Review Article:

Diversity in Soil Microbes: An Essential Factor in Food Security and Human Health-A Review

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Received on Sep 16, 2024, accepted for publication on Oct 21, 2024, dx.doi.org/10.5455/mjhs.2025.01.012

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Abstract

A varied collection of microbes called the soil microbiome plays a major role in various human health issues and sustainable agriculture. Due to its distinct bioactive chemicals and ecological roles, soil microbiota, which is made up of a wide variety of microorganisms such as fungi, bacteria, and archaea, has great promise as therapeutic agents such as antibiotics Streptomycin, Penicillin, Erythromycin, Phosphatase enzymes etc. Moreover, through a variety of mechanisms, including nitrogen fixation, mineralization, solubilization, and nutrient mobilization, these microbes support plants growth. They also generate antagonistic chemicals, siderophores, antimicrobial agents, and hormonal substances that aid in the growth of plants, such as auxin and gibberellins. The goal of low-input agriculture is to increase long-term production while reducing the need for artificial fertilizers and pesticides. Using the possibilities of the soil microbiome promotes healthier surroundings and environmentally friendly agricultural practices, which eventually improve human health. Even though they are among the most diverse species of organisms in this habitat, hardly anything is known about them. Therefore, this study highlight the crucial role of soil microbial diversity that plays an important role in enhancing agricultural productivity, ensuring sustainable food systems, and promoting human health. It seeks to demonstrate how diverse soil microbes improve nutrient cycling, plant growth, and disease resistance, while also supporting ecosystems that are vital for long-term food security.

Key words:
Biofertilizers; Bioremediation; Microbiota; Ecosystem; Food Security; Human Health

Introduction:

By 2050, it is expected that there will be 9.7 billion people on the planet, greatly increasing the demand for both water and food [1]. By then, food production will have to increase by 70% in order to satisfy this demand. Historically, intensive agricultural techniques, such as the heavy use of water, agrochemicals, and fertilizers based on minerals, have been used to achieve this rise. Nevertheless, these practices have aided in resource depletion, contamination of the environment, and destruction of land. n. A wide variety of microorganisms are hosted by plants in the rhizosphere (root zone), phyllosphere (surface tissue), and endosphere (interior tissue), resulting in an elaborate ecosystem with multiple niches for life. These microbes engage in a variety of ways that may be advantageous, neutral, or dangerous.

In addition to being an essential resource for food, fibre, and biodiversity, soil is also important for agriculture, human health, and the environment [2] as healthy soil gives plants access to clean water and key nutrients. Even though the land produces 95% of our food, we frequently underestimate the role that healthy soil plays in the food chain. The resilience of ecological systems, plant development, and soil health are all dependent on the soil microbiome. It is made up of a variety of microbes, including algae (e.g., Chlorella), fungus (e.g., Mycorrhizae, Trichoderma), and bacteria (e.g., Rhizobium, Bacillus). By fixing nitrogen and breaking down organic materials, bacteria improve the nutrients in soil. Through symbiotic connections, fungi enhance plants' ability to absorb nutrients, and through the process of photosynthesis, algae provide organic matter.

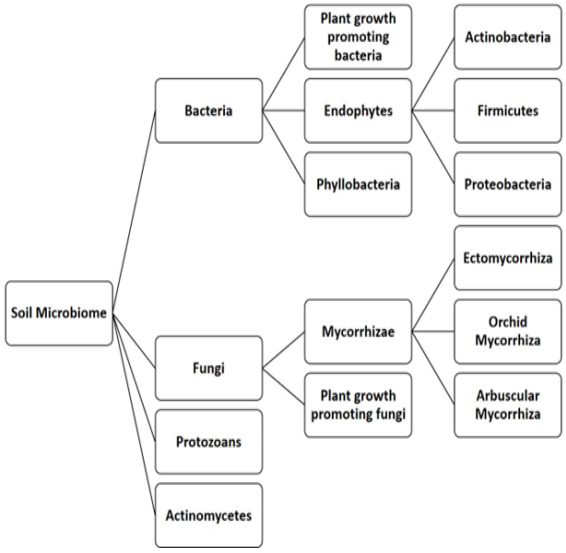


Figure 1: Microbes helpful in sustainable Agriculture.

When these organisms work together, they improve resistance towards diseases, soil structure, and water retention capacity that support a sustainable agricultural system [3]. Additionally, the production of secondary metabolites by various microbes, many of which act as antibiotics, fungicides, and other medications, is influenced by the soil microbiome [Fig.1] . Antibiotics like streptomycin are produced by bacteria like Streptomyces, whilst antifungal substances are secreted by Bacillus species. Penicillin

is a renowned antibiotic that is produced by fungi, such as Penicillium [4]. Algae, including Cyanobacteria, produce bioactive substances that may have medical applications. These chemical compounds offer plants pathogen defence as well as a wealth of information for the development of new drugs for human use [5]. Thus, this review focus on the importance of soil microbiome across medicine, agriculture, and the environment.

Soil Microbiota for Human health as therapeutic agent:

In order to promote knowledge transfer for sustainable agriculture, agricultural microbiology is essential to the integration of biotechnology, microbiology, and microbial ecology. There are several approaches focused for human health improvement which have been discussed in previous literature by the use of computational methods, protein targeting, and exploration of natural products. Natural products are the chemicals that are useful in the treatment and management of a wide range of infectious and non-communicable disorders[6-15]. they are believed to be affordable, safe, and have substantial bioactive potential in the treatment of a wide range of illnesses that are resistant to several medications, such as metabolites originating from fungus, bacteria, and plants. Plants and microbes are a rich source of naturally occurring chemical substances that possess potent antioxidant properties. These compounds have potential use in the treatment of hepatic, neurological, and cardiovascular illnesses, diseases associated with oxidative stress [16-24]. In order to restore microbiota in agricultural and natural ecosystems, it is crucial to comprehend the microbial flux between soil, plants, and animals [25]. Due to its distinct bioactive chemicals and ecological roles [13] soil microbiota, which is made up of a wide variety of microorganisms such as fungi, bacteria, and archaea, has great promise as therapeutic agents [26] [Fig. 2]. Using soil microbiota for medicinal purposes involves the following major uses.

1. **Antibiotics Production:** A variety of microbes, including those in the genera Bacillus and Streptomyces, are capable of producing antibiotics, which are useful against infections [27]. Certain bacteria isolated from natural sources play a crucial role in treating human diseases. For example, Streptomyces species produce antibiotics like streptomycin, which inhibits protein synthesis in harmful bacteria, treating infections such as tuberculosis. Lactobacillus species, commonly found in probiotics, help restore gut flora balance and treat gastrointestinal disorders. Another example is Escherichia coli, genetically modified to produce insulin for managing diabe-

tes, where it synthesizes the hormone used in insulin therapies. These bacteria work by either directly attacking pathogens or producing vital compounds for human health. Penicillin and streptomycin act as a natural antibiotic produced by microbes. Among microbes, one of the most common microorganisms, Actinomycetes, can be found in a variety of locations including both soil and water. They are well-known for their inherent capacity for yielding antibiotics, which include tetracycline, macrolides, chloramphenicol, nucleosides, and polyenes [28], erythromycin, gentamycin, rifamycin, and streptomycin, etc.[29,30]. These microbial compounds are essential for treating a wide range of diseases, but despite their enormous potential to produce secondary metabolites, difficulties persist in streamlining identification and production procedures [31, 32]. Moreover, the emergence of microbial immune towards antibiotics highlights the pressing need to investigate alternative sources of antibiotics [33]. A number of fungi are recognized for releasing antibiotics which help manage diseases. Penicillium chrysogenum generates penicillin, used to deal with bacterial infections such as strep throat and syphilis. Cephalosporium acremonium produces cephalosporins, which are efficient against skin infections, respiratory illnesses, and urinary tract infections. Aspergillus terreus yields lovastatin, primarily utilized to lower cholesterol but also displaying antimicrobial effects. Fusidium coccineum produces fusidic acid, utilized in treating skin infections including impetigo and infected wounds [34]. These fungal antibiotics or fungal mediated nanoparticles have been essential in medical treatments [30, 35, 36]

2. **Probiotic Applications:** The probiotic potential of some soil-derived microorganisms is being investigated. Through fostering advantageous microbial communities, improving digestion, and bolstering the immune system, these microbes help improve gut health [37]. As probiotics, for example, many bacteria found in soil have been demonstrated to possess antibacterial qualities and may be able to stabilize the gut microbiota. Probiotics originating from microorganisms found in soil are crucial for improving immunological performance. These helpful microbes, which are frequently discovered in soil, influence the gut microbiota, which is closely related to the immune system. Soil-based probiotics, such as some species of Bacillus and Lactobacillus, can boost the development of immune cells, including T

cells and macrophages, by maintaining a healthy balance of gut bacteria [38]. By strengthening the gut barrier and lowering inflammation, they help improve the body's defences against infections. Thus, general immunity is bolstered and potential defences against infections, autoimmune disorders, and allergies may be strengthened.

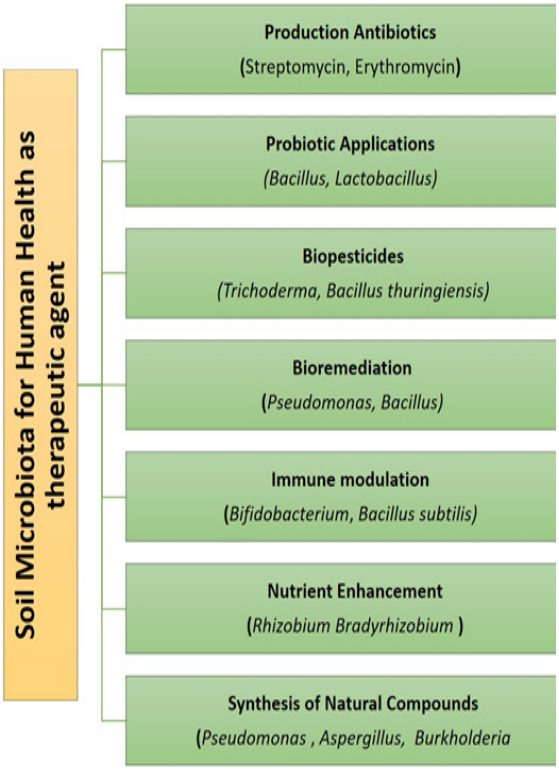


Figure 2: Utility of Soil Microbes as therapeutic agent.

3. **Immune modulation:** Soil microbes play an important role in immune modulation by interacting with the human immune system and influencing its response to pathogens [39]. Bacteria such as Lactobacillus, Bifidobacterium, and Bacillus subtilis found in soil and the environment can promote immune tolerance and anti-inflammatory responses. These microbes interact with immune cells like macrophages, dendritic cells, and T-cells through the release of metabolites such as short-chain fatty acids (SCFAs), which help regulate immune function[40]. Certain soil-derived mycobacteria, such as Mycobacterium vaccae, have been shown to trigger anti-inflammatory pathways by stimulating the production of anti-inflammatory cytokines like IL-10. They also influence the gut microbiota, which plays a key role in shaping immune responses through the gut-associated lymphoid tissue (GALT). Additionally, these microbes can help prime the immune system by promoting a balanced Th1/Th2 response, enhancing resistance to autoimmune diseases and allergies. Through their effects on both innate and adaptive immunity, soil microbes contribute to a healthier, more regulated immune system.

Soil-Microbiota in Sustainable Agriculture :

One prospective long-term answer to concerns with food security, human health, and environmental pollution is the employing of soil bacteria in agriculture. It is anticipated that important agricultural microorganisms would be crucial to a number of approaches meant to lessen the need for

agrochemicals while preserving crop yield. This is particularly valid for strategies like integrated control of diseases and pests and the control of nutrients. Microbes are used in agriculture as bio stimulants, which help plants absorb nutrients[41], biocontrol agents, which help manage pests and diseases, and biofertilizers [42]. There is no need for repeated applications because these organisms are self-sustaining and self-replicating [43]. A variety of environmental circumstances, plant species, and the makeup of the microbial community influence how well these microbes work to improve soil health and encourage plant development. These microorganisms generate substances that inhibit pathogenic organisms and regulate phytopathogens, such as auxins, gibberellins, and antibiotics. Additionally, they are essential to crop biofortification, raising the concentrations of micronutrients like zinc, iron, and selenium in staple crops. These helpful bacteria can lessen the negative effects of conventional farming methods by encouraging plant growth, nutrient cycling, cutting waste, and decomposing pollutants and pesticides [44]. Multiple benefits of sustainable agriculture comprise improved social welfare, economic prosperity, and environmental protection. Communities with greater diversity are more durable and robust to environmental stress. Sustainable agriculture lowers input costs financially by reducing the demand for synthetic pesticides and fertilizers [Fig. 3]. Furthermore, it creates new markets for products made organically and sustainably, giving farmers more chances to make money. Sustainable agriculture benefits both farmers and consumers by lowering environmental damage and enhancing soil health, which results in a more dependable food system [44]. Improved nutritional value, greater farmworker safety, and community-focused methods that promote long-term agricultural sustainability are examples of social advantages.

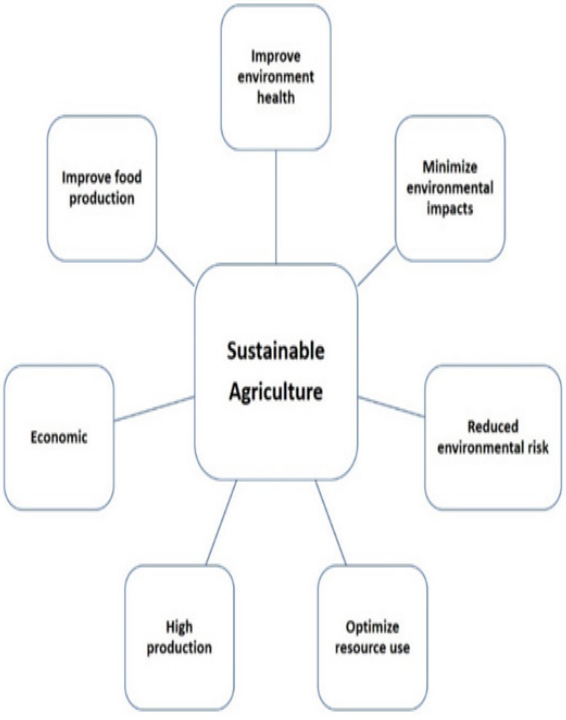


Figure 3: Advantages of Sustainable Agriculture.

1. **Biofertilizers:** Now a days, maintaining food security and sustainability at the same time is getting more and harder. To enhancing the crop yields and agroecosystem health while reduc-

ing the effects of climate change is the goal of sustainable agriculture. It entails combining ecological, chemical, physical, and biological aspects. Thus, by using microorganisms in the form of biofertilizers, biodiversity is preserved through improved root growth, nitrogen cycling, water retention, carbon storage, pollution filtration, and nutrient cycling [45] as conventional agricultural activities, nevertheless, has the potential to deteriorate soil health, underscoring the necessity of methods to enhance it. Biofertilizers are natural fertilizers containing living microorganisms that enhance plant growth by increasing the availability of essential nutrients. These microorganisms, including bacteria, fungi, and cyanobacteria, form symbiotic relationships with plants, improving soil health and reducing the need for chemical fertilizers. Types of biofertilizers include nitrogen-fixers like Rhizobium and Azotobacter, phosphate-solubilizers like Pseudomonas, potassium-solubilizers like Frateuria aurantia, and mycorrhizal fungi that enhance nutrient absorption. The mechanism involves these microbes converting atmospheric nitrogen into usable forms, solubilizing phosphorus and potassium, or extending the plant's root system for better nutrient uptake. Examples include Rhizobium for legumes, Azospirillum for cereals, and mycorrhiza for various crops. Overall, biofertilizers promote sustainable agriculture by boosting crop productivity, improving soil structure, and reducing dependency on chemical inputs. Biofertilizers are eco-friendly, improve soil health, and provide a sustainable nutrient supply, unlike chemical fertilizers which can harm the environment. They are cost-effective and enhance beneficial soil microbes, promoting long-term plant growth.

In current agriculture, integrated pest management (IPM) is a useful strategy that tries to keep insect populations under controlled at reasonable levels without endangering the environment or public health. Integrated Pest Management (IPM) integrates diverse techniques to avert pest infestations and employs plant protection chemicals in a cost-effective and ecologically conscious manner. Natural pesticides include substances like limonene, pyrethrins, rotenone, and sabadilla and are produced from plants including neem, custard apple, tobacco, and pyrethrum [46]. Pests like fleas, aphids, ants, beetles, and caterpillars are managed using these all over the world. Effective pest management while lowering hazards to the environment and public health is the aim of integrated pest man-

agement (IPM).

2. **Biopesticides:** An eco-friendly substitute for conventional pesticides, biopesticides are made from the microbiota found in soil. Compounds produced by fungus and bacteria in the soil have the ability to inhibit pests and plant diseases. For instance, fungi like Trichoderma spp. are used to fight soil-borne diseases and enhance plant health [47], whereas Bacillus thuringiensis is employed as a biopesticide to manage insect pests. Biopesticides are excellent at controlling pests and stimulating plant growth because they come from natural sources like bacteria and plants. Well-known biopesticide Bacillus thuringiensis (Bt) works against insect pests, particularly caterpillars, by creating toxins that interfere with their digestive processes [48]. By reducing damage caused by pests this can be achieved without the use of hazardous chemical pesticides, resulting in more nutritious crops and higher yields. Another example is Trichoderma harzianum, a fungus which preserves crops by outcompeting dangerous soil fungi such as Pythium and Rhizoctonia. It establishes the root zone, where it enhances root growth and boosts nutrient uptake by producing growth-promoting hormones like auxins and gibberellins.
3. **Nutrient Enhancement:** Soil microbes are essential for nutrient enhancement by facilitating the availability and cycling of vital nutrients for plant growth [49,50]. Bacteria like Rhizobium and Bradyrhizobium engage in nitrogen fixation, converting atmospheric nitrogen into ammonia, a form plants can absorb and use [51]. Similarly, free-living nitrogen fixers like Azotobacter enrich the soil nitrogen content. Phosphate-solubilizing bacteria such as Pseudomonas and Bacillus release organic acids that dissolve bound phosphorus, making it more accessible to plants. Mycorrhizal fungi form symbiotic relationships with plant roots, extending their hyphae to improve water and nutrient uptake, particularly phosphorus[52] and micronutrients like zinc and copper [53, 54]. Fungi such as Glomus also enhance soil structure, improving nutrient retention. Additionally, microbes like Trichoderma decompose organic matter, breaking down complex organic compounds into simpler forms, enriching the soil with carbon, nitrogen, and other essential elements. These microbial processes enhance soil fertility, promoting better plant growth and productivity through efficient nutrient cycling and availability.
4. **Crop Rotation:** In crop rotation, different types of plants are strategically

planted in successive seasons to enhance soil fertility, control pests, and improve crop yields. Common plant groups used include legumes (e.g., peas, beans, and clover), cereals (e.g., wheat, corn, and barley), root crops (e.g., potatoes and carrots), and cover crops (e.g., rye, alfalfa). Legumes are often rotated into fields due to their ability to fix atmospheric nitrogen through symbiotic bacteria like Rhizobium, enriching the soil with nitrogen for the next crop [55]. Crop rotation is typically designed around seasonal changes. For example, cereals may be planted in spring or fall, while legumes are often grown in summer. Cover crops like rye or clover are planted in off-seasons to prevent soil erosion and improve organic matter. Mechanistically, crop rotation promotes sustainable agriculture by breaking pest and disease cycles, as different crops host different pathogens and insects. Rotating crops with deep and shallow root systems improves soil structure and aeration. By alternating nitrogen-fixing legumes with nitrogen-demanding crops like cereals, farmers reduce the need for synthetic fertilizers [56]. This practice enhances biodiversity, improves soil health, and contributes to long-term agricultural sustainability and productivity.

5. **Intercropping:** In intercropping, multiple crop species are grown together in the same field to maximize resource use, increase biodiversity, and promote sustainable agriculture[57]. Common plant combinations include cereals (e.g., maize, wheat) with legumes (e.g., beans, peas), as legumes fix atmospheric nitrogen, enriching the soil for the cereals. Other combinations include root crops (e.g., carrots, onions) with leafy crops (e.g., lettuce), and tall plants (e.g., corn) with shade-tolerant crops (e.g., squash). Intercropping can be practiced in various seasons depending on the crop species involved, typically based on complementary growing patterns—warm-season crops (e.g., corn) are often paired with cool-season crops (e.g., peas or spinach) [58]. Mechanistically, intercropping enhances sustainable agriculture by optimizing light, water, and nutrient use. Tall plants provide shade for smaller ones, while deep-rooted crops bring up nutrients from lower soil layers, benefiting shallow-rooted plants [59]. The combination of different plants breaks pest and disease cycles, reducing the need for pesticides. Microbial activity is also stimulated by intercropping. The diversity of plant roots supports a wider range of beneficial soil microbes, such as nitrogen-fixing bac-

teria in legume roots and mycorrhizal fungi, which improve nutrient uptakes for all plants. Increased organic matter from diverse crops supports microbial populations, boosting soil health, nutrient cycling, and long-term agricultural sustainability.

6. **Conservation Tillage:** Using a Plow and leaving at least 30% of crop residue on the soil's surface following harvest is known as conventional tillage (CT). To counteract the detrimental consequences of traditional farming, sustainable agriculture supports conservation tillage (CT) techniques including reduced tillage (RT) and no tillage (NT) [60]. NT modifies the dispersion of soil microorganisms and raises the carbon and nitrogen content in the surface soil, improving moisture, microbial activity, and enzyme function. Although they may result in decreased crop yields, these techniques minimize the danger of erosion, increase soil stability, variety, and fungal networks, and cut tillage expenses. Furthermore, the amount of organic matter in surface soil influences gas exchange, rainfall, fertilizer efficiency, and organic material performance [61].
7. **Green Manuring:** Green manure crops such as sunn hemp and dhaincha improve soil fertility, promote microbial development, and improve soil framework through root secretions and polysaccharide gums [62] .Breaking down more gradually than traditional nitrogen fertilizers, GM crops result in greater crop yields, more effectively soil health, and minimized nitrogen loss. Green manuring (GM) is the feasible practice of adding green plants to the soil prior they bloom to boost soil nutrients and organic material [63].
8. **Agroforestry:** Soil erosion reduction is one of agroforestry's main ecological advantages. Tree roots serve to stabilize the soil, limiting the amount of topsoil that is lost to wind and water. Furthermore, through boosting nutrient cycling and adding more organic matter, agroforestry systems strengthen the health of the soil [64]. As tree leaves fall to the ground, they break down and add nutrients to the soil while also improving its structure. This enhances moisture retention, strengthening the land's resistance to dry spells. Additionally essential to the promotion of biodiversity is agroforestry. It generates homes for a variety of wildlife, including insects, birds, and small mammals, by incorporating a variety of plant types. This lessens the need for chemical pesticides by promoting natural pest management and preserving ecological equilibrium [65]. Furthermore, trees in these

systems provide habitat for pollinators, which are essential to crop productivity. Significant socio-economic benefits of agroforestry extend beyond its ecological advantages. Enhancing farmers' livelihoods, it supplies vital resources like food, fuelwood, timber, and medicinal goods. Moreover, it facilitates long-term productivity without causing degradation to the land, which supports sustainable land use.

9. **Vermicomposting:** Often referred to as "the farmer's friend," earthworms are important for improving the chemical, microbiological, and physical characteristics of soil. They release more organic materials for microbial breakdown by dissolving big soil particles and leaf litter. Earthworms use both aerobic and anaerobic bacteria to break down organic waste into vermicompost, which is a rich source of micro- and macronutrients that are vital for human health as well as microbial enzymes [66].

Their actions enhance the availability of nutrients and inhibit pathogenic microorganisms while fostering healthy microflora. Earthworms increase soil aeration through their digging, which promotes microbiological activity. Beneficial soil microbes such as rhizospheric bacteria like Pseudomonas, Rhizobium, Bacillus, Azospirillum, and Azotobacter, which all assist plant growth, proliferate more in this improved habitat [67]. Earthworm-soil microbe interaction improves overall soil health and nutrient cycling by indirectly influencing soil chemical processes. In order to preserve productive, healthy soils for sustainable agriculture, worms that live are essential for their contributions to soil structure, aeration, and diversity of microbial species. Table 1 offers a succinct summary of some important microbes and the beneficial substances they generate, emphasizing the wide range of uses they have in environmental management, the agricultural sector, and medicine.

Table 1: Important microbial strains and the beneficial metabolites:

Microbe	Released Compounds	Utility	References
Streptomyces	Antibiotics e.g., Streptomycin,) (Erythromycin	Treatment of bacterial infections, including tuberculosis and other serious infections	68
Bacillus	Bacitracin, Polymyxin, Lipopeptides	Antibiotic use and pest control; some strains used as biopesticides in agriculture	69

Penicillium	Penicillin, Griseofulvin	Antibiotic for treating bacterial infections and fungal infections	70
Actinomyces	Actinomycin, Streptothricin	Antibiotic and anti-tumour agents; useful in cancer treatment and bacterial infections	71
Pseudomonas	Pyocyanin, Phenazines, Antibiotics	Antimicrobial properties, plant growth promotion, bioremediation of pollutants	72
Trichoderma	Enzymes (e.g., chitinase, (cellulase	Biological control of soil-borne plant pathogens, promoting plant growth	73
Bacillus thuringiensis	Cry proteins	Biopesticides for controlling insect pests in agriculture	74
Clostridium	Acetone, Butanol	Used in industrial fermentation processes; potential for biofuel production	75

Sustainable Agriculture for Environmental Health.

The excessive application of fertilizers and agrochemicals throws off the nutrient cycles of the soil, and pesticide runoff contaminates water systems, damaging insects that are beneficial, plants, and soil microbes [76]. In addition to creating temperature changes and inconsistent rainfall, these farming methods also contribute to climate change. This damages the soil's composition and productivity by reducing soil moisture levels. In sustainable agriculture, soil microbiota is essential for fertility of the soil, plant growth, stress resistance, and the recycling of nutrients. Through rhizospheric, endophytic, and phyllospheric interactions, different microbial communities assist plants in accessing nutrients either symbiotically or autonomously [77]. To further safeguard crops, bio fungicides and biopesticides are applied. Conserving natural resources like soil and water is essential for ensuring nutrient availability, agricultural productivity, human health, and environmental safety. Sustainable farming practices focus on protecting these resources, preventing degradation, and maintaining soil health and biodiversity. Farmyard manure (FYM) and crop residues are examples of how renewable and non-renewable resources are effectively used in sustainable agriculture to meet food and fibre demands, improve farmers' livelihoods, and protect environmental quality [78]. Other sustainable farming practices include agroforestry, growing cover crops, conservation agriculture, green manuring, intercropping, crop rotation, and the use of biofertilizers.

In terms of environmental health, microbes such as Alcaligenes and Sphingomonas degrade organic pollutants and detoxify heavy metals through bioremediation[79]. By metabolizing toxic compounds and converting them into less harmful forms, these microbes reduce pollution and restore soil ecosystems. Overall, soil microbes sustain plant growth, improve soil aeration and

water retention, and mitigate environmental contamination, making them crucial for both soil health and environmental restoration.

Bioremediation:

To remove environmental pollutants like pesticides, heavy metals, and hydrocarbons, soil microorganisms are used in bioremediation procedures. By breaking down or changing dangerous compounds into less toxic forms, these bacteria help restore damaged habitats and improve the quality of soil and water. Soil microbes play a crucial role in bioremediation by breaking down or neutralizing pollutants in contaminated environments. Bacteria such as Pseudomonas, Bacillus, and Mycobacterium degrade hydrocarbons and organic pollutants through enzymatic reactions, transforming them into less harmful substances [80]. Fungi like Trichoderma and Aspergillus break down complex pollutants like heavy metals and pesticides by secreting extracellular enzymes and organic acids. Actinomycetes, like Streptomyces, contribute to the degradation of aromatic compounds in soil. In the case of heavy metals, microbes can employ biosorption, bioaccumulation, and biomineralization to immobilize or detoxify metals. Some microbes, like Thiobacillus, oxidize harmful substances like sulfur compounds into less toxic forms [81]. These microbial processes improve soil health and reduce pollution in a sustainable way, making bioremediation a valuable tool for environmental restoration

Factors affecting microbial diversity:

The impact of alterations and disruptions to the environment on soil bacterial communities has been investigated in recent research. The makeup of the microbial community is shaped locally by variables such crop rotation, carbon and nitrogen availability, and type of vegetation [82]. Soil pH is a more significant predictor of microbial structure on a broader continental scale. Redox potential (Eh), which is crucial for sustaining life through oxidation-reduction reactions, has not gotten as much attention as pH. According to research, vegetation type has a major impact on the organization of microbial communities, and soil parameters, rather than land-use practices, are the main determinants of bacterial diversity in soil [83].

Role of Biotechnology in Agriculture:

While the mid-1900s Green Revolution increased food production, it also had unfavourable ecological effects such pollution, climate change, and decreased biodiversity. Through the use of transgenic crops and genetically modified organisms (GMOs), biotechnology and microbiology provide a sustainable substitute while increasing agricultural [84]. Sustainable agriculture depends on microbial biotechnology because it cre-

ates biopesticides, bioherbicides, and fertilizers that solve biotic and abiotic problems and encourage environmentally friendly farming methods [Fig. 4]. This depends on genetically modifying microbial organisms to lower the virulence of diseases, enhance biocontrol, and facilitate bioremediation. The accomplishment of microbial biotechnology depends on soil microbiomes, which offer a variety of rhizosphere homes for a broad spectrum of microbes. Microbiome research has been transformed by advances in genetic sequencing and computation, such as metagenomics and Next-Generation Sequencing (NGS), which allow for quick gene annotation and high-throughput analysis. By revealing the diversity, composition, and interactions of microbes, these technologies aid in the development of methods to enhance nutrient absorption and stress tolerance [85]. Microbiomes need to be carefully controlled and altered in order to enhance agricultural output and reduce environmental impact. Among the many advantages of biotechnological interventions are less chemical consumption and improved environmental stewardship. More environmentally friendly agriculture is supported by genetically modified crops that have longer shelf lives, are resistant to fungi and insects, and can withstand herbicides. In order to promote knowledge transfer for sustainable agriculture, agricultural microbiology is essential to the integration of biotechnology, microbiology, and microbial ecology[86]. In order to restore microbiota in agricultural and natural ecosystems, it is crucial to comprehend the microbial flux between soil, plants, and animals.



Figure 4: The utilization of microbial technology in numerous applications:

Future Prospects:

One of the biggest scientific challenges in agricultural soils is maintaining rhizosphere biodiversity [87]. While microbial inoculants have shown promise in treating specific agronomic problems, their limited applicability in many environmental settings stems from their variable effectiveness. Global interest in sustainable agriculture and the microbiome is rising as worries about food safety and technological break-

throughs grow [88]. It is essential to comprehend the effects of climate change and agronomic practices on the composition and activity of soil microbes. Because of its ability to lessen soil degradation brought on by the widespread use of agrochemicals and mineral fertilizers, sustainable agriculture is becoming more and more important in a variety of areas.

The variety and abundance of organisms in the soil rhizosphere play a major role in determining the health of the soil, which is essential for human well-being and sustainable agriculture. The microbiome provides a non-transgenic way to increase agricultural yields and improve soil health [89]. It is important for plant productivity and soil quality. Examining the effects of various production methods on the rhizosphere, plant systems, and soil will help us evaluate soil health markers more accurately and advance sustainability in the short- and long-term.

A number of the Sustainable Development Goals (SDGs) centre on soil, emphasizing the significance of sustainable land management [90]. An essential component of maintaining agroecosystems is soil health, which is characterized by its ability to sustain biological productivity and improve environmental quality. Resources like fuel, water, and soil become scarcer as the world's population rises, underscoring the necessity of efficient and sustainable management [91]. Even if conventional agriculture can feed a burgeoning population, the environment may suffer from its intensive methods. In general, organic farming techniques are superior to conventional approaches when it comes to fostering soil health.

Conclusion:

Sustainable agriculture and human well-being depend heavily on healthy soil, which is mostly determined by the variety and quantity of microorganisms in the rhizosphere. The microbiome provides a natural way to raise agricultural yields and improve soil health by improving plant production and soil quality. An understanding of the effects that various agricultural techniques have on plant and soil systems can aid in advancing long-term sustainability. A number of the Sustainable Development Goals (SDGs) depend on healthy soil, which emphasizes the necessity of sustainable land management. An increasing number of people means that there are less resources available globally, making proper soil management even more crucial. Although productive, traditional agriculture can have negative environmental effects; in contrast, organic farming practices typically improve soil health. Due to conventional pesticides' 10% efficacy and decline in biodiversity, human activities pose a threat to microbial diversity. Enhancing soil health

and biodiversity can be accomplished through integrated pest management and intercropping. The need for sustainable farming methods that guarantee food security and reduce environmental damage is growing as the population increases.

Conflict of Interest:

Author declares that there is no conflict of interest.

Financial support:

The author declares that there is no financial support sought/received to carry out this study.

Acknowledgments:

The author extends the appreciation to the Deanship of Postgraduate Studies and Scientific Research at Majmaah University.

References:

1. Bahar, N. H.; Lo, M.; Sanjaya, M.; Van Vianen, J.; Alexander, P.; Ickowitz, A.; Sunderland, T. Meeting the food security challenge for nine billion people in 2050: What impact on forests? Global Environmental Change 2020, 62, 102056.
2. Suman, J.; Rakshit, A.; Ogireddy, S. D.; Singh, S.; Gupta, C.; Chandrakala, J. Microbiome as a key player in sustainable agriculture and human health. Frontiers in Soil Science 2022, 2, 821589.
3. (3) Zheng, W.; Zeng, S.; Bais, H.; LaManna, J. M.; Hussey, D. S.; Jacobson, D. L.; Jin, Y. Plant growth-promoting rhizobacteria (PGPR) reduce evaporation and increase soil water retention. Water Resources Research 2018, 54 (5), 3673-3687.
4. Hayee, S. Novel Bioactive Compound Production by Microbial Biota: Potential Antimicrobials: Potential antimicrobials produced by microbial biota. Pakistan BioMedical Journal 2020, 3 (1).
5. Anand, U.; Jacobo-Herrera, N.; Altemimi, A.; Lakhssassi, N. A comprehensive review on medicinal plants as antimicrobial therapeutics: potential avenues of biocompatible drug discovery. Metabolites 2019, 9 (11), 258.
6. Jana, A.; Bhattacharjee, A.; Das, S. S.; Srivastava, A.; Choudhury, A.; Bhattacharjee, R.; De, S.; Perveen, A.; Iqbal, D.; Gupta, P. K. Molecular insights into therapeutic potentials of hybrid compounds targeting Alzheimer's disease. Molecular Neurobiology 2022, 59 (6), 3512-3528.
7. Bhattacharjee, R.; Negi, A.; Bhattacharya, B.; Dey, T.; Mitra, P.; Preetam, S.; Kumar, L.; Kar, S.; Das, S. S.; Iqbal, D. Nanotheranostics to target antibiotic-resistant bacteria: Strategies and applications. OpenNano 2023, 11, 100138.
8. Alsagaby, S. A.; Iqbal, D.; Ahmad, I.;

Patel, H.; Mir, S. A.; Madkhali, Y. A.; Oyouni, A. A. A.; Hawsawi, Y. M.; Alhumaydhi, F. A.; Alshehri, B. In silico investigations identified Butyl Xanalterate to competently target CK2α (CSNK2A1) for therapy of chronic lymphocytic leukemia. Scientific reports 2022, 12 (1), 17648.

9. Alturaiki, W.; Alhamad, A.; Alturaiqy, M.; Mir, S. A.; Iqbal, D.; Bin Dukhyil, A. A.; Alaidarous, M.; Alshehri, B.; Alsagaby, S. A.; Almalki, S. G. Assessment of IL-1β, IL-6, TNF-α, IL-8, and CCL 5 levels in newly diagnosed Saudi patients with rheumatoid arthritis. International Journal of Rheumatic Diseases 2022, 25 (9), 1013-1019.
10. Bano, N.; Iqbal, D.; Al Othaim, A.; Kamal, M.; Albadrani, H. M.; Algehainy, N. A.; Alyenbaawi, H.; Alghofaili, F.; Amir, M.; Roohi. Antibacterial efficacy of synthesized silver nanoparticles of Microbacterium proteolyticum LA2 (R) and Streptomyces rochei LA2 (O) against biofilm forming meningitis causing microbes. Scientific Reports 2023, 13 (1), 4150.
11. Amir, M.; Bano, N.; Baker, A.; Zia, Q.; Banawas, S.; Zaheer, M. R.; Shariq, M.; Nawaz, M. S.; Khan, M. F.; Azad, Z. A. A. Isolation and optimization of extracellular PHB depolymerase producer Aeromonas caviae Kuk1-(34) for sustainable solid waste management of biodegradable polymers. Plos one 2022, 17 (4), e0264207.
12. Bijani, S.; Iqbal, D.; Mirza, S.; Jain, V.; Jahan, S.; Alsaweed, M.; Madkhali, Y.; Alsagaby, S. A.; Banawas, S.; Algarni, A. Green synthesis and anticancer potential of 1, 4-dihydropyridines-based triazole derivatives: In silico and in vitro study. Life 2022, 12 (4), 519.
13. Iqbal, D.; Rehman, M. T.; Bin Dukhyil, A.; Rizvi, S. M. D.; Al Ajmi, M. F.; Alshehri, B. M.; Banawas, S.; Khan, M. S.; Alturaiki, W.; Alsaweed, M. High-throughput screening and molecular dynamics simulation of natural product-like compounds against Alzheimer's disease through multitarget approach. Pharmaceuticals 2021, 14 (9), 937.
14. Khare, N.; Maheshwari, S. K.; Rizvi, S. M. D.; Albadrani, H. M.; Alsagaby, S. A.; Alturaiki, W.; Iqbal, D.; Zia, Q.; Villa, C.; Jha, S. K. Homology modelling, molecular docking and molecular dynamics simulation studies of CALMH1 against secondary metabolites of Bauhinia variegata to treat alzheimer's disease. Brain Sciences 2022, 12 (6), 770.
15. Iqbal, D.; Khan, A.; Ansari, I. A.; Khan, M. S. Investigating the role of novel bioactive compound from ficus virens

ait on cigarette smoke induced oxidative stress and hyperlipidemia in rats. Iranian Journal of Pharmaceutical Research: IJPR 2017, 16 (3), 1089.

16. Khan, M. S.; Dukhyil, A. B.; Iqbal, D. Geno-protective, free radical scavenging and antimicrobial potential of Hyptis suaveolens Methanolic fraction: an in-vitro study. Journal of Pharmaceutical Research International 2021, 33 (11), 46-57.
17. (17) Jahan, S.; Redhu, N. S.; Siddiqui, A. J.; Iqbal, D.; Khan, J.; Banawas, S.; Alaidarous, M.; Alshehri, B.; Mir, S. A.; Adnan, M. Nobiletin as a neuroprotectant against NMDA receptors: an in silico approach. Pharmaceutics 2022, 14 (6), 1123.
18. Jangra, A.; Gola, P.; Singh, J.; Gond, P.; Ghosh, S.; Rachamalla, M.; Dey, A.; Iqbal, D.; Kamal, M.; Sachdeva, P. Emergence of taurine as a therapeutic agent for neurological disorders. Neural Regeneration Research 2024, 19 (1), 62-68.
19. Bano, N.; Siddiqui, S.; Amir, M.; Zia, Q.; Banawas, S.; Iqbal, D. Bioprospecting of the novel isolate Microbacterium proteolyticum LA2 (R) from the rhizosphere of Rauwolfia serpentina. Saudi Journal of Biological Sciences 2022, 29 (3), 1858-1868.
20. Sultana, S.; Ali, M.; Mir, S. R.; Iqbal, D. Isolation and characterization of glycosides from Convolvulus prostratus, Ficus virens, Phoenix dactifera, Spondias mangifera and Terminalia belerica. Eur. J. Pharm. Med. Res 2018, 5, 310-318.
21. Hussain, T.; Habib, A. H.; Rafeeq, M. M.; Alafnan, A.; Khafagy, E.-S.; Iqbal, D.; Jamal, Q. M. S.; Unissa, R.; Sharma, D. C.; Moin, A. Oleuropein as a potent compound against neurological complications linked with COVID-19: A computational biology approach. Entropy 2022, 24 (7), 881.
22. Iqbal, D.; Burhan, I. W.; Choudhary, R. K.; Alaidarous, M.; Alshehri, B. M.; Banawas, S.; Mir, S. A. Analysis between cigarette and shisha smokers for early atherogenesis: A cardiovascular disease. Journal of Pharmaceutical Research International 2021, 33 (41A), 175-186.
23. Nelson, V. K.; Jha, N. K.; Nuli, M. V.; Gupta, S.; Kanna, S.; Gahtani, R. M.; Hani, U.; Singh, A. K.; Abomughaid, M. M.; Abomughayedh, A. M. Unveiling the impact of Aging on BBB and Alzheimer's disease: Factors and Therapeutic implications. Ageing research reviews 2024, 98, 102224.
24. Albadrani, H. M.; Chauhan, P.; Ashique, S.; Babu, M. A.; Iqbal, D.; Almutary, A. G.; Abomughaid, M. M.; Kamal, M.; Paiva-Santos, A. C.; Alsaweed, M.

Mechanistic insights into the potential role of dietary polyphenols and their nanoformulation in the management of Alzheimer's disease. Biomedicine & Pharmacotherapy 2024, 174, 116376.

25. Iqbal, D.; Rehman, M. T.; Alajmi, M. F.; Alsaweed, M.; Jamal, Q. M. S.; Alasiry, S. M.; Albaker, A. B.; Hamed, M.; Kamal, M.; Albadrani, H. M. Multitargeted virtual screening and molecular simulation of natural product-like compounds against GSK3β, NMDA-receptor, and BACE-1 for the management of Alzheimer's disease. Pharmaceuticals 2023, 16 (4), 622.
26. Haruna, A.; Yahaya, S. M. Recent advances in the chemistry of bioactive compounds from plants and soil microbes: A review. Chemistry Africa 2021, 4 (2), 231-248.
27. Olanrewaju, O. S.; Babalola, O. O. Streptomyces: implications and interactions in plant growth promotion. Applied microbiology and biotechnology 2019, 103, 1179-1188.
28. Hussain, N.; Baqar, Z. Microbial synthesized antibiotics in healthcare management. In Microbial Biomolecules, Elsevier, 2023; pp 375-403.
29. Izhar, S. K.; Rizvi, S. F.; Afaq, U.; Fatima, F.; Siddiqui, S. Bioprospecting of Metabolites from Actinomycetes and their Applications. Recent Patents on Biotechnology 2024, 18 (4), 273-287.
30. Talwar, A.; Nayyar, A.; Anand, S.; Zahera, M.; Fatima, F. A Futuristic Approach on the Multifunctionality of Nanomaterials: Relevance of Nanoparticles. In Technological Applications of Nano-Hybrid Composites, IGI Global, 2024; pp 1-36.
31. Zahera, M.; Khan, A.; Mishra, K.; Fatima, F. Graphene Nanoparticles: Technological Concepts and Future Applications. The 2-Dimensional World of Graphene 2024, 100.
32. Zahera, M.; Mishra, K.; Fatima, F. Exploiting the Bioprospecting Potential of Nanoparticles with Micro-organisms. In The Nanotechnology Driven Agriculture, CRC Press, 2024; pp 245-263.
33. Muteeb, G.; Rehman, M. T.; Shahwan, M.; Aatif, M. Origin of antibiotics and antibiotic resistance, and their impacts on drug development: A narrative review. Pharmaceuticals 2023, 16 (11), 1615.
34. Devi, L. J.; Khunjanmayum, R.; Asem, R. S.; Singh, E. S.; Banerjee, S.; Ningthoujam, D. S. Understanding the Realm of Antibiotics: Mechanisms of Action and Their Applications as Anti-infective Agents. Current Perspectives on Anti-Infective Agents 2019, 1, 195.
35. Alqurashi, Y. E.; Almalki, S. G.; Ibra-

him, I. M.; Mohammed, A. O.; Abd El Hady, A. E.; Kamal, M.; Fatima, F.; Iqbal, D. Biological Synthesis, Characterization, and Therapeutic Potential of S. commune-Mediated Gold Nanoparticles. Biomolecules 2023, 13 (12), 1785.

36. Fatima, F.; Wahid, I. Eco-friendly synthesis of silver and copper nanoparticles by Shizophyllum commune fungus and its biomedical applications. International Journal of Environmental Science and Technology 2022, 19 (8), 7915-7926.
37. Zhou, P.; Chen, C.; Patil, S.; Dong, S. Unveiling the therapeutic symphony of probiotics, prebiotics, and postbiotics in gut-immune harmony. Frontiers in Nutrition 2024, 11, 1355542.
38. Singh, S.; Gupta, R.; Chawla, S.; Gauba, P.; Singh, M.; Tiwari, R. K.; Upadhyay, S.; Sharma, S.; Chanda, S.; Gaur, S. Natural sources and encapsulating materials for probiotics delivery systems: Recent applications and challenges in functional food development. Frontiers in Nutrition 2022, 9, 971784.
39. Tzipilevich, E.; Russ, D.; Dangl, J. L.; Benfey, P. N. Plant immune system activation is necessary for efficient root colonization by auxin-secreting beneficial bacteria. Cell host & microbe 2021, 29 (10), 1507-1520. e1504.
40. Hmar, E. B. L.; Paul, S.; Sharma, H. K. An Insight into the Combination of Probiotics and their Implications for Human Health. Endocrine, Metabolic & Immune Disorders-Drug Targets (Formerly Current Drug Targets-Immune, Endocrine & Metabolic Disorders) 2024, 24 (1), 1-12.
41. Pattnaik, S.; Mohapatra, B.; Gupta, A. Plant growth-promoting microbe mediated uptake of essential nutrients (Fe, P, K) for crop stress management: Microbe–soil–plant continuum. Frontiers in Agronomy 2021, 3, 689972.
42. Fatima, F.; Ahmad, M.; Verma, S.; Pathak, N. Relevance of phosphate solubilizing microbes in sustainable crop production: a review. International Journal of Environmental Science and Technology 2022, 19 (9), 9283-9296.
43. Pavlinova, P.; Lambert, C. N.; Malaterre, C.; Nghe, P. Abiogenesis through gradual evolution of autocatalysis into template-based replication. FEBS letters 2023, 597 (3), 344-379.
44. Saeed, Q.; Xiukang, W.; Haider, F. U.; Kučerik, J.; Mumtaz, M. Z.; Holatko, J.; Naseem, M.; Kintl, A.; Ejaz, M.; Naveed, M. Rhizosphere bacteria in plant growth promotion, biocontrol, and bioremediation of contaminated sites: a comprehensive review of effects and mechanisms. International journal of molecular sciences 2021, 22 (19),

10529.

45. Yousaf, A.; Khalid, N.; Aqeel, M.; Noman, A.; Naeem, N.; Sarfraz, W.; Ejaz, U.; Qaiser, Z.; Khalid, A. Nitrogen dynamics in wetland systems and its impact on biodiversity. Nitrogen 2021, 2 (2), 196-217.
46. Walia, S.; Saha, S.; Tripathi, V.; Sharma, K. Phytochemical biopesticides: some recent developments. Phytochemistry reviews 2017, 16, 989-1007.
47. Asad, S. A. Mechanisms of action and biocontrol potential of Trichoderma against fungal plant diseases-A review. Ecological Complexity 2022, 49, 100978.
48. Kumar, P.; Kamle, M.; Borah, R.; Mahato, D. K.; Sharma, B. Bacillus thuringiensis as microbial biopesticide: uses and application for sustainable agriculture. Egyptian Journal of Biological Pest Control 2021, 31 (1), 95.
49. Srivastava, D.; Maurya, R.; Khan, N.; Nayyer, M. A.; Mishra, A.; Fatima, F.; Ahmad, S.; Siddiqui, S.; Siddiqui, M. H. General Introduction of Bio-Inputs Versus Chemical Inputs in Agriculture and Ill Effects. In Biofertilizers and Biopesticides in Sustainable Agriculture, Apple Academic Press, 2019; pp 1-22.
50. Fatima, F.; Pathak, N.; Verma, S. R. Isolation and characterization of potential phosphate solubilizing bacteria from the rhizoplane of Kukrail forest, Lucknow. International Journal of Advancement in Engineering Technolgy, Management y Applied Science 2015, 2.
51. Igiehon, N. O.; Babalola, O. O. Rhizosphere microbiome modulators: contributions of nitrogen fixing bacteria towards sustainable agriculture. International journal of environmental research and public health 2018, 15 (4), 574.
52. Fatima, F.; Rastogi Verma, S.; Pathak, N. Genotyping assessment of phosphate solubilizing bacteria isolated from rhizospheric soil from central regions of Lucknow. Geomicrobiology Journal 2018, 35 (10), 848-853.
53. Khaliq, A.; Perveen, S.; Alamer, K. H.; Zia Ul Haq, M.; Rafique, Z.; Alsudays, I. M.; Althobaiti, A. T.; Saleh, M. A.; Hussain, S.; Attia, H. Arbuscular mycorrhizal fungi symbiosis to enhance plant–soil interaction. Sustainability 2022, 14 (13), 7840.
54. Fatima, F.; Pathak, N.; Srivastava, D.; Verma, S. R. Molecular detection and exploration of diversity among fungal consortium involved in phosphate solubilization. Geomicrobiology Journal 2021, 38 (1), 29-35.
55. Kebede, E. Contribution, utilization,

and improvement of legumes-driven biological nitrogen fixation in agricultural systems. Frontiers in Sustainable Food Systems 2021, 5, 767998.

56. Squire, G. R.; Young, M. W.; Hawes, C. Agroecological management and increased grain legume area needed to meet nitrogen reduction targets for greenhouse gas emissions. Nitrogen 2022, 3 (3), 539-554.
57. Brooker, R. W.; Bennett, A. E.; Cong, W. F.; Daniell, T. J.; George, T. S.; Hallett, P. D.; Hawes, C.; Iannetta, P. P.; Jones, H. G.; Karley, A. J. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. New Phytologist 2015, 206 (1), 107-117.
58. Khan, M. R.; Quintanilla, M. Nematode Diseases of Crops and Their Sustainable Management; Academic Press, 2023.
59. Alagele, S. M.; Jose, S.; Anderson, S. H.; Udawatta, R. P. Hydraulic lift: processes, methods, and practical implications for society. Agroforestry Systems 2021, 95 (4), 641-657.
60. Issaka, F.; Zhang, Z.; Zhao, Z.-Q.; Asenso, E.; Li, J.-H.; Li, Y.-T.; Wang, J.-J. Sustainable conservation tillage improves soil nutrients and reduces nitrogen and phosphorous losses in maize farmland in Southern China. Sustainability 2019, 11 (8), 2397.
61. Iqbal, A.; He, L.; Khan, A.; Wei, S.; Akhtar, K.; Ali, I.; Ullah, S.; Munsif, F.; Zhao, Q.; Jiang, L. Organic manure coupled with inorganic fertilizer: An approach for the sustainable production of rice by improving soil properties and nitrogen use efficiency. Agronomy 2019, 9 (10), 651.
62. Nazir, S.; uz Zaman, Q.; Al-Omran, A.; Hopmans, J. W.; Ashraf, K.; Komal, N.; Baig, M. B. Bioresource Nutrient Recycling and Its Relationship with Soil Health Under Irrigated Agro-ecosystems. In The Food Security, Biodiversity, and Climate Nexus, Springer, 2022; pp 441-477.
63. Kumar, S.; Samiksha; Sukul, P. Green manuring and its role in soil health management. Soil health 2020, 219-241.
64. Fahad, S.; Chavan, S. B.; Chichaghare, A. R.; Uthappa, A. R.; Kumar, M.; Kakade, V.; Pradhan, A.; Jinger, D.; Rawale, G.; Yadav, D. K. Agroforestry systems for soil health improvement and maintenance. Sustainability 2022, 14 (22), 14877.
65. Souto, A. L.; Sylvestre, M.; Tölke, E. D.; Tavares, J. F.; Barbosa-Filho, J. M.; Cebrián-Torrejón, G. Plant-derived pesticides as an alternative to pest management and sustainable agricultural

production: Prospects, applications and challenges. Molecules 2021, 26 (16), 4835.

66. Yatoo, A. M.; Bhat, S. A.; Ali, M. N.; Baba, Z. A.; Zaheen, Z. Production of nutrient-enriched vermicompost from aquatic macrophytes supplemented with kitchen waste: Assessment of nutrient changes, phytotoxicity, and earthworm biodynamics. Agronomy 2022, 12 (6), 1303.
67. Rawat, P.; Shankhdhar, D.; Shankhdhar, S. Plant growth-promoting rhizobacteria: A booster for ameliorating soil health and agriculture production. Soil health 2020, 47-68.
68. Alam, K.; Mazumder, A.; Sikdar, S.; Zhao, Y.-M.; Hao, J.; Song, C.; Wang, Y.; Sarkar, R.; Islam, S.; Zhang, Y. Streptomyces: The biofactory of secondary metabolites. Frontiers in Microbiology 2022, 13, 968053.
69. Olishevska, S.; Nickzad, A.; Déziel, E. Bacillus and Paenibacillus secreted polyketides and peptides involved in controlling human and plant pathogens. Applied microbiology and biotechnology 2019, 103, 1189-1215.
70. (70) Laich, F.; Fierro, F.; Martín, J. F. Production of penicillin by fungi growing on food products: identification of a complete penicillin gene cluster in Penicillium griseofulvum and a truncated cluster in Penicillium verrucosum. Applied and environmental microbiology 2002, 68 (3), 1211-1219.
71. Abu Zaid, A.; Yassien, M.; Aboshanab, K.; Elissawy, A. Streptomyces variabilis Isolate MW091521: a New Microbial Source of Heliomycin. Applied Biochemistry and Microbiology 2021, 57, 564-570.
72. Sidorova, T. M.; Tomashevich, N. S.; Allahverdyan, V. V.; Tupertsev, B. S.; Kostyukevich, Y. I.; Asaturova, A. M. New Pseudomonas Bacterial Strains: Biological Activity and Characteristic Properties of Metabolites. Microorganisms 2023, 11 (8), 1943.
73. Labuschagne, N.; Pretorius, T.; Idris, A. Plant growth promoting rhizobacteria as biocontrol agents against soil-borne plant diseases. Plant growth and health promoting bacteria 2011, 211-230.
74. Sanchis, V.; Bourguet, D. Bacillus thuringiensis: applications in agriculture and insect resistance management. A review. Agronomy for sustainable development 2008, 28, 11-20.
75. Li, J.; Baral, N. R.; Jha, A. K. Acetone–butanol–ethanol fermentation of corn stover by Clostridium species: present status and future perspectives. World Journal of Microbiology and Biotechnology 2014, 30, 1145-1157.
76. Ertop, H.; Atilgan, A.; Saltuk, B. Effects

of agricultural polluting factors on the environment. Infrastruktura i Ekologia Terenów Wiejskich 2024, 19.

77. Hassani, M. A.; Durán, P.; Hacquard, S. Microbial interactions within the plant holobiont. Microbiome 2018, 6, 1-17.
78. Palsaniya, D.; Kumar, S.; Das, M.; Kumar, T. K.; Kumar, S.; Chaudhary, M.; Chand, K.; Rai, S.; Ahmed, A.; Sahay, C. Integrated multi-enterprise agricultural system for sustaining livelihood, energy use and resource recycling: a case study from semi-arid tropics of central India. Agroforestry Systems 2021, 95 (8), 1619-1634.
79. Ojuederie, O. B.; Babalola, O. O. Microbial and plant-assisted bioremediation of heavy metal polluted environments: a review. International journal of environmental research and public health 2017, 14 (12), 1504.
80. Dudhagara, D. R.; Dave, B. P. Mycobacterium as polycyclic aromatic hydrocarbons (PAHs) degrader. Mycobacterium-Research and Development 2018.
81. McNeice, J.; Mahandra, H.; Ghahreman, A. Biogenesis of thiosulfate in microorganisms and its applications for sustainable metal extraction. Reviews in Environmental Science and Bio/Technology 2022, 21 (4), 993-1015.
82. Schmidt, J. E.; Kent, A. D.; Brisson, V. L.; Gaudin, A. C. Agricultural management and plant selection interactively affect rhizosphere microbial community structure and nitrogen cycling. Microbiome 2019, 7, 1-18.
83. Tian, Q.; Taniguchi, T.; Shi, W.-Y.; Li, G.; Yamanaka, N.; Du, S. Land-use types and soil chemical properties influence soil microbial communities in the semiarid Loess Plateau region in China. Scientific reports 2017, 7 (1), 45289.
84. Saxena, G.; Kishor, R.; Saratale, G. D.; Bharagava, R. N. Genetically modified organisms (GMOs) and their potential in environmental management: constraints, prospects, and challenges. Bioremediation of Industrial Waste for Environmental Safety: Volume II: Biological Agents and Methods for Industrial Waste Management 2020, 1-19.
85. Khan, N.; Ali, S.; Shahid, M. A.; Mustafa, A.; Sayyed, R.; Curá, J. A. Insights into the interactions among roots, rhizosphere, and rhizobacteria for improving plant growth and tolerance to abiotic stresses: a review. Cells 2021, 10 (6), 1551.
86. Yadav, V.; Pal, D.; Poonia, A. K. A study on genetically engineered foods: need, benefits, risk, and current knowledge. Cell Biochemistry and Biophysics 2024, 1-16.

87. Lemanceau, P.; Maron, P.-A.; Mazurier, S.; Mougel, C.; Pivato, B.; Plassart, P.; Ranjard, L.; Revellin, C.; Tardy, V.; Wipf, D. Understanding and managing soil biodiversity: a major challenge in agroecology. Agronomy for Sustainable Development 2015, 35, 67-81.
88. Chouhan, G. K.; Verma, J. P.; Jaiswal, D. K.; Mukherjee, A.; Singh, S.; de Araujo Pereira, A. P.; Liu, H.; Abd_Allah, E. F.; Singh, B. K. Phytomicrobiome for promoting sustainable agriculture and food security: opportunities, challenges, and solutions. Microbiological Research 2021, 248, 126763.
89. Babujia, L. C.; Silva, A. P.; Nakatani, A. S.; Cantão, M. E.; Vasconcelos, A. T. R.; Visentainer, J. V.; Hungria, M. Impact of long-term cropping of glyphosate-resistant transgenic soybean [Glycine max (L.) Merr.] on soil microbiome. Transgenic research 2016, 25, 425-440.
90. Visser, S.; Keesstra, S.; Maas, G.; De Cleen, M.; Molenaar, C. Soil as a basis to create enabling conditions for transitions towards sustainable land management as a key to achieve the SDGs by 2030. Sustainability 2019, 11 (23), 6792.
91. Richardson, R. B. Ecosystem services and food security: Economic perspectives on environmental sustainability. Sustainability 2010, 2 (11), 3520-3548.