Cambon, M. C., Vacher, C., Mitter, B., Samad, A., & Sessitsch, A. (2020). The plant endosphere world Bacterial life within plants. *Environmental Microbiology*.

Compant, S., Clément, C., & Sessitsch, A. (2010). Plant growth-promoting bacteria in the rhizo- and endosphere of plants: Their role, colonization, mechanisms involved and prospects for utilization. *Soil Biology and Biochemistry, 42*(5), 669–678.

Compant, S., Duffy, B., Nowak, J., Clément, C., & Barka, E. A. (2005). Use of plant growth-promoting rhizobacteria for biocontrol of plant diseases: Principles, mechanisms of action, and future prospects. *Applied and Environmental Microbiology*, 71, 4951–4959.

Compant, S., Mitter, B., Colli-Mull, J. G., Gangl, H., & Sessitsch, A. (2011). Endophytes of grapevine flowers, berries, and seeds: Identification of cultivable bacteria, comparison with other plant parts, and visualization of niches of colonization. *Microbial Ecology, 62*(1), 188–197.

Dahiya, A., Kumar, R., & Sindhu, S. S. (2021). Microbial endophytes: Sustainable approach for managing phosphorus deficiency in agricultural soils. *Endophytes: Mineral Nutrient Management, Volume 3*, 35-75.

Das, P. P., Singh, K. R., Nagpure, G., Mansoori, A., Singh, R. P., Ghazi, I. A., ... & Singh, J. (2022). Plant-soil-microbes: A tripartite interaction for nutrient acquisition and better plant growth for sustainable agricultural practices. *Environmental Research*, *214*, 113821.

Das, S., Bhattacharyya, P., & Adhya, T.K. (2011). Interaction effects of elevated CO₂ and temperature on microbial biomass and enzyme activities in tropical rice soils. *Environmental Monitoring and Assessment*, 182, 555–569.

Dong, C. J., Wang, L. L., Li, Q., & Shang, Q. M. (2019). Bacterial communities in the rhizosphere, phyllosphere and endosphere of tomato plants. *PloS one*, *14*(11), e0223847.

Donn, S., Kirkegaard, J. A., Perera, G., Richardson, A. E., & Watt, M. (2015). Evolution of bacterial communities in the wheat crop rhizosphere. *Environmental Microbiology, 17*(2), 610–621.

Drenovsky, R.E., Vo, D., Graham, K.J., & Scow, K.M. (2004). Soil water content and organic carbon availability are major determinants of soil microbial community composition. *Microbial Ecology*, 48, 424–430.

Ehrmann, J., & Ritz, K. (2014). Plant: soil interactions in temperate multi-cropping production systems. *Plant and Soil*, *376*, 1-29.

Fahad, S., Chavan, S. B., Chichaghare, A. R., Uthappa, A. R., Kumar, M., Kakade, V., ... & Poczai, P. (2022). Agroforestry systems for soil health improvement and maintenance. *Sustainability*, *14*(22), 14877.

Farmaha, B. S., Sekaran, U., & Franzluebbers, A. J. (2022). Cover cropping and conservation tillage improve soil health in the southeastern United States. *Agronomy Journal*, *114*(1), 296-316.

Fierer, N. (2017). Embracing the unknown: Disentangling the complexities of the soil microbiome. *Nature Reviews Microbiology, 15*(10), 579–590.

Fierer, N., & Jackson, R.B. (2006). The diversity and biogeography of soil bacterial communities. Proceedings of the National Academy of Sciences, 103, 626–631.

Fonta, W., Edame, G., Anam, B. E., & Duru, E. J. (2011). Climate change, food security and agricultural productivity in Africa: Issues and policy directions.

Gage, D. J. (2004). Infection and invasion of roots by symbiotic, nitrogen-fixing rhizobia during nodulation of temperate legumes. *Microbiology and Molecular Biology Reviews*, 68, 280–300.

Hanschen, F. S., & Winkelmann, T. (2020). Biofumigation for fighting replant disease-A Review. *Agronomy*, *10*(3), 425.

Hardoim, P. R., Hardoim, C. C., van Overbeek, L. S., & van Elsas, J. D. (2012). Dynamics of seedborne rice endophytes on early plant growth stages. *PLoS ONE, 7*(2), e30438.

Hardoim, P. R., van Overbeek, L. S., Berg, G., Pirttilä, A. M., Compant, S., Campisano, A., ... & Sessitsch, A. (2015). The hidden world within plants: Ecological and evolutionary considerations for defining functioning of microbial endophytes. *Microbiology and Molecular Biology Reviews, 79*(3), 293–320.

Hartmann, M., & Six, J. (2023). Soil structure and microbiome functions in agroecosystems. *Nature Reviews Earth & Environment*, *4*(1), 4-18.

Hassani, M. A., Durán, P., & Hacquard, S. (2018). Microbial interactions within the plant holobiont. *Microbiome*, *6*, 1-17.

Hernández-Salmerón, J. E., Valencia-Cantero, E., & Santoyo, G. (2013). Genome-wide analysis of long, exact DNA repeats in rhizobia. *Genes & Genomics*, 35, 441–449.

Hiltner, L. (1904). Über neuere Erfahrungen und Probleme auf dem Gebiete der Bodenbakteriologie unter besonderer Berücksichtigung der Gründüngung und Brache. *Soil Biology and Biochemistry, 98*, 59–78. *(Note: Original article is from 1904; reprinted/reference in Soil Biology and Biochemistry.)*

Homulle, Z., George, T. S., & Karley, A. J. (2022). Root traits with team benefits: understanding belowground interactions in intercropping systems. *Plant and Soil*, 1-26.

Homulle, Z., George, T. S., & Karley, A. J. (2022). Root traits with team benefits: understanding belowground interactions in intercropping systems. *Plant and Soil*, 1-26.

Hu, Q., Tan, L., Gu, S., Xiao, Y., Xiong, X., Zeng, W., Feng, K., Wei, Z., & Deng, Y. (2020). Network analysis infers the wilt pathogen invasion associated with non-detrimental bacteria. *NPJ Biofilms and Microbiomes, 6*(1), 1–8.

Hurni, H., Giger, M., Liniger, H., Studer, R. M., Messerli, P., Portner, B., ... & Breu, T. (2015). Soils, agriculture and food security: the interplay between ecosystem functioning and human well-being. *Current Opinion in Environmental Sustainability*, *15*, 25-34.

Javed, Z., Tripathi, G. D., Mishra, M., & Dashora, K. (2021). Actinomycetes–the microbial machinery for the organic-cycling, plant growth, and sustainable soil health. *Biocatalysis and Agricultural Biotechnology*, *31*, 101893.

Jiang, Y., Zhang, J., Manuel, D. B., De Beeck, M. O., Shahbaz, M., Chen, Y., ... & Liu, Z. (2022). Rotation cropping and organic fertilizer jointly promote soil health and crop production. *Journal of Environmental Management*, *315*, 115190.

Jiang, Y., Zhang, J., Manuel, D. B., De Beeck, M. O., Shahbaz, M., Chen, Y., ... & Liu, Z. (2022). Rotation cropping and organic fertilizer jointly promote soil health and crop production. *Journal of Environmental Management*, *315*, 115190.

Jing, J., Cong, W. F., & Bezemer, T. M. (2022). Legacies at work: plant–soil–microbiome interactions underpinning agricultural sustainability. *Trends in Plant Science*, *27*(8), 781-792.

Kafeel, U., Jahan, U., & Khan, F. A. (2023). Role of mineral nutrients in biological nitrogen fixation. In *Sustainable Plant Nutrition* (pp. 87-106). Academic Press.

Khan, D., Kabiraj, A., Biswas, R., Roy, R. K., & Bandopadhyay, R. (2023). Plant-microbe community dynamics in rhizosphere: reviewing the grassroots ecology towards sustainable agriculture. *Indian J Agric Sci*, *93*, 247-257.

Koch, M., Delmotte, N., Rehrauer, H., Vorholt, J. A., Pessi, G., & Hennecke, H. (2010). Rhizobial adaptations to hosts: A new facet in the legume root-nodule symbiosis. *Molecular Plant-Microbe Interactions*, 23, 784–790.

Kopittke, P. M., Menzies, N. W., Wang, P., McKenna, B. A., & Lombi, E. (2019). Soil and the intensification of agriculture for global food security. *Environment international*, *132*, 105078.

Kumar, A., & Verma, J. P. (2019). The role of microbes to improve crop productivity and soil health. *Ecological wisdom inspired restoration engineering*, 249-265.

Kumar, J., Singh, D., Ghosh, P., & Kumar, A. (2017). Endophytic and epiphytic modes of microbial interactions and benefits. *Plant-Microbe Interactions in Agro-Ecological Perspectives: Volume 1: Fundamental Mechanisms, Methods and Functions*, 227-253.

Lal, R. (2012). Climate change and soil degradation mitigation by sustainable management of soils and other natural resources. *Agricultural Research*, *1*, 199-212.

Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability*, *7*(5), 5875-5895.

Lal, R. (2020). Soil organic matter and water retention. *Agronomy Journal*, *112*(5), 3265-3277.

Liu, X., Lindemann, W.C., Whitford, W.G., & Steiner, R.L. (2000). Microbial diversity and activity of disturbed soil in the northern Chihuahuan Desert. Biology and Fertility of Soils, 32, 243–249.

Liu-Xu, L., González-Hernández, A. I., Camañes, G., Vicedo, B., Scalschi, L., & Llorens, E. (2024). Harnessing Green Helpers: Nitrogen-Fixing Bacteria and Other Beneficial Microorganisms in Plant–Microbe Interactions for Sustainable Agriculture. *Horticulturae*, *10*(6), 621.

Lugtenberg, B., & Kamilova, F. (2009). Plant-growth-promoting rhizobacteria. *Annual Review of Microbiology, 63*, 541–556.

M. Tahat, M., M. Alananbeh, K., A. Othman, Y., & I. Leskovar, D. (2020). Soil health and sustainable agriculture. *Sustainability*, *12*(12), 4859.

Ma, W., Tang, S., Dengzeng, Z., Zhang, D., Zhang, T., & Ma, X. (2022). Root exudates contribute to belowground ecosystem hotspots: A review. *Frontiers in Microbiology*, *13*, 937940.

Martínez-Mena, M., Carrillo-López, E., Boix-Fayos, C., Almagro, M., Franco, N. G., Díaz-Pereira, E., ... & de Vente, J. (2020). Long-term effectiveness of sustainable land management practices to control runoff, soil erosion, and nutrient loss and the role of rainfall intensity in Mediterranean rainfed agroecosystems. *Catena*, *187*, 104352.

McCauley, K., & Barlow, K. (2023). Regenerative agriculture: increasing plant diversity and soil carbon sequestration on agricultural landscapes. *Surg Journal*, *15*(1).

Mishra, A. K., Dash, P. K., Mishra, A., & Sharma, S. (2024). Regenerative Agriculture: A Multifaceted Approach to One Health and Soil Restoration. In *Key Drivers and Indicators of Soil Health Management: Transitioning from Conventional to Regenerative Agriculture* (pp. 1-32). Singapore: Springer Nature Singapore.

Mosier, A.C., Li, Z., Thomas, B.C., Hettich, R.L., Pan, C., & Banfield, J.F. (2015). Elevated temperature alters proteomic responses of individual organisms within a biofilm community. *The ISME Journal*, *9*, 180–194.

Munawar, S., ul Qamar, M. T., Mustafa, G., Khan, M. S., & Joyia, F. A. (2020). Role of biotechnology in climate resilient agriculture. *Environment, climate, plant and vegetation growth*, 339-365.

Nair, P. R., Kumar, B. M., Nair, V. D., Nair, P. R., Kumar, B. M., & Nair, V. D. (2021). Soil organic matter (SOM) and nutrient cycling. *An introduction to agroforestry: Four decades of scientific developments*, 383-411.

Niu, B., Wang, W., Yuan, Z., Sederoff, R. R., Sederoff, H., Chiang, V. L., & Borriss, R. (2020). Microbial interactions within multiple-strain biological control agents impact soil-borne plant disease. *Frontiers in Microbiology*, *11*, 585404.

Odelade, K. A., & Babalola, O. O. (2019). Bacteria, fungi and archaea domains in rhizospheric soil and their effects in enhancing agricultural productivity. *International Journal of Environmental Research and Public Health*, *16*(20), 3873.

Ortiz, A., & Sansinenea, E. (2022). The role of beneficial microorganisms in soil quality and plant health. *Sustainability*, *14*(9), 5358.

Panta, S., & Parajulee, D. (2021). Integrated Nutrient Management (INM) in soil and sustainable agriculture. *International Journal of Applied Sciences and Biotechnology*, *9*(3), 160-165.

Pathan, S. I., Ceccherini, M. T., Sunseri, F., & Lupini, A. (2020). Rhizosphere as hotspot for plant-soil-microbe interaction. *Carbon and nitrogen cycling in soil*, 17-43.

Pizano, G. S., Pacheco, C. H., Salmerón, J. H., & León, R. H. (2017). The role of abiotic factors modulating the plant-microbe-soil interactions: toward sustainable agriculture. A review. *Spanish journal of agricultural research*, *15*(1), 13.

Raaijmakers, J. M., Paulitz, T. C., Steinberg, C., Alabouvette, C., & Moënne-Loccoz, Y. (2008). The rhizosphere: A playground and battlefield for soilborne pathogens and beneficial microorganisms. *Plant and Soil, 321*(1–2), 341–361.

Raymond, J., Siefert, J. L., Staples, C. R., & Blankenship, R. E. (2004). The natural history of nitrogen fixation. *Molecular Biology and Evolution*, 21, 541–554.

Rehman, A., Farooq, M., Lee, D. J., & Siddique, K. H. (2022). Sustainable agricultural practices for food security and ecosystem services. *Environmental Science and Pollution Research*, *29*(56), 84076-84095.

Roesch, L.F.W., Fulthorpe, R.R., Riva, A., Casella, G., Hadwin, A.K.M., Kent, A.D., & Triplett, E.W. (2007). Pyrosequencing enumerates and contrasts soil microbial diversity. *The ISME Journal*, *1*, 283–290.

Rousk, J., Bååth, E., Brookes, P.C., et al. (2010). Soil bacterial and fungal communities across a pH gradient in an arable soil. *The ISME Journal*, *4*, 1340–1351.

Sauer, T. J., Dold, C., Ashworth, A. J., Nieman, C. C., Hernandez-Ramirez, G., Philipp, D., ... & Chendev, Y. G. (2021). Agroforestry practices for soil conservation and resilient agriculture. *Agroforestry and ecosystem services*, 19-48.

Schirawski, J., & Perlin, M. H. (2018). Plant–microbe interaction 2017—the good, the bad and the diverse. *International Journal of Molecular Sciences*, *19*(5), 1374.

Selim, M. M. (2020). Introduction to the integrated nutrient management strategies and their contribution to yield and soil properties. *International Journal of Agronomy*, *2020*(1), 2821678.

Shah, F., & Wu, W. (2019). Soil and crop management strategies to ensure higher crop productivity within sustainable environments. *Sustainability*, *11*(5), 1485.

Sharma, P. K., & Kumar, S. (2023). Soil structure and plant growth. In *Soil physical environment and plant growth: Evaluation and management* (pp. 125-154). Cham: Springer International Publishing.

Shrivastav, P., Prasad, M., Singh, T. B., Yadav, A., Goyal, D., Ali, A., & Dantu, P. K. (2020). Role of nutrients in plant growth and development. *Contaminants in agriculture: Sources, impacts and management*, 43-59.

Singh, B., Dawson, L.A., McDonald, C.A., & Buckland, S.M. (2009). Impact of biotic and abiotic interaction on soil microbial communities and functions: A field study. *Applied Soil Ecology*, 41, 239–248.

Singh, D., Shi, L., & Adams, J.M. (2013). Bacterial diversity in the mountains of South-West China: Climate dominates over soil parameters*. Journal of Microbiology*, 51, 439–447.

Singh, J. S., Pandey, V. C., & Singh, D. P. (2011). Efficient soil microorganisms: A new dimension for sustainable agriculture and environmental development. *Agriculture, Ecosystems & Environment, 140*(3–4), 339–353.

Srivastav, A. L., Dhyani, R., Ranjan, M., Madhav, S., & Sillanpää, M. (2021). Climate-resilient strategies for sustainable management of water resources and agriculture. *Environmental Science and Pollution Research*, *28*(31), 41576-41595.

Srivastava, P., Sachan, K., Baskar, P., Saikanth, D. R. K., Lytand, W., Kumar, R. K. M., & Singh, B. V. (2023). Soil microbes expertly balancing nutrient demands and environmental preservation and ensuring the delicate stability of our ecosystems-a review. *International Journal of Plant & Soil Science*, *35*(18), 989-1000.

Stomeo, F., Makhalanyane, T.P., Valverde, A., et al. (2012). Abiotic factors influence microbial diversity in permanently cold soil horizons of a maritime-associated Antarctic Dry Valley. *FEMS Microbiology Ecology*, 82, 326–340.

Terrazas, R. A., Giles, C., Paterson, E., Robertson-Albertyn, S., Cesco, S., Mimmo, T., ... & Bulgarelli, D. (2016). Plant–microbiota interactions as a driver of the mineral turnover in the rhizosphere. *Advances in applied microbiology*, *95*, 1-67.

Timmis, K., & Ramos, J. L. (2021). The soil crisis: the need to treat as a global health problem and the pivotal role of microbes in prophylaxis and therapy. *Microbial Biotechnology*, *14*(3), 769-797.

Tully, K., & Ryals, R. (2017). Nutrient cycling in agroecosystems: Balancing food and environmental objectives. *Agroecology and Sustainable Food Systems*, *41*(7), 761-798.

Usharani, K. V., Roopashree, K. M., & Naik, D. (2019). Role of soil physical, chemical and biological properties for soil health improvement and sustainable agriculture. *Journal of Pharmacognosy and Phytochemistry*, *8*(5), 1256-1267.

Vacheron, J., Desbrosses, G., Bouffaud, M. L., Touraine, B., Moënne-Loccoz, Y., Muller, D., ... & Prigent-Combaret, C. (2013). Plant growth-promoting rhizobacteria and root system functioning. *Frontiers in plant science*, *4*, 356.

Van Horn, D.J., Van Horn, M.L., Barrett, J.E., et al. (2013). Factors controlling soil microbial biomass and bacterial diversity and community composition in a cold desert ecosystem: Role of geographic scale. PLoS ONE, 8, e66103.

Vassilev, N., Vassileva, M., & Nicolaeva, I. (2006). Simultaneous P-solubilizing and biocontrol activity of microorganisms: Potentials and future trends. *Applied Microbiology and Biotechnology*, 71, 137–144.

Verma, B. C., Pramanik, P., & Bhaduri, D. (2019). Organic fertilizers for sustainable soil and environmental management. In *Nutrient dynamics for sustainable crop production* (pp. 289-313). Singapore: Springer Singapore.

Vorholt, J. A. (2012). Microbial life in the phyllosphere. *Nature Reviews Microbiology, 10*(12), 828–840.

Wallace, J. G., Kremling, K. A., Kovar, L. L., & Buckler, E. S. (2018). Quantitative genetics of the maize leaf microbiome. *Phytobiomes Journal, 2*(4), 208–224.

Wang, G., Bei, S., Li, J., Bao, X., Zhang, J., Schultz, P. A., ... & Zhang, J. (2021). Soil microbial legacy drives crop diversity advantage: Linking ecological plant–soil feedback with agricultural intercropping. *Journal of Applied Ecology*, *58*(3), 496-506.

Wang, R., Yang, Q., Deng, Z., & Nian, W. (2025). The research on soil-plant-climate interactions: An integrated assessment of water management and drought resilience. *Advances in Resources Research*, *5*(1), 456-476.

Wang, X., Cheng, L., Xiong, C., Whalley, W. R., Miller, A. J., Rengel, Z., ... & Shen, J. (2024). Understanding plant–soil interactions underpins enhanced sustainability of crop production. *Trends in Plant Science*.

Wang, Y., Liu, H., Shen, Z., Miao, Y., Wang, J., Jiang, X., ... & Li, R. (2022). Richness and antagonistic effects co-affect plant growth promotion by synthetic microbial consortia. *Applied Soil Ecology*, *170*, 104300.

Wang, Y., Qin, Y., Chai, Q., Feng, F., Zhao, C., & Yu, A. (2018). Interspecies interactions in relation to root distribution across the rooting profile in wheat-maize intercropping under different plant densities. *Frontiers in Plant Science*, *9*, 483.

Wittwer, R. A., Klaus, V. H., Oliveira, E. M., Sun, Q., Liu, Y., Gilgen, A. K., ... & van der Heijden, M. G. (2023). Limited capability of organic farming and conservation tillage to enhance agroecosystem resilience to severe drought. *Agricultural Systems*, *211*, 103721.

Wu, W., & Ma, B. (2015). Integrated nutrient management (INM) for sustaining crop productivity and reducing environmental impact: A review. *Science of the Total Environment*, *512*, 415-427.

Xing, Y., Wang, X., & Mustafa, A. (2025). Exploring the link between soil health and crop productivity. *Ecotoxicology and Environmental Safety*, *289*, 117703.

Yang, C., Liu, N., & Zhang, Y. (2019). Soil aggregates regulate the impact of soil bacterial and fungal communities on soil respiration. *Geoderma*, *337*, 444-452.

Zhuang, X., Chen, J., Shim, H., & Bai, Z. (2007). New advances in plant growth-promoting rhizobacteria for bioremediation. *Environment International*, 33, 403–413.

Zhuang, Y., Wang, H., Tan, F., Wu, B., Liu, L., Qin, H., ... & He, M. (2024). Rhizosphere metabolic cross-talk from plant-soil-microbe tapping into agricultural sustainability: Current advance and perspectives. *Plant Physiology and Biochemistry*, 108619.