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Air, Water, and Soil Microbiomes as Catalysts for Smart Agriculture, Urban Ecosystem Revitalization, Climate Adaptation, and Public Health Advancements

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Abstract

The interconnected challenges of food security, urban sustainability, climate change, and public health demand innovative and integrative solutions. Microbiomes—communities of microorganisms in air, water, and soil—hold transformative potential in addressing these issues. This review explores how microbiomes act as catalysts for sustainable development in smart agriculture, urban ecosystem revitalization, climate adaptation, and public health advancements. Soil microbiomes enhance nutrient cycling, improve crop resilience, and promote sustainable farming practices, while air and water microbiomes contribute to pollution mitigation, pathogen suppression, and water resource sustainability. In urban settings, microbiomes support green infrastructure, bioremediation, and waste recycling, fostering healthier and more resilient cities. Furthermore, their role in carbon sequestration, greenhouse gas reduction, and disease prevention highlights their critical contributions to climate adaptation and public health. This review synthesizes recent advances, identifies knowledge gaps, and proposes future directions for harnessing microbiomes as pivotal tools for global sustainability. The findings emphasize the importance of interdisciplinary approaches and policy support to maximize the benefits of microbiomes in addressing 21st-century challenges.

Keywords: *Microbiomes; Bioremediation; Sustainability; Precision Agriculture; Public Health.*

I. INTRODUCTION

- *Importance of Microbiomes in Natural Ecosystems.*

Microbiomes are integral to the functioning of natural ecosystems, shaping their structure and influencing biogeochemical cycles. Soil microbiomes, for instance, play a critical role in nutrient cycling by decomposing organic matter and mediating the availability of essential nutrients like nitrogen and phosphorus, which are vital for plant growth (Banerjee et al., 2018). Similarly, aquatic microbiomes contribute to water quality and nutrient cycling in marine and freshwater systems, supporting biodiversity and maintaining ecosystem health.

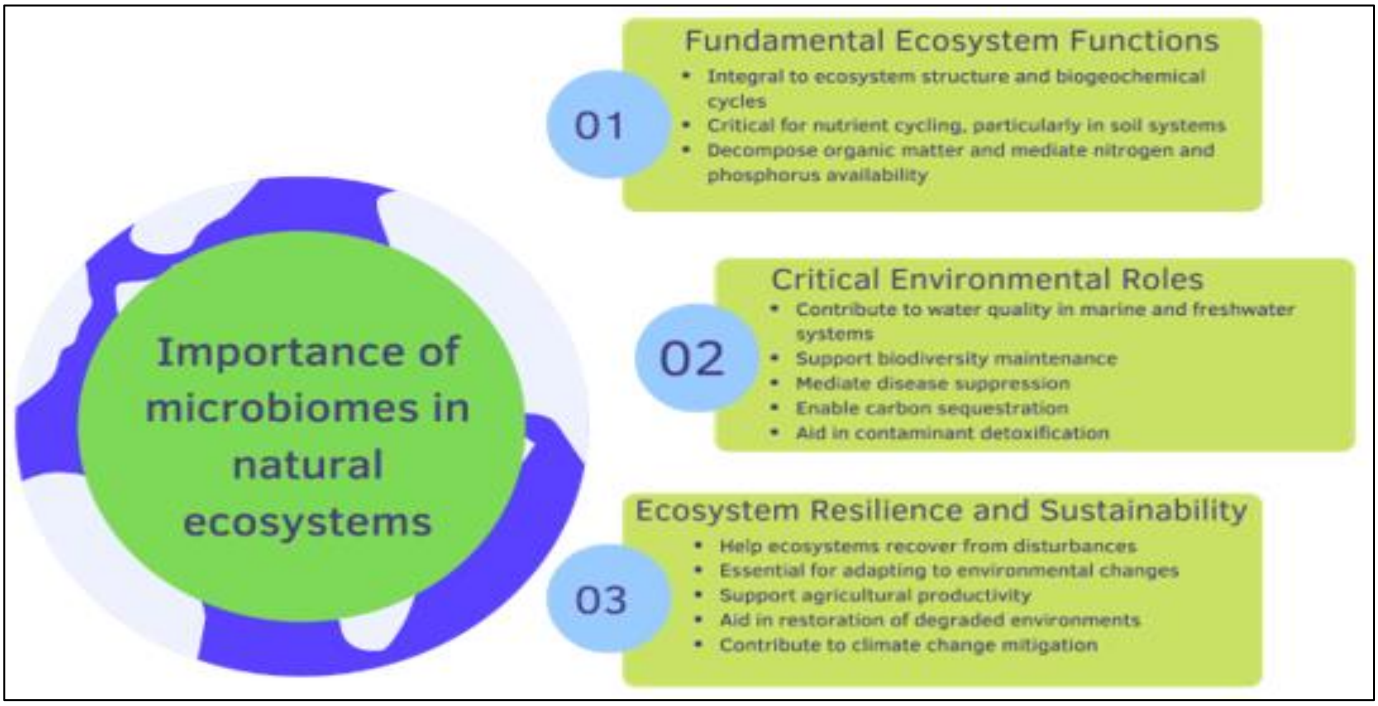

Fig 1 Key Functions of Microbiomes in Natural Ecosystem Sustainability.

Figure 1 illustrates three critical aspects of microbiomes in ecosystems: fundamental functions in nutrient cycling, environmental roles in maintaining biodiversity, and their contribution to ecosystem resilience and sustainability.

The concept of keystone taxa highlights the disproportionately large impact specific microbial groups can have on ecosystem processes. These microorganisms often mediate critical functions such as disease suppression, carbon sequestration, and the detoxification of contaminants (Banerjee et al., 2018). Their presence and activities underscore the necessity of studying microbiomes at meaningful scales to predict their contributions to global ecological processes. Furthermore, the resilience of microbiomes enables ecosystems to recover from disturbances, a characteristic crucial in the face of environmental changes (Berg et al., 2020).

Recognizing the importance of microbiomes can lead to innovative strategies for ecosystem management. By harnessing their functions, it is possible to enhance agricultural productivity, restore degraded environments, and mitigate the effects of climate change. This realization not only underscores the need for interdisciplinary research but also emphasizes the role of microbiomes as foundational elements of sustainable ecosystems (Dini-Andreote et al., 2021; Berg et al., 2020).

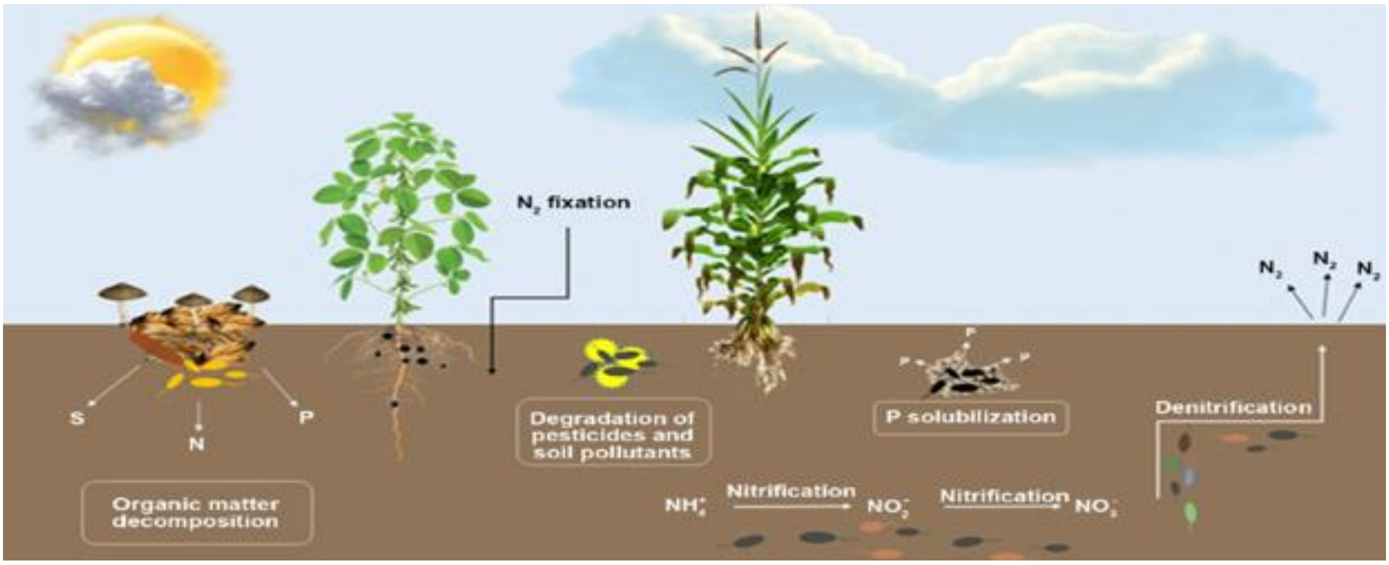

Fig 2 Microbiomes as Solutions to Global Challenges (Glodowska et al., 2019).

Figure 2 shows a conceptual diagram highlighting the role of microbiomes in nutrient cycling, carbon sequestration, and ecosystem resilience across soil, water, and air systems.

- *Overview of Challenges in Agriculture, Urbanization, Climate Change, and Public Health.*

Agriculture, urbanization, climate change, and public health are deeply intertwined, each presenting significant challenges to global sustainability. In agriculture, intensification to meet the food demands of a growing population has led to soil degradation, biodiversity loss, and water scarcity, threatening long-term productivity and ecosystem health (Ahmed et al., 2016). Urbanization exacerbates these issues by transforming natural landscapes into built environments, which disrupt ecological balances and lead to increased pollution and resource consumption (Song et al., 2016). The rapid expansion of urban areas has also introduced challenges in waste management and air quality, directly affecting human health .

Climate change intensifies these problems by altering weather patterns, increasing the frequency of extreme events, and accelerating the degradation of ecosystems. Rising temperatures and shifting precipitation patterns affect agricultural yields and food security, while urban heat islands further stress urban populations (McMichael, 2000). The interconnected nature of these changes highlights a cascading effect, where disruptions in one system—such as agriculture—can amplify vulnerabilities in others, such as urban infrastructure and public health.

Table 1 Interconnected Global Sustainability Challenges and their Impacts

Sector	Primary Challenges	Environmental Impact	Health & Social Impact
Agriculture	Food demand intensification, soil degradation, water scarcity	Biodiversity loss, ecosystem disruption	Food security threats, reduced productivity
Urbanization	Natural landscape transformation, resource consumption	Ecological balance disruption, increased pollution	Waste management issues, air quality deterioration
Climate Change	Altered weather patterns, extreme events	Ecosystem degradation, urban heat islands	Vector-borne diseases, heat stress
Public Health	Ecosystem stability dependence, urban population vulnerability	Environmental health degradation	Respiratory illnesses, climate-related health issues

Public health is particularly vulnerable due to its dependence on stable ecosystems. Climate-related health challenges include the resurgence of vector-borne diseases, heat stress, and respiratory illnesses linked to pollution (Frumkin & McMichael, 2008). Urban populations, concentrated in areas prone to climate-induced disasters, are disproportionately affected. Addressing these interconnected challenges requires interdisciplinary approaches and innovative solutions that integrate ecological, technological, and policy-driven strategies to build resilience across sector.

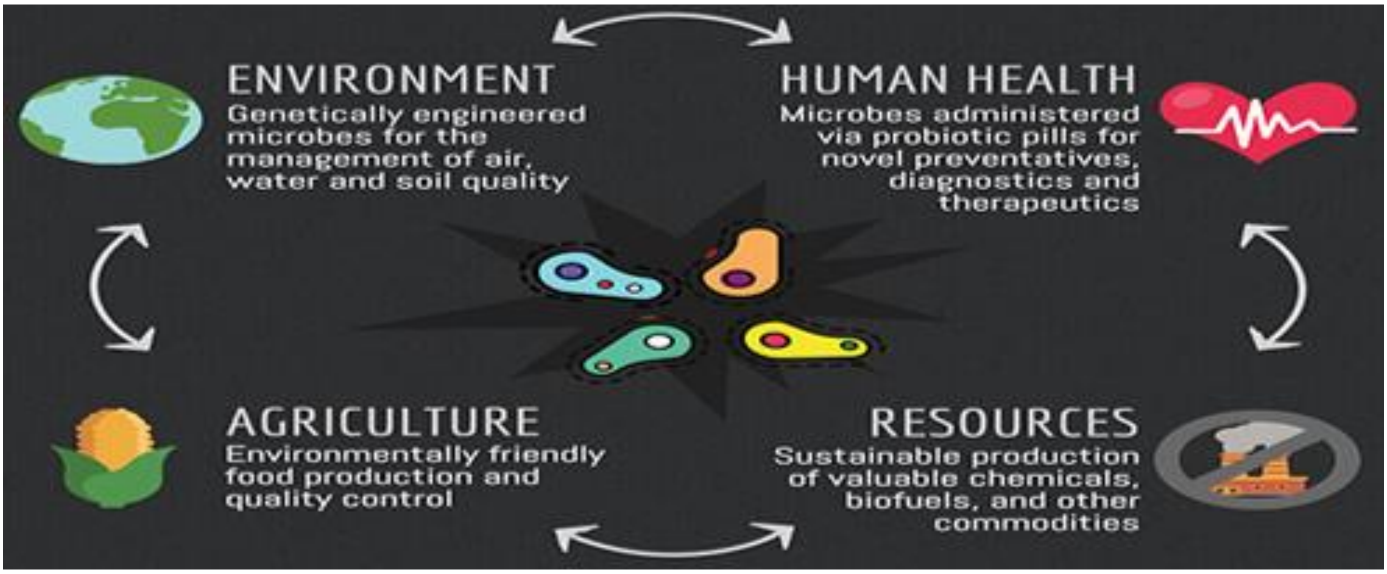

Fig 3 Microbiomes as Solutions to Global Challenges (Wyss Institute, 2020).

This image shows an infographic demonstrating microbiomes' contributions to mitigating challenges in agriculture, climate change, urbanization, and public health through sustainable ecological functions.

- *Objectives of Leveraging Microbiomes for these Challenges.*

Microbiomes represent a powerful tool in addressing global challenges across agriculture, urbanization, climate change, and public health. In agriculture, the objective of leveraging microbiomes centers on enhancing soil fertility and crop resilience through natural nutrient cycling and disease suppression, reducing reliance on synthetic inputs and mitigating environmental damage. Urban ecosystems, in turn, benefit from microbial interventions aimed at improving air and water quality, contributing to sustainable urban development and public health. These interventions align with broader goals of ecological restoration and resilience against pollution and resource depletion.

In the context of climate change, microbiomes play a critical role in carbon sequestration, bioremediation of pollutants, and the stabilization of ecosystems affected by extreme weather events. Harnessing soil and water microbiomes to adapt to shifting environmental conditions has emerged as a priority to sustain ecosystems under climate-induced stresses. Moreover, public health objectives involve utilizing microbiomes to manage infectious diseases, improve gut and respiratory health, and mitigate the impacts of urban pollution, particularly in densely populated areas. This highlights the intersection of microbiome research with preventive healthcare and sustainable urban planning.

Ultimately, the integration of microbiome-focused strategies into global sustainability initiatives aims to bridge ecological conservation with socio-economic benefits. By adopting a One Health perspective, researchers and policymakers seek to address interconnected issues across human, animal, and environmental health, achieving long-term stability and well-being for diverse populations. This interdisciplinary approach underscores the transformative potential of microbiomes in reshaping practices and policies for global sustainability.

II. MICROBIOMES AND SMART AGRICULTURE

- *Soil Microbiomes in Nutrient Cycling and Plant Health.*

Soil microbiomes are critical drivers of nutrient cycling and plant health, shaping the foundation of terrestrial ecosystems. Microorganisms in the soil, including bacteria, fungi, and archaea, decompose organic matter, facilitating the release of essential nutrients such as nitrogen, phosphorus, and potassium. This nutrient cycling is fundamental for plant growth, as it ensures the bioavailability of key elements that are otherwise locked in organic or mineral forms (Chaparro et al., 2012). By engaging in symbiotic relationships, such as those between mycorrhizal fungi and plant roots, soil microbiomes enhance nutrient uptake, particularly in nutrient-poor soils, significantly improving plant productivity and resilience (Dubey et al., 2019).

The health of soil microbiomes directly correlates with plant health, influencing both growth and resistance to pathogens. Beneficial microbes in the rhizosphere, such as plant-growth-promoting rhizobacteria (PGPR), produce bioactive compounds that suppress soil-borne diseases while simultaneously stimulating root development (Yadav et al., 2021). This dual role of protection and growth enhancement underscores the importance of maintaining a diverse and functional soil microbiome. External factors, such as soil amendments and agricultural practices, can either promote or disrupt microbial communities, emphasizing the need for sustainable land management strategies (Prasad et al., 2021).

Table 2 Key Aspects of Soil Microbiomes and Their Ecosystem Functions

Aspect	Function	Impact	Supporting Evidence
Nutrient Cycling	Decomposition of organic matter and release of nutrients (N, P, K)	Enhanced bioavailability of essential elements for plant growth	Chaparro et al., 2012
Symbiotic Relationships	Formation of partnerships between mycorrhizal fungi and plant roots	Improved nutrient uptake and plant productivity, especially in nutrient-poor soils	Dubey et al., 2019
Plant Health Protection	Production of bioactive compounds by plant-growth-promoting rhizobacteria (PGPR)	Suppression of soil-borne diseases and enhanced root development	Yadav et al., 2021
Environmental Response	Influence of soil amendments and agricultural practices on microbial communities	Impact on sustainable land management and ecosystem stability	Prasad et al., 2021

In light of climate change and increased agricultural intensification, leveraging soil microbiomes offers a sustainable pathway to enhance crop productivity and ecosystem stability. Advancements in microbiome research, including metagenomic techniques, have uncovered the immense functional diversity of soil microorganisms, paving the way for innovative applications in precision agriculture and bioremediation. By understanding and optimizing these microbial communities, it is possible to develop strategies that ensure long-term soil fertility and resilience against environmental stresses (Dubey et al., 2019; Chaparro et al., 2012). Air microbiomes play an emerging role in pathogen suppression and crop protection, acting as a natural barrier against plant diseases. These microbial communities, composed of bacteria, fungi, and other microorganisms, inhabit the phyllosphere—the aerial surfaces of plants—where they contribute to disease prevention (Ayoola, et al., 2024). Airborne microorganisms, often transported from the soil and surrounding environment, form microbial consortia on leaf surfaces, creating competitive environments that inhibit the colonization and proliferation of plant pathogens (Deng et al., 2021). Additionally, these microbes produce bioactive compounds, such as antibiotics and enzymes, which directly suppress pathogenic organisms, reducing disease incidence in crops.

Figure 4 shows a soil food web diagram illustrating microbiomes' roles in nitrogen fixation, phosphate solubilization, and organic matter decomposition to enhance plant health.

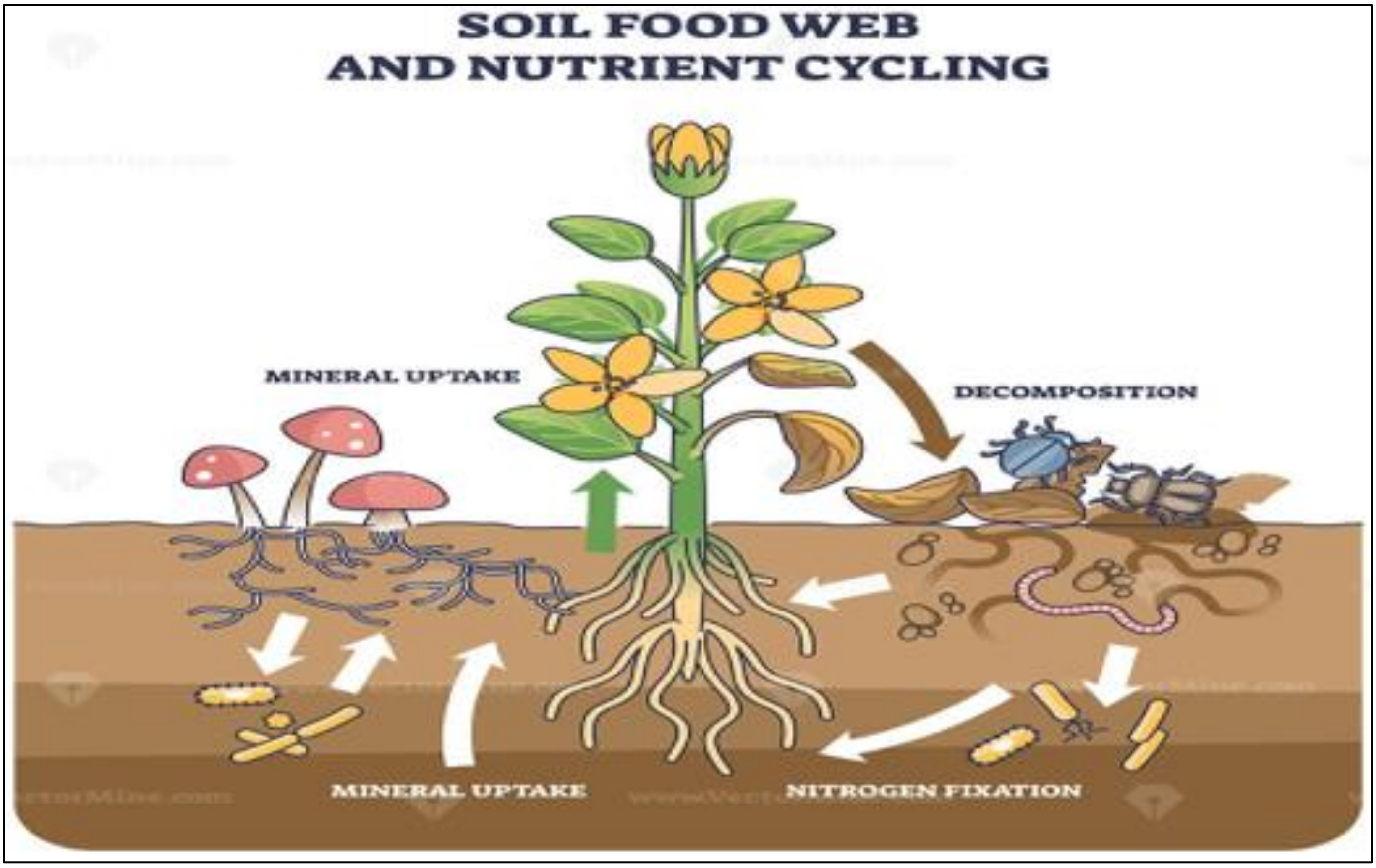

Fig 4 Soil Microbiomes in Plant Growth and Nutrient Cycles [(VectorMine. (n.d.)].

- *Air Microbiomes in Pathogen Suppression and Crop Protection.*

One significant advantage of air microbiomes is their role in priming plant immune responses. Certain airborne microbes act as elicitors of systemic resistance, enhancing a plant's innate defense mechanisms against various pathogens. This interaction has been particularly noted in fungal pathogens, where air microbiomes serve as a biological control measure to mitigate the impact of diseases like powdery mildew and rusts (Chen et al., 2023). The application of microbial inoculants derived from air microbiomes has also been explored as a sustainable alternative to chemical pesticides, offering an eco-friendly approach to crop protection.

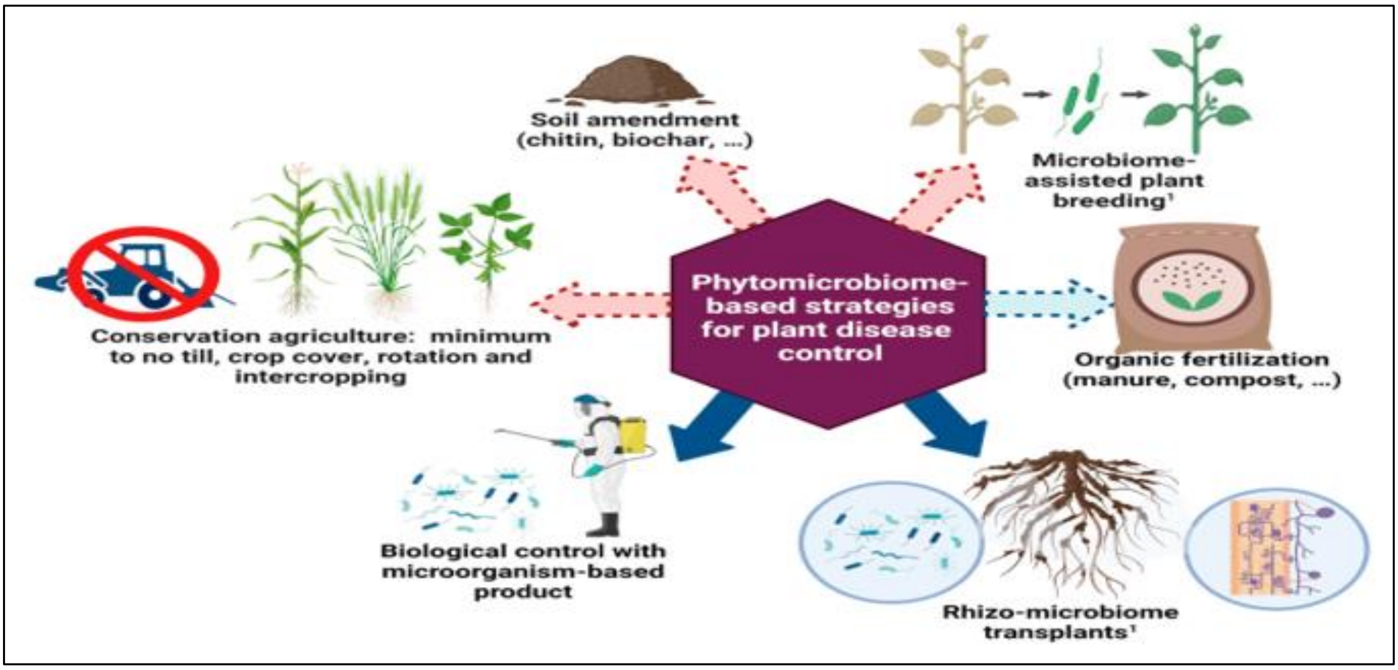

Fig 5 Phytomicrobiome-Based Strategies for Sustainable Plant Disease Management (Chen et al., 2023).

Figure 5 illustrates various ecological approaches to plant disease control, including conservation agriculture, soil amendments, biological control agents, organic fertilization, and microbiome-assisted techniques, forming an integrated disease management system.

Table 3 Air Microbiomes in Agricultural Disease Management and Crop Protection

Project Type	Microbial Intervention	Environmental Impact	Research Evidence
Sahara Forest Project	Enhancement of soil fertility and water retention	Vegetation establishment in arid landscapes	Shiels et al., 2021
Urban Park Rewilding	Implementation of tailored soil microbiomes	Improved biodiversity and soil health	Desai et al., 2024
Coastal Habitat Restoration	Application of microbial inoculants	Enhanced plant resilience and coastline stabilization	Trevathan-Tackett & Sherman, 2019
Urban Planning Integration	Utilization of metagenomic advances	Balance between development and ecosystem conservation	Li et al., 2024

The integration of air microbiomes into agricultural systems not only improves disease management but also enhances crop resilience to environmental stresses. Advances in metagenomics and molecular profiling have revealed the vast functional diversity of airborne microbial communities, enabling researchers to identify and utilize beneficial strains for pathogen suppression and plant health promotion (Zhou et al., 2023). This underscores the importance of preserving and harnessing air microbiomes as a critical component of integrated pest and disease management strategies in sustainable agriculture.

- *Water Microbiomes in Irrigation and Sustainable Aquaculture.*

Water microbiomes play a pivotal role in sustainable agriculture and aquaculture by maintaining water quality and enhancing nutrient cycles. In irrigation systems, microbial communities within the water contribute to nutrient recycling by breaking down organic matter and facilitating the availability of essential nutrients like nitrogen and phosphorus (Chen et al., 2017). This function is particularly important in wastewater-irrigated fields, where microbiomes help mitigate the accumulation of harmful substances while supporting crop productivity. These microbial activities improve water efficiency and reduce the dependency on chemical fertilizers, promoting eco-friendly agricultural practices.

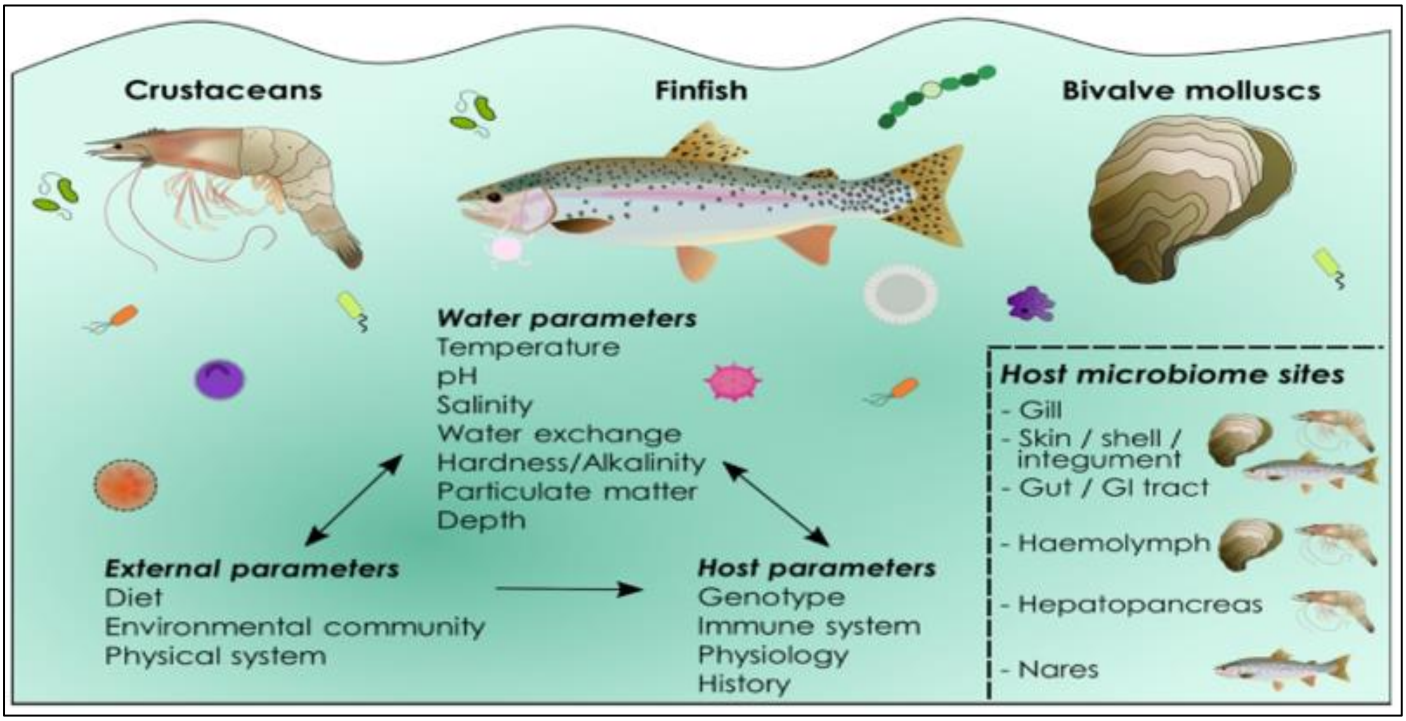

Fig 6 Host-Environment-Microbiome Interactions in Aquatic Species (Lorgen-Ritchie et al., 2023).

Figure 6 illustrates the complex relationships between aquatic organisms (crustaceans, finfish, and bivalves), their microbiome locations, and environmental factors, showing how water parameters and external conditions influence host physiology and microbiome development.

In sustainable aquaculture, water microbiomes are integral to ecosystem stability and fish health. By modulating water quality, these communities reduce the build-up of waste products such as ammonia and nitrites, which can be toxic to aquatic organisms (Idowu, O. S., et al., 2025). Additionally, certain bacterial species provide biocontrol against fish pathogens, reducing the prevalence of diseases and improving overall aquaculture yield (Ruiz et al., 2023). Advanced systems like aquaponics integrate the benefits of water microbiomes by combining fish farming and hydroponics, wherein microbial processes maintain the nutrient balance and water quality across both systems, fostering a closed-loop system of sustainability (Kasozi et al., 2021).

Table 4 Water Microbiomes in Agricultural and Aquaculture Systems

Intervention Type	Target Crops	Environmental Challenge	Outcomes & Benefits
Plant Growth-Promoting Rhizobacteria	Maize, wheat	Drought conditions	Improved water efficiency, enhanced root development
Salinity-Tolerant Consortia	Various crops	Saline soils	Modulated ionic balance, reduced stress damage
Integrated Microbial Inoculants	Rice, soybean	Nutrient deficiency, pests	Enhanced nutrient uptake, reduced chemical fertilizer use
Biofertilizer Combinations	Multiple crops	Soil health degradation	Improved nitrogen fixation, sustainable soil systems

Efforts to leverage water microbiomes extend to addressing environmental and health challenges associated with aquaculture wastewater. For instance, microbiomes in aquaculture wastewater can improve soil fertility when used for irrigation, benefiting integrated agricultural systems (Zhang et al., 2023). Understanding and managing the complex dynamics of water microbiomes through innovative technologies can unlock significant potential for enhancing productivity and sustainability in agriculture and aquaculture.

- *Case Studies: Microbial Interventions Improving Crop Yield and Resilience.*

Microbial interventions have shown remarkable potential in enhancing crop yield and resilience under challenging environmental conditions. For instance, the application of plant growth-promoting rhizobacteria (PGPR) in drought-prone regions has significantly improved water use efficiency and yield in crops like maize and wheat (Mikiciuk et al., 2024). These microbes facilitate better root development and soil aggregation, thereby increasing the plant's ability to access and retain water. Furthermore, microbial consortia engineered for salinity tolerance have demonstrated the capability to support crop productivity in saline soils by modulating ionic balance and reducing stress-related damage (Olmo et al., 2022). In another case, integrated microbial inoculants designed to enhance nutrient uptake and pest resistance have proven effective in increasing the productivity of rice and soybean fields. For example, biofertilizers combining nitrogen-fixing bacteria and mycorrhizal fungi have been successfully used to enhance nitrogen and phosphorus availability, reducing the reliance on chemical fertilizers while boosting yield (Roberts & Mattoo, 2018). Such interventions also improve soil health, fostering a self-sustaining agricultural system resilient to biotic and abiotic stressors.

Table 5 Microbial Interventions in Agricultural Enhancement and Sustainability

Function	Impact	Application	Research Support
Urban Stress Mitigation	Degradation of pollutants and improved soil quality in green spaces	Enhanced resilience of urban forests and parks	Gill et al., 2020
Climate Change Response	Carbon stabilization and reduced methane emissions	Effective climate change mitigation in urban areas	Mills et al., 2020
Ecosystem Support	Growth promotion of native vegetation and enhanced biodiversity	Improved ecological integrity of green spaces	Robinson et al., 2021
Urban Planning Integration	Identification of key microbial species for soil health	Development of multifunctional urban landscapes	Robinson et al., 2021

These examples underscore the transformative potential of microbial technologies in sustainable agriculture. By leveraging microbiome research, farmers and scientists are addressing global challenges such as food security, climate change, and resource depletion. The integration of tailored microbial interventions into crop management practices highlights the need for continued exploration of microbial diversity and its applications, particularly in light of advancing genomic and biotechnological tools (Singh et al., 2025).

III. ROLE IN URBAN ECOSYSTEM REVITALIZATION

- *Air Microbiomes in Pollution Mitigation and Urban Air Quality.*

Air microbiomes are emerging as critical contributors to urban air quality and pollution mitigation. Comprising diverse microbial communities, these microbiomes influence the atmospheric environment through bioremediation processes, wherein microorganisms metabolize or degrade pollutants such as particulate matter (PM), volatile organic compounds (VOCs), and nitrogen oxides (NOx) (Canedoli et al., 2024). Urban trees and green infrastructure support these microbial communities, creating microenvironments that enhance pollutant capture and degradation. For instance, tree phyllosphere microbiomes have been shown to actively participate in the breakdown of harmful organic compounds, underscoring their role in improving urban air quality.

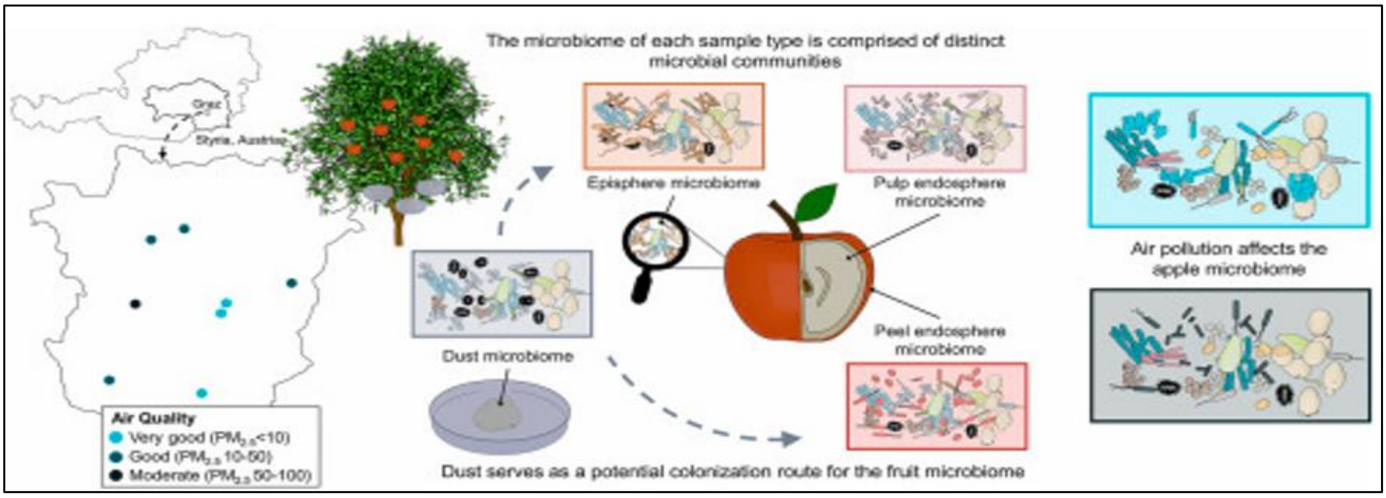

Fig 7 Microbial Communities in Apple Fruit and Environmental Interactions [A Case Study from Styria, Austria] (Schweitzer et al., 2024).

Figure 7 illustrates distinct microbial communities across different apple regions (episphere, pulp, peel) and shows how dust microbiomes and air quality (PM2.5 levels) potentially influence fruit colonization patterns.

The functional diversity of air microbiomes also impacts the dynamics of atmospheric chemistry. Research has highlighted how specific microbial taxa can reduce the bioavailability of hazardous airborne substances, mitigating their health impacts on urban populations (Fouladi et al., 2020). Furthermore, air microbiomes interact with particulate matter, altering its composition and reducing the toxicity of aerosols, a process particularly relevant in densely populated cities with high levels of industrial emissions (Xu et al., 2020). These interactions exemplify the ecological services provided by air microbiomes in reducing environmental and public health risks.

To harness the potential of air microbiomes for urban air quality improvement, interdisciplinary research is essential to map microbial diversity and understand their metabolic capabilities. Advances in metagenomics and environmental monitoring technologies are enabling the identification of microbial species that thrive in polluted environments and their specific roles in pollution mitigation. Integrating these findings into urban planning and green infrastructure development can significantly contribute to sustainable urbanization (Franchitti et al., 2022).

- *Soil microbiomes in Green Infrastructure (e.g., Urban Forests and Parks).*

Soil microbiomes are integral to the sustainability and functionality of green infrastructure in urban environments, including forests and parks. These microbial communities contribute significantly to nutrient cycling, soil structure, and the mitigation of urban stressors such as pollution. Research shows that urban soil microbiomes enhance the resilience of green spaces by maintaining essential ecological processes, including the degradation of pollutants and organic matter, thereby improving soil quality and supporting plant health (Gill et al., 2020). Their role is particularly crucial in urban forests, where soil microbes help counteract the adverse effects of soil compaction and limited water availability caused by human activity.

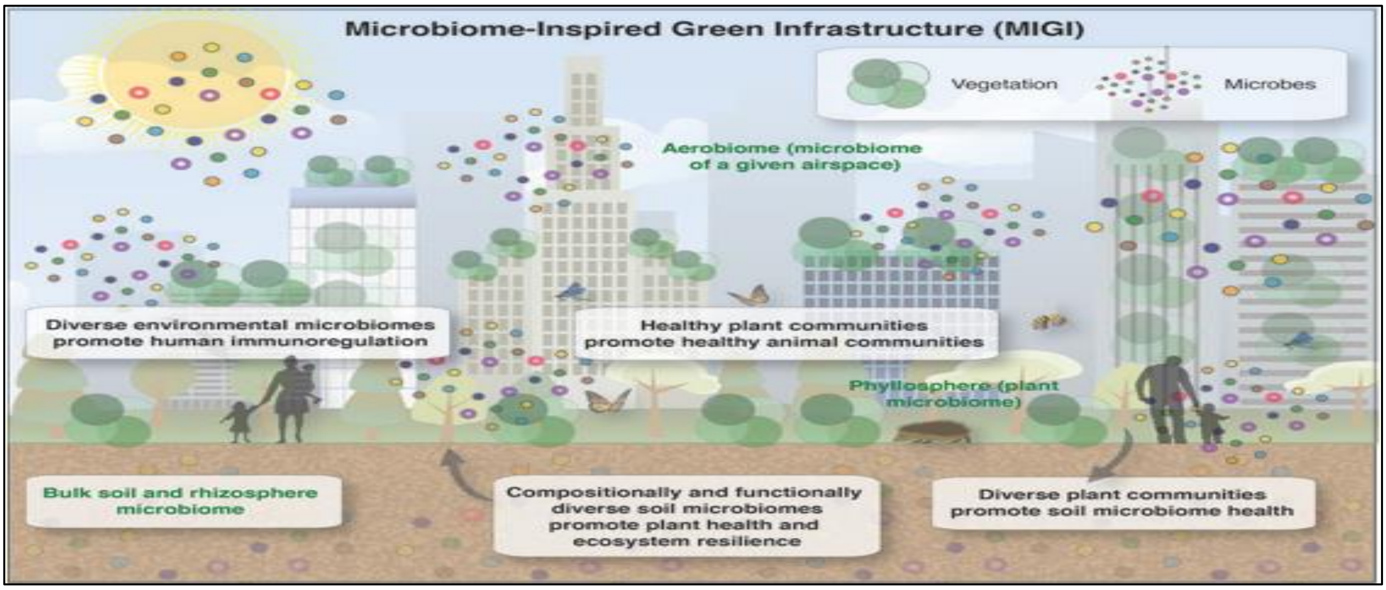

Fig 8 Integration of Environmental Microbiomes in Urban Ecosystems (Robinson et al., 2021).

Figure 8 illustration demonstrates how diverse microbiomes in air, plants, and soil interact within urban green infrastructure, promoting ecosystem health, human immunoregulation, and environmental resilience through interconnected biological communities.

The diversity and functionality of soil microbiomes in urban green spaces also influence carbon sequestration and greenhouse gas emissions. Studies have revealed that specific microbial taxa in park soils contribute to the stabilization of organic carbon and the reduction of methane emissions, offering an effective strategy for climate change mitigation (Mills et al., 2020). Furthermore, the soil microbial communities in urban parks support the growth of native vegetation, fostering biodiversity and enhancing ecosystem services. This interaction underscores the potential of microbiome management to improve the ecological integrity of urban green infrastructure.

Table 6 Soil Microbiomes in Urban Green Infrastructure

Application Area	Microbial Function	Benefits	Research Support
Irrigation Systems	Breakdown of organic matter and nutrient recycling	Enhanced nutrient availability and reduced chemical fertilizer dependency	Chen et al., 2017
Sustainable Aquaculture	Water quality modulation and pathogen control	Reduced toxin accumulation and improved fish health	Ruiz et al., 2023
Aquaponics	Maintenance of nutrient balance in integrated systems	Creation of closed-loop sustainable systems	Kasozi et al., 2021
Wastewater Management	Nutrient processing in aquaculture wastewater	Improved soil fertility when used for irrigation	Zhang et al., 2023

Implementing microbiome-informed strategies in urban planning and restoration projects can amplify the benefits provided by green spaces. Advances in metagenomics have facilitated the identification of key microbial species that thrive in urban environments, providing opportunities to enhance soil health through targeted interventions. By integrating microbiome research into the design and maintenance of green infrastructure, cities can create multifunctional landscapes that address environmental, social, and economic challenges effectively (Robinson et al., 2021).

- *Water Microbiomes in Waste Treatment and Water Recycling.*

Water microbiomes play a crucial role in waste treatment and water recycling by breaking down organic pollutants and facilitating nutrient cycling, thereby enhancing the efficiency of these processes. In wastewater treatment plants, microbial communities drive key biological processes such as nitrification, denitrification, and phosphorus removal, which are essential for reducing nutrient loads in effluent water (Wu et al., 2019). The diversity of these microbiomes enables the degradation of a wide range of contaminants, including complex organic compounds and emerging pollutants, making them indispensable in modern waste management systems (Idoko, et al., 2024).

Table 7 Water Microbiomes in Waste Treatment and Water Recycling Systems

Process Type	Microbial Functions	Treatment Applications	Environmental Benefits
Wastewater Treatment	Nitrification, denitrification, phosphorus removal	Reduction of nutrient loads, pollutant degradation	Improved effluent water quality
Water Recycling	Biofilm formation, pathogen removal	Membrane bioreactors, chemical contaminant removal	Enhanced water safety and quality
Biofouling Prevention	Microbial community regulation	System maintenance, operational efficiency	Sustainable water management
Advanced Treatment	Metabolic pathway utilization	Targeted microbial interventions	Water scarcity mitigation

In water recycling, microbiomes contribute significantly to maintaining water quality and safety. Advanced filtration systems, such as membrane bioreactors, rely on biofilms formed by microbial communities to remove pathogens and chemical contaminants from wastewater (Zhu et al., 2022). Furthermore, studies have shown that the microbial dynamics in recycled water systems are critical for preventing biofouling and ensuring long-term operational efficiency (Enyejo, et al., 2024). This highlights the need for understanding and managing microbial compositions to enhance the sustainability and reliability of water recycling systems (Liu et al., 2019). The application of molecular tools and metagenomics has expanded our knowledge of microbial communities in wastewater and recycled water systems, enabling the identification of key microbial taxa and their metabolic pathways (Idoko, et al., 2024). By leveraging these insights, it is possible to design targeted microbial interventions to optimize treatment processes and support water reuse initiatives, addressing global challenges such as water scarcity and pollution (Gupta et al., 2012). Integrating microbiome research into water management practices holds significant promise for improving environmental and public health outcomes.

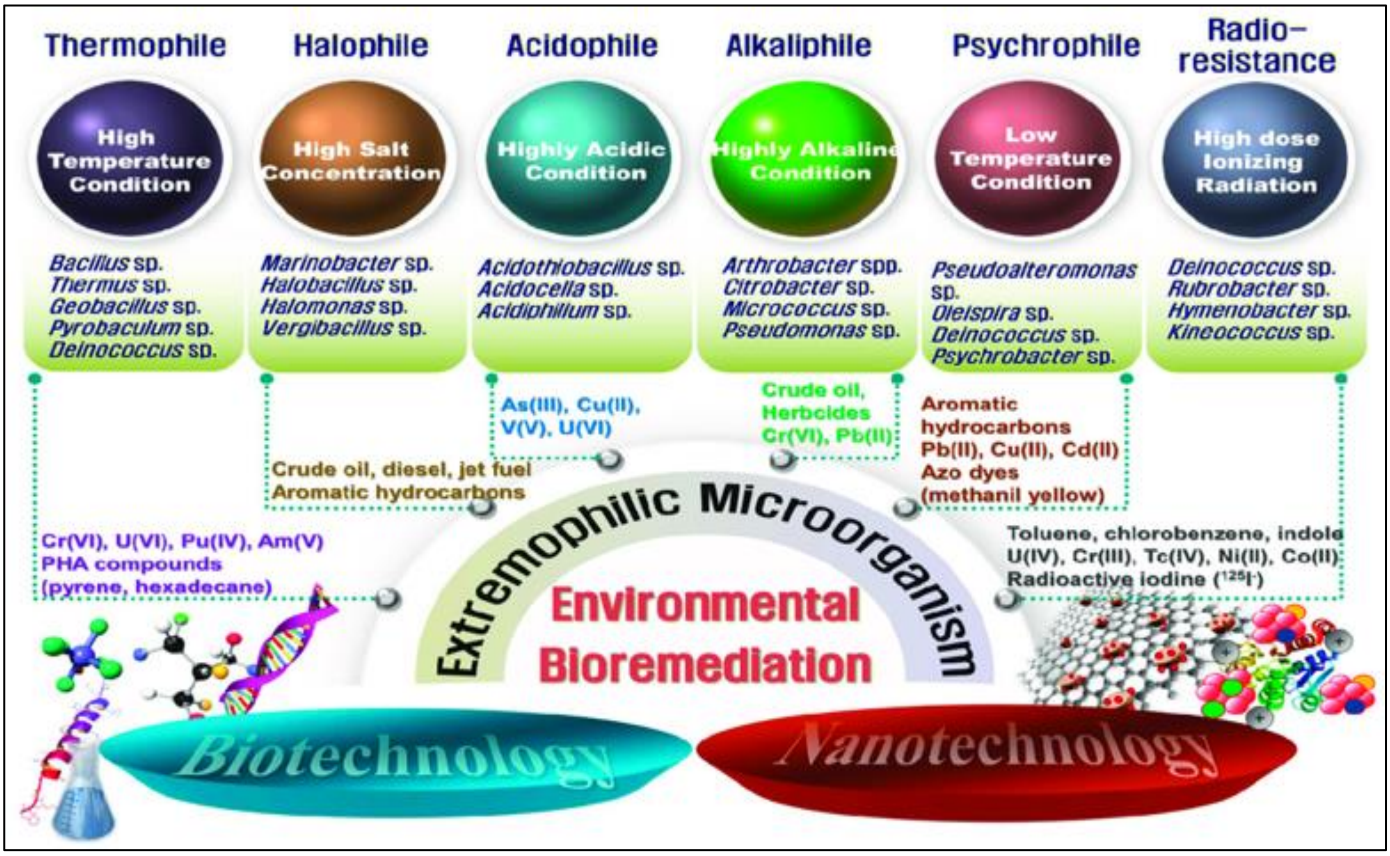

Fig 9 Extremophilic Microorganisms in Environmental Bioremediation (Jeong et al., 2020).

Figure 9 shows different types of extremophilic microorganisms and their applications in environmental bioremediation, showing their specific roles in degrading various pollutants alongside biotechnological and nanotechnological approaches.

- *Examples of Microbiome-Driven Urban Ecosystem Restoration Projects.*

Microbiome-driven urban ecosystem restoration projects have demonstrated the transformative potential of microbial interventions in reviving degraded environments. For example, the Sahara Forest Project integrates microbial processes to enhance soil fertility and water retention in arid regions, supporting the establishment of vegetation in previously barren landscapes. This initiative exemplifies how microbiomes can drive nutrient cycling and water efficiency, making ecosystems more resilient to extreme climates (Shiels et al., 2021). Similarly, urban rewilding projects, such as those implemented in metropolitan parks, have used tailored soil microbiomes to restore biodiversity and improve soil health, promoting sustainable green infrastructure (Desai et al., 2024). Another notable case is the use of plant-associated microbiomes for coastal habitat restoration. In mangrove and salt marsh ecosystems, microbial inoculants have been applied to enhance plant growth and resilience against salinity stress (Enyejo, et al., 2024). These efforts not only restore vegetation but also stabilize the coastline and support aquatic biodiversity (Trevathan-Tackett & Sherman, 2019). By targeting specific microbial communities, these projects align restoration goals with ecosystem services, showcasing the scalability of microbiome-based solutions.

Table 8 Microbiome Applications in Urban Ecosystem Restoration

Project Type	Microbial Intervention	Environmental Impact	Research Evidence
Sahara Forest Project	Enhancement of soil fertility and water retention	Vegetation establishment in arid landscapes	Shiels et al., 2021
Urban Park Rewilding	Implementation of tailored soil microbiomes	Improved biodiversity and soil health	Desai et al., 2024
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Urban Planning Integration	Utilization of metagenomic advances	Balance between development and ecosystem conservation	Li et al., 2024

Such examples underscore the importance of integrating microbiome research into urban and environmental planning. By leveraging microbial diversity, cities can achieve ecological restoration goals while addressing urban challenges like pollution and habitat loss. With advances in metagenomics and microbial ecology, future projects are likely to harness microbiomes even more effectively, fostering a balance between urban development and ecosystem conservation (Li et al., 2024).

IV. MICROBIOMES IN CLIMATE ADAPTATION AND PUBLIC HEALTH

➢ *Contributions of Microbiomes to Carbon Cycling and Greenhouse Gas Reduction.*

Microbiomes are fundamental to the global carbon cycle, significantly influencing carbon sequestration and greenhouse gas emissions. Soil microbiomes, for example, play a pivotal role in the stabilization and storage of soil organic carbon (SOC). Through processes such as decomposition and carbon assimilation, microbial communities contribute to long-term carbon storage while simultaneously regulating the release of carbon dioxide (CO_2) and methane (CH_4) (Sadler et al., 2020). Additionally, symbiotic relationships between soil microbes and plants, such as those formed with mycorrhizal fungi, enhance the capture and storage of atmospheric carbon, mitigating the effects of climate change (Jok, et al., 2024).

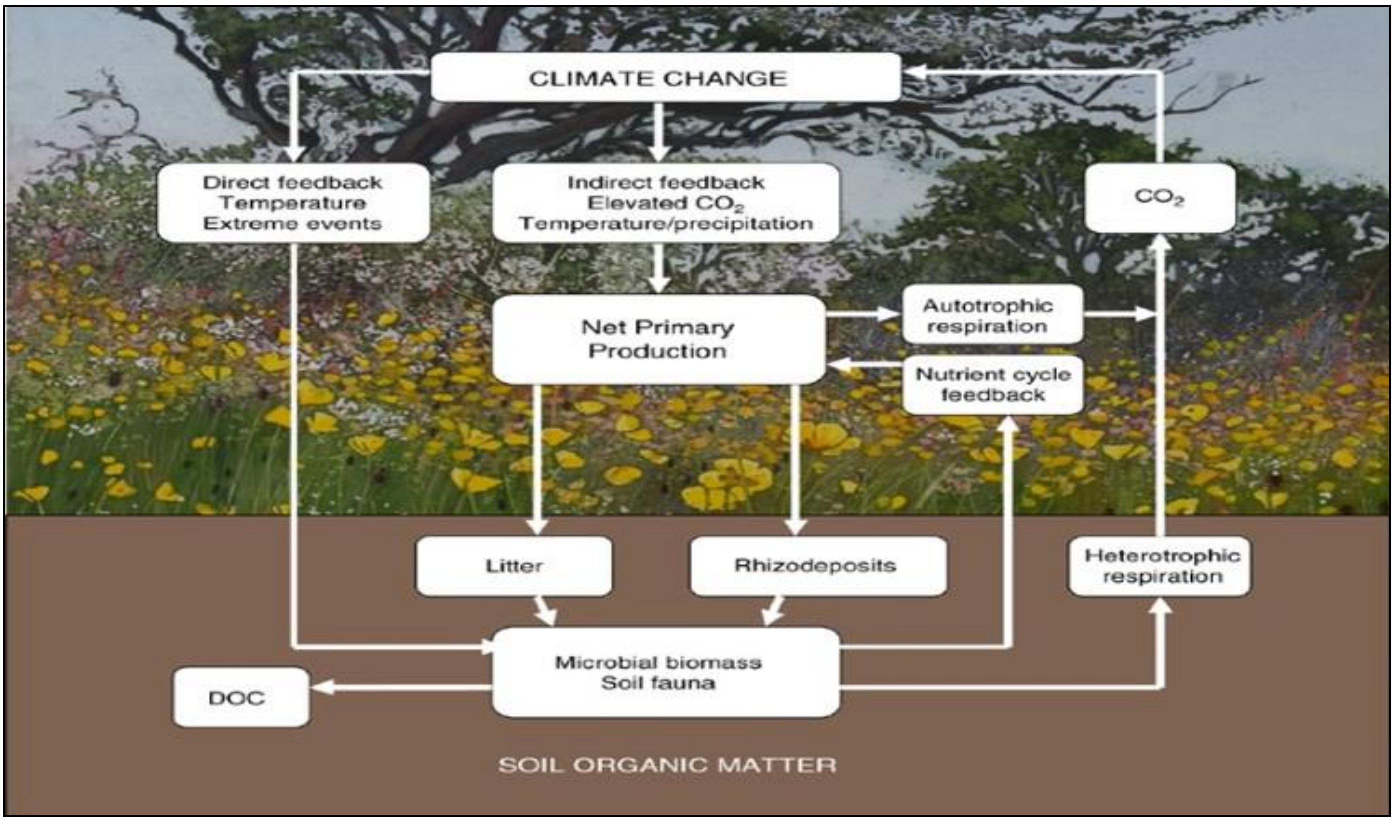

Fig 10 Climate Change Effects on Soil Organic Matter Dynamics and Carbon Cycling (Bardgett et al., 2008).

Figure 10 shows how climate change impacts soil organic matter through direct and indirect feedback mechanisms, illustrating the interactions between primary production, microbial processes, and carbon cycling in ecosystems.

Beyond carbon sequestration, microbiomes are integral to the reduction of greenhouse gas emissions. Certain microbial taxa are involved in the oxidation of methane and the reduction of nitrous oxide (N_2O), two potent greenhouse gases. In wetland ecosystems, for instance, methanotrophic bacteria consume methane before it escapes into the atmosphere, significantly lowering overall emissions (Zhu et al., 2022). Similarly, nitrogen-fixing bacteria can regulate nitrogen availability in soils, reducing the production of nitrous oxide through denitrification processes (Arora & Chaudhry, 2021). These microbial activities underscore the potential of harnessing microbiomes for greenhouse gas mitigation strategies.

Advances in metagenomic technologies have provided deeper insights into the functional diversity of microbiomes and their contributions to carbon cycling (Akindote, et al., 2024). By identifying key microbial communities and their metabolic pathways, researchers are exploring ways to enhance microbial activity for carbon capture and emission reduction. The integration of microbiome-focused strategies into climate action plans holds great promise for addressing global carbon imbalances and fostering environmental sustainability (Martin-Pozas et al., 2022)

➢ *Role in Bioremediation of Climate-Induced Pollutants.*

Microbiomes play a crucial role in the bioremediation of climate-induced pollutants, offering sustainable solutions to environmental challenges. Microbial communities in soil and water degrade or transform pollutants, such as hydrocarbons, heavy metals, and persistent organic compounds, reducing their toxicity and environmental impact (Kumari et al., 2023). In response to climate change-induced pollution, microbiomes have shown adaptive capabilities, enabling effective bioremediation even under extreme conditions. For example, microbes in contaminated wetlands have demonstrated resilience in degrading oil spills and heavy metals, restoring ecosystem health (Hora et al., 2022).

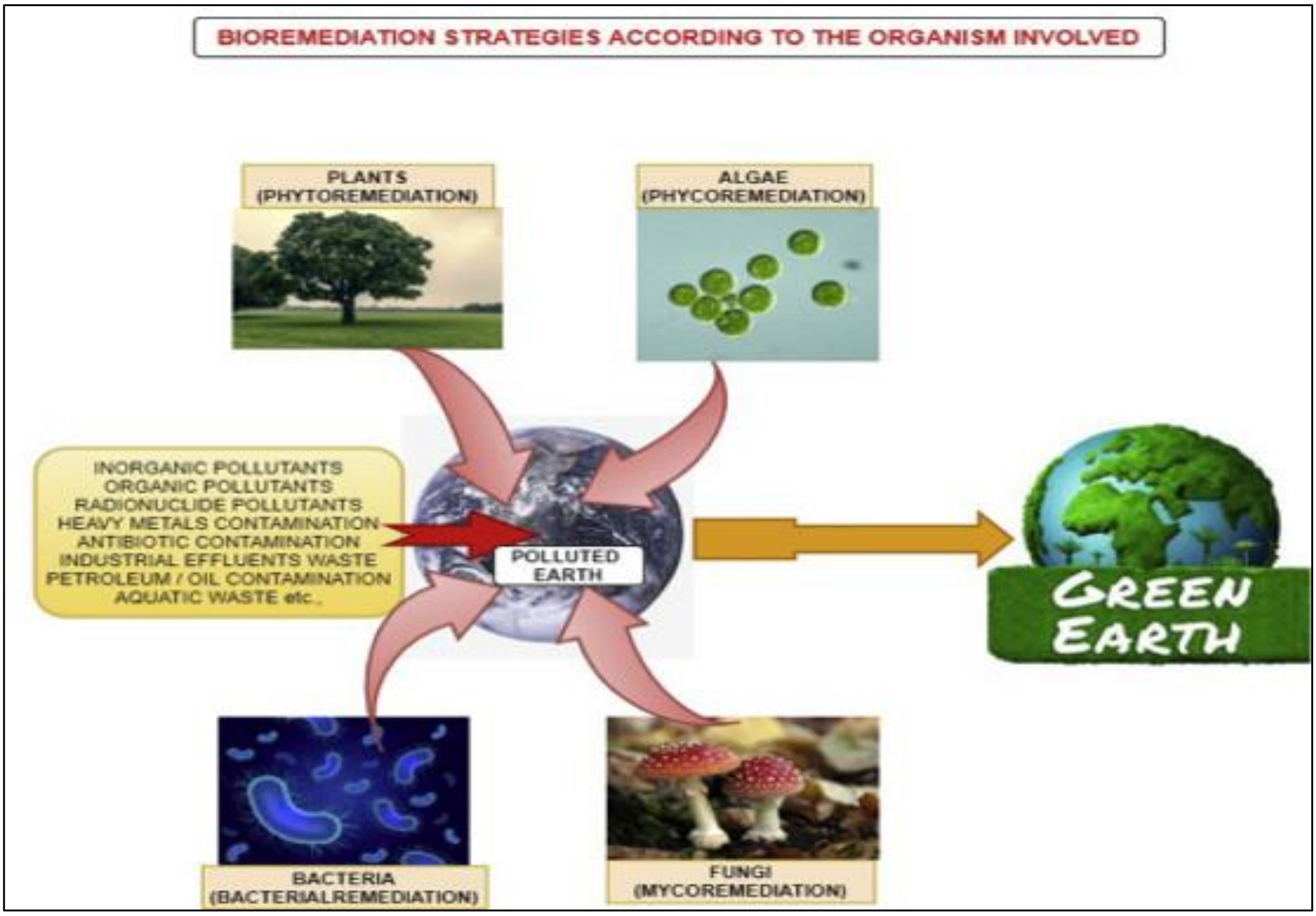

Fig 11 Diverse Organisms in Environmental Cleanup (Chatterji, T., & Kumar, S., 2022).

Figure 11 shows four major bioremediation approaches - phytoremediation (plants), phycoremediation (algae), bacterial remediation, and mycoremediation (fungi) - working together to transform polluted environments into a sustainable "Green Earth."

The rhizosphere microbiome, the microbial community associated with plant roots, is particularly effective in bioremediation. These microbes produce enzymes that facilitate the breakdown of organic pollutants and enhance plant uptake of heavy metals, effectively removing contaminants from the soil (Gomes, 2024). In aquatic ecosystems, microbial consortia are employed in phytoremediation strategies to clean up industrial effluents and pesticide residues, showcasing their potential in mitigating pollution in water bodies (Ibokette, et al., 2024). These approaches not only detoxify pollutants but also enhance the resilience of ecosystems against further environmental stressors (Toor et al., 2024).

Table 9 Microbiomes in Environmental Bioremediation and Pollution Management

Environment Type	Microbial Function	Health Impact	Research Support
Aquatic Systems	Pathogen suppression through competitive exclusion and antimicrobial production	Prevention of waterborne diseases and improved water quality	Dufossé & Tiwari, 2024
Soil Ecosystems	Production of natural antibiotics and enhancement of plant resistance	Reduced need for chemical pesticides and improved agricultural health	Carrillo-Tripp & de Los Santos-Villalobos, 2024
Wildlife Habitats	Regulation of pathogen reservoirs and zoonotic disease control	Management of disease transmission between wildlife and livestock	Dzvene & Chiduza, 2024
Degraded Ecosystems	Restoration of microbial diversity through bioaugmentation	Enhanced ecosystem resilience against pathogen invasions	Lievens et al., 2024

Technological advancements, such as metagenomics and biotechnological tools, have expanded our understanding of microbial diversity and functionality, enabling the development of targeted bioremediation strategies (Onuh, J. E., et al., 2024). By harnessing the potential of microbiomes, researchers aim to address complex pollution challenges and adapt to changing climatic conditions. Integrating microbiome research into environmental management frameworks is vital for promoting sustainability and mitigating the impacts of climate-induced pollutants on ecosystems and human health (Mishra et al., 2022).

➢ *Air Microbiomes and Respiratory Health.*

Microbiomes play a crucial role in mitigating climate-induced pollution through bioremediation, a process that leverages microbial communities to degrade and detoxify environmental contaminants. Climate change exacerbates pollution levels by increasing the frequency of extreme weather events, which in turn mobilize pollutants, including heavy metals and organic contaminants, into air, water, and soil systems. Soil microbiomes, for example, have been identified as key agents in bioremediation due to their ability to degrade hydrocarbons, immobilize heavy metals, and neutralize xenobiotic compounds (Kumari et al., 2023). However, climate change-induced alterations in temperature, moisture, and pH can significantly impact microbial community composition and function, thereby influencing bioremediation efficacy (Alkorta et al., 2017).

Airborne microbiomes also contribute to pollutant degradation, particularly in urban environments where particulate matter and volatile organic compounds (VOCs) pose significant health risks. Some bacterial and fungal species have demonstrated the ability to degrade airborne pollutants, reducing their toxicity and persistence in the atmosphere. However, rising global temperatures and changing humidity patterns may disrupt microbial dynamics, potentially reducing their efficiency in air pollution mitigation (Gomes, 2024). Similarly, aquatic microbiomes facilitate the breakdown of industrial pollutants and agricultural runoff, playing a critical role in wastewater treatment and natural water purification. Yet, climate-induced shifts in precipitation patterns and rising water temperatures may alter microbial diversity and metabolic activity, affecting pollutant removal rates (Sarkar & Gupta, 2024).

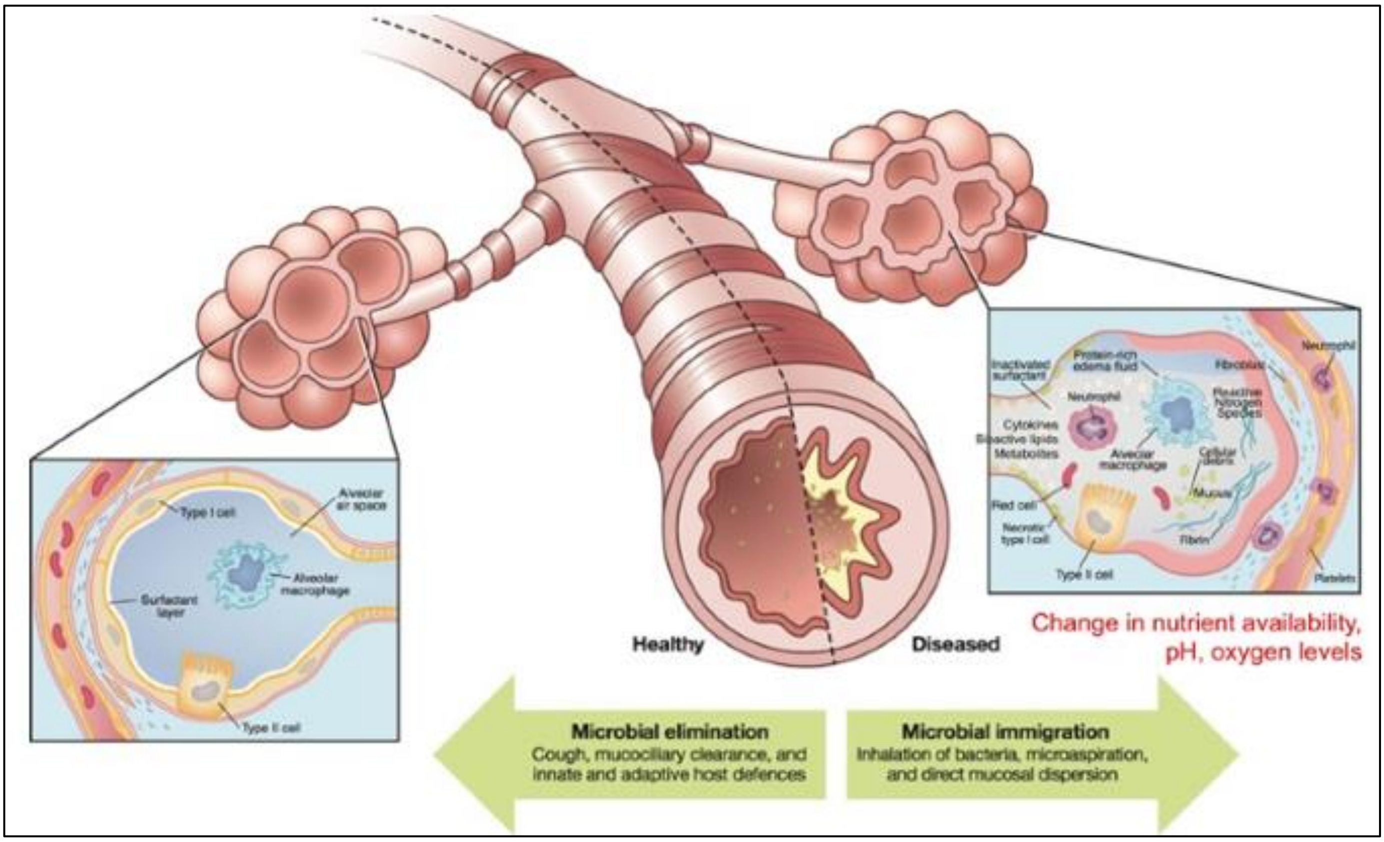

Fig 12 Respiratory Microbiome Dynamics (Huffnagle et al., 2016).

Figure 12 illustrates the dynamics between healthy and diseased airways, showing microbial elimination through host defenses and microbial immigration processes, alongside changes in local environmental conditions.

Despite these challenges, advancements in microbiome engineering and synthetic biology offer promising solutions to enhance microbial resilience and bioremediation capacity in the face of climate change. Genetic modifications and microbial consortia optimization are emerging as viable strategies to sustain pollutant degradation under variable environmental conditions. Future research must focus on integrating microbiome-based approaches with policy frameworks to establish scalable, climate-resilient bioremediation strategies. Understanding the interplay between climate change and microbiome functionality is essential for leveraging microbial communities as sustainable agents in pollution control and environmental restoration.

➢ *Water and Soil Microbiomes in Disease Prevention and Management.*

Water and soil microbiomes play a fundamental role in disease prevention and management by influencing pathogen suppression, enhancing immune responses, and contributing to overall ecosystem health. In aquatic environments, microbial communities regulate water quality and inhibit the proliferation of waterborne pathogens through competitive exclusion and antimicrobial compound production. Beneficial bacteria, such as those belonging to the Bacillus and Pseudomonas genera, have been shown to outcompete pathogenic microbes and mitigate their impact on human and environmental health (Dufossé & Tiwari, 2024). However, anthropogenic activities, including agricultural runoff and industrial pollution, can disrupt microbial diversity, potentially leading to the emergence of antibiotic-resistant bacteria in water systems (Lievens et al., 2024).

Soil microbiomes also play a critical role in disease suppression through the promotion of plant and human health (Ijiga, A. C., et al.,2024). Beneficial soil microbes, including mycorrhizal fungi and nitrogen-fixing bacteria, improve plant resistance to soilborne diseases while simultaneously contributing to human health by maintaining nutrient-rich agricultural systems. Certain soil bacteria, such as *Streptomyces* species, produce antibiotics that naturally suppress harmful pathogens in the soil, thereby reducing the need for chemical pesticides (Carrillo-Tripp & de Los Santos-Villalobos, 2024). Additionally, soil microbiomes influence the prevalence of zoonotic diseases by regulating pathogen reservoirs in wildlife and livestock environments. Environmental disturbances such as climate change and deforestation have been linked to shifts in microbial composition, potentially increasing the risk of disease outbreaks and reducing the resilience of natural microbial communities (Dzvene & Chiduza, 2024).

Given their importance, strategies aimed at preserving and restoring healthy microbiomes are essential for sustainable disease prevention and environmental management. Advances in microbiome engineering and bioaugmentation have shown promise in restoring microbial diversity in degraded ecosystems, enhancing the capacity of natural microbiomes to resist pathogen invasions (Ijiga, A. C., et al., 2024). Integrating microbiome-based approaches into public health policies, water sanitation programs, and agricultural practices can significantly improve disease resilience while reducing reliance on chemical interventions. Future research should focus on understanding microbial interactions at a systemic level, enabling the development of targeted interventions that harness microbiome stability for improved human and environmental health.

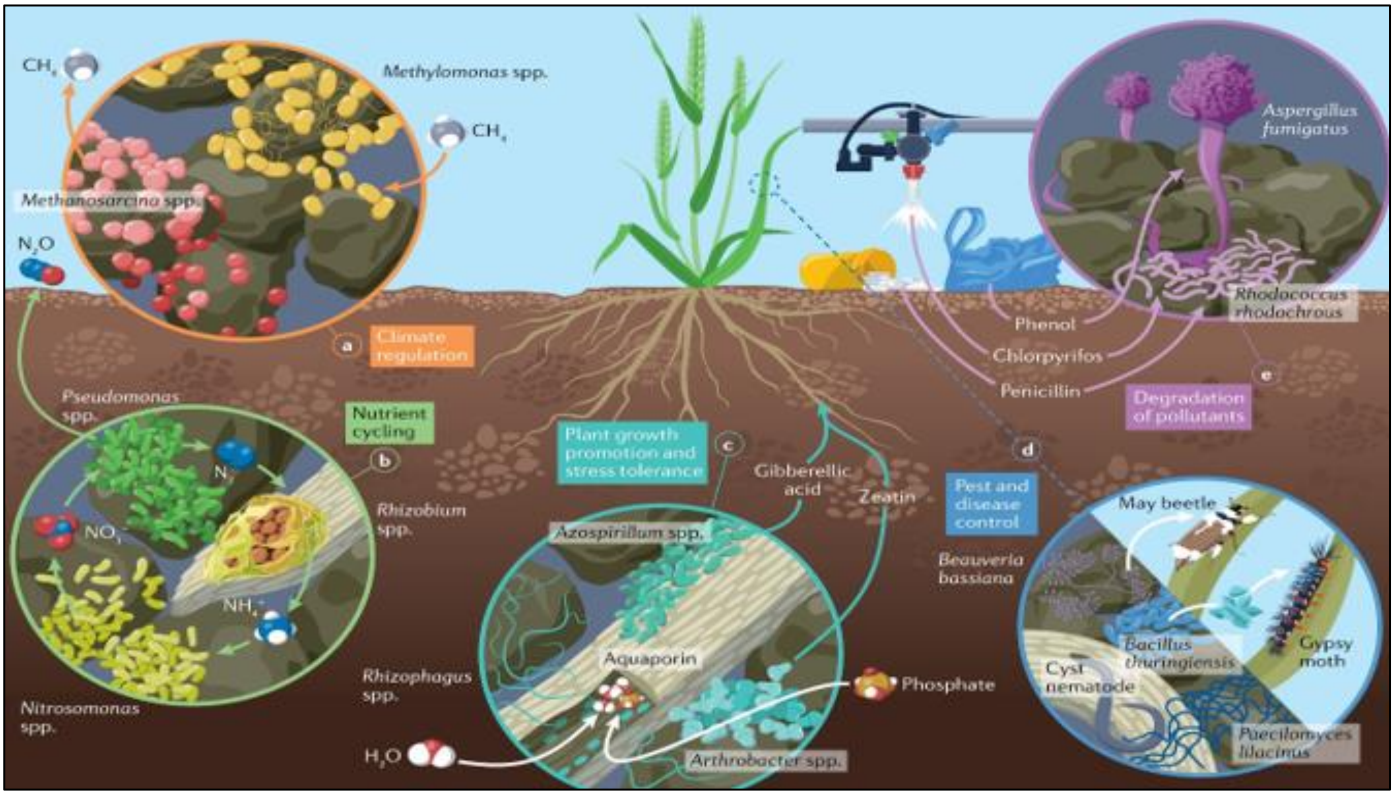

Fig 13 Beneficial Microorganisms in Plant-Microbe Interactions and Environmental Services (Hartmann, 2023).

Figure 13 illustration depicts various microorganisms and their ecological functions, including climate regulation, nutrient cycling, plant growth promotion, pest control, and pollutant degradation in agricultural ecosystems.

Table 10 Microbiomes in Disease Prevention and Environmental Health Management

Environment Type	Microbial Functions	Pollutant Types	Remediation Benefits
Soil Systems	Enzyme production, pollutant degradation	Hydrocarbons, heavy metals, organic compounds	Reduced toxicity, enhanced soil health
Wetland Ecosystems	Adaptive degradation, metal transformation	Oil spills, heavy metals	Ecosystem restoration, pollution reduction
Rhizosphere	Organic pollutant breakdown, metal uptake enhancement	Heavy metals, organic contaminants	Soil decontamination, plant health support
Aquatic Systems	Phytoremediation support, pollutant degradation	Industrial effluents, pesticide residues	Water quality improvement, ecosystem resilience

V. INTEGRATION AND FUTURE PROSPECTS

- *Cross-Sector Applications of Microbiomes for Sustainability.*

Microbiomes have emerged as a crucial component in cross-sector sustainability applications, offering innovative solutions for environmental conservation, public health, and industrial processes. In agriculture, microbiome-based interventions enhance soil fertility, reduce dependence on chemical fertilizers, and promote plant health through natural pathogen suppression. The application of microbial consortia as biofertilizers and biopesticides fosters more sustainable agricultural practices, mitigating soil degradation and improving crop resilience in the face of climate change. Similarly, in water management, microbial communities play a key role in bioremediation, breaking down pollutants, improving water quality, and sustaining aquatic ecosystems. Engineered microbiomes are now being developed to accelerate the removal of industrial contaminants and pharmaceutical residues from wastewater, thereby reducing environmental toxicity.

Beyond agriculture and water treatment, microbiomes are gaining recognition in the healthcare and pharmaceutical sectors, particularly through the One Health framework, which integrates human, animal, and environmental health. Research suggests that environmental microbiomes influence human immune responses and gut microbiota composition, highlighting the interconnectedness between biodiversity loss and rising disease prevalence. Industrial applications are also leveraging microbiomes for sustainable manufacturing and bioengineering, including bio-based plastics production, textile processing, and biofuel development. These innovations reduce reliance on fossil fuels and synthetic chemicals while promoting circular economy principles by utilizing microbial metabolic pathways for waste-to-resource conversion.

Despite these advances, challenges remain in standardizing microbiome-based applications across sectors due to regulatory limitations and the complexity of microbial interactions. Cross-disciplinary collaborations and dedicated funding are essential to bridge scientific knowledge with policy implementation and commercial scalability. Developing microbiome repositories and predictive modeling tools will further optimize microbial applications for sustainability. As research progresses, microbiome-driven solutions will continue to transform industries, driving more resilient, adaptive, and environmentally friendly systems that align with global sustainability goals.

- *Challenges in Research, Deployment, and Ethical Considerations.*

The research and deployment of microbiome-based technologies face several scientific, logistical, and ethical challenges. One of the primary obstacles in microbiome research is the complexity and variability of microbial communities. The intricate interactions within microbiomes, influenced by environmental factors, host genetics, and external disturbances, make it difficult to standardize findings and develop universally effective applications. Additionally, microbiome research requires large-scale, high-resolution sequencing data, which necessitates advanced computational tools and bioinformatics expertise. The cost and accessibility of such technologies further limit widespread adoption, particularly in low-resource settings.

Deployment of microbiome-based solutions presents additional challenges, including regulatory and safety concerns. Given the dynamic nature of microbial ecosystems, the introduction of engineered or modified microbes into environments such as agriculture, healthcare, or bioremediation carries potential risks. Regulatory agencies must assess long-term ecological impacts and unintended consequences before approving microbiome-based interventions. Moreover, the effectiveness of microbiome applications can vary depending on geographic and climatic conditions, making it difficult to create standardized products. There is also a need for robust quality control measures to ensure microbial formulations remain stable, viable, and efficacious in real-world conditions.

Ethical considerations in microbiome research and deployment include concerns about data privacy, informed consent, and bioprospecting. Human microbiome studies, particularly those involving clinical applications, raise questions regarding the ownership and commercialization of microbiome data. The potential for companies to patent microbial strains or microbial-derived therapeutics has sparked debates over equitable access and benefit-sharing, particularly when indigenous or traditional knowledge is involved. Additionally, microbiome interventions could disproportionately benefit certain populations while leaving others behind due to cost barriers and regulatory disparities. Addressing these challenges requires international collaboration, transparent regulatory frameworks, and the inclusion of ethical considerations in microbiome research and development.

- *Future Directions for microbiome-Based Solutions in Agriculture, Urban Revitalization, and Health.*

Future directions for microbiome-based solutions in agriculture, urban revitalization, and health are centered on leveraging advancements in synthetic biology, precision microbiome engineering, and sustainable ecosystem management. In agriculture, microbiome interventions are expected to shift towards more targeted applications that enhance soil fertility, improve drought resistance, and reduce reliance on chemical fertilizers and pesticides. The development of bioengineered microbial consortia and microbiome-informed precision farming techniques will enable tailored interventions that enhance crop resilience while minimizing environmental impact. Additionally, the integration of artificial intelligence and machine learning with microbiome research will provide predictive models for optimizing plant-microbe interactions under varying climatic conditions, further improving agricultural sustainability.

In urban revitalization, the application of microbiome science is gaining momentum as cities explore nature-based solutions to improve air quality, enhance green infrastructure, and restore degraded urban ecosystems. Strategies such as microbiome-enhanced bioremediation of pollutants and the use of microbial communities in urban soil restoration are being explored to support healthier and more resilient urban environments. Moreover, the role of environmental microbiomes in modulating human health in urban spaces, such as through microbiome-enriched urban parks and biodiversity interventions, is becoming increasingly recognized. Future efforts will likely focus on integrating microbiome-informed urban planning with public health policies to design environments that promote microbial diversity beneficial to human well-being.

The intersection of microbiomes and health is another promising frontier, particularly in disease prevention, personalized medicine, and immunotherapy. Advances in microbiome-based therapeutics, such as live biotherapeutic products and microbiome transplants, offer novel treatment options for a range of conditions, including gastrointestinal disorders, metabolic diseases, and even mental health issues. However, the successful deployment of these solutions will require addressing regulatory, ethical, and standardization challenges, particularly concerning microbiome stability and safety across diverse populations. Collaborative research efforts integrating microbiome science with biomedical engineering and public health initiatives will be essential to unlocking the full potential of microbiomes in healthcare. As the field evolves, a multidisciplinary approach that bridges microbiome applications across agriculture, urban sustainability, and medicine will be critical in shaping a more resilient and health-conscious future.

- *Policy Recommendations and Global Collaboration.*

The establishment of robust policy frameworks and international collaboration is essential for advancing microbiome research and its applications across agriculture, environmental sustainability, and public health. Policymakers must prioritize the integration of microbiome science into regulatory frameworks by establishing standardized guidelines for microbiome-based products, including biofertilizers, probiotics, and bioremediation agents. Additionally, data-sharing policies should be reinforced to facilitate open access to microbiome research findings, ensuring that knowledge is equitably distributed across scientific and industrial sectors. Global regulatory harmonization is also critical to prevent inconsistencies in microbiome-related legislation, which may otherwise hinder the commercialization and widespread adoption of microbiome-based solutions.

International collaboration is imperative for fostering innovation and addressing global challenges related to climate change, food security, and disease management. Cross-border research initiatives should be encouraged through multinational funding programs and interdisciplinary consortia that bring together experts from microbiology, environmental science, and public health. Capacity-building programs in microbiome science must be promoted, particularly in low-income countries, to ensure equitable participation in research and technological advancements. Furthermore, ethical considerations related to microbiome applications, such as bioprospecting and indigenous knowledge, should be addressed through frameworks that ensure fair benefit-sharing and adherence to ethical research principles.

Future policy recommendations should emphasize the incorporation of microbiome science into sustainable development agendas, recognizing its potential in mitigating environmental degradation, improving soil and water health, and enhancing disease resilience. Governments and international organizations must work collaboratively to integrate microbiome research into global climate adaptation strategies, ensuring that microbiome-based interventions contribute to biodiversity conservation and ecosystem restoration. Strengthening public-private partnerships will also be crucial in scaling up microbiome-based technologies, driving their transition from laboratory research to practical applications that support environmental and human well-being. A unified, globally coordinated approach to microbiome policy and collaboration will be essential in realizing the full potential of microbiome science in addressing some of the most pressing global challenges.

VI. CONCLUSION

Microbiomes play a transformative role in addressing complex global challenges, offering sustainable solutions in agriculture, environmental conservation, and human health. The research presented throughout this review highlights the multifaceted applications of microbiomes, from enhancing soil fertility and crop resilience to mitigating climate-induced pollutants and improving urban air and water quality. Advances in microbiome-based interventions are driving progress in bioremediation, disease prevention, and resource management, demonstrating their vast potential to promote ecological balance and sustainability. However, the dynamic nature of microbiomes and their interactions with external factors necessitate continued research to optimize their deployment and ensure long-term efficacy.

The growing recognition of microbiomes in public health and medicine underscores their potential in disease management, gut health, and precision nutrition. Microbiome-targeted therapies, such as probiotics and microbiome transplants, are emerging as viable treatment options for various health conditions, from gastrointestinal disorders to metabolic diseases. Furthermore, microbiomes are central to sustainable food systems, where functional microbial communities contribute to food safety, nutrient cycling, and bioprocessing innovations. As microbial research advances, integrating microbiome science into healthcare, agriculture, and environmental policies will be critical in ensuring equitable access to these innovations while addressing ethical and regulatory challenges.

To harness the full potential of microbiomes in global sustainability efforts, interdisciplinary collaboration and policy support must be prioritized. Strengthening international partnerships, standardizing microbiome research methodologies, and fostering public-private cooperation will be instrumental in scaling up microbiome-based technologies. Future research should focus on leveraging microbiome data for predictive modeling, optimizing microbial consortia for targeted applications, and ensuring the responsible use of microbiome interventions. By embracing microbiome science as a cornerstone of sustainable development, we can unlock new opportunities for ecological restoration, food security, and public health improvements on a global scale.

REFERENCES

[1]. Abd El-Galil, A. A., El-Dein, A. N., Awad, H. M., & Helmy, W. A. (2021). Chemical composition and biological activities of aqueous extracts and their sulfated derivatives of pea peel (Pisum sativum L.). Biocatalysis and Agricultural Biotechnology, 35, 102077.

[2]. Afridi, M. S., Javed, M. A., Ali, S., De Medeiros, F. H. V., Ali, B., Salam, A., ... & Santoyo, G. (2022). New opportunities in plant microbiome engineering for increasing agricultural sustainability under stressful conditions. Frontiers in Plant Science, 13, 899464.

[3]. Akindote, O., Enyejo, J. O., Awotiwon, B. O. & Ajayi, A. A. (2024). Integrating Blockchain and Homomorphic Encryption to Enhance Security and Privacy in Project Management and Combat Counterfeit Goods in Global Supply Chain Operations. *International Journal of Innovative Science and Research Technology* Volume 9, Issue 11, NOV. 2024, ISSN No:-2456-2165. https://doi.org/10.38124/ijisrt/IJISRT24NOV149.

[4]. Alkorta, I., Epelde, L., & Garbisu, C. (2017). Environmental parameters altered by climate change affect the activity of soil microorganisms involved in bioremediation. FEMS microbiology letters, 364(19), fnx200.

[5]. Arora, P., & Chaudhry, S. (2021). Microbial mediated soil carbon sequestration and mitigation of green house gases. COJ Rev. Res., 3, 000562.

[6]. Ayoola, V. B., Audu, B. A., Boms, J. C., Ifoga, S. M., Mbanugo, O. J., & Ugochukwu, U. N. (2024). Integrating Industrial Hygiene in Hospice and Home Based Palliative Care to Enhance Quality of Life for Respiratory and Immunocompromised Patients. NOV 2024 | *IRE Journals* | Volume 8 Issue 5 | ISSN: 2456-8880.

[7]. Ayoola, V. B., Ugochukwu, U. N., Adeleke, I., Michael, C. I. Adewoye, M. B., & Adeyeye, Y. (2024). Generative AI-Driven Fraud Detection in Health Care Enhancing Data Loss Prevention and Cybersecurity Analytics for Real-Time Protection of Patient Records. *International Journal of Scientific Research and Modern Technology (IJSRMT)*, Volume 3, Issue 11, 2024.https://www.ijsrmt.com/index.php/ijsrmt/article/view/112

[8]. Banerjee, S., Schlaeppi, K., & van der Heijden, M. G. (2018). Keystone taxa as drivers of microbiome structure and functioning. Nature Reviews Microbiology, 16(9), 567-576.

[9]. Bardgett, R. D., Freeman, C., & Ostle, N. J. (2008). Microbial contributions to climate change through carbon cycle feedbacks. The ISME journal, 2(8), 805-814.

[10]. Berg, G., Rybakova, D., Fischer, D., Cernava, T., Vergès, M. C. C., Charles, T., ... & Schloter, M. (2020). Microbiome definition re-visited: old concepts and new challenges. Microbiome, 8, 1-22.

[11]. Carrillo-Tripp, J., de Los Santos-Villalobos, S., Sepúlveda, E., & Martínez-Soto, D. (2024). Study on plant differentiation between beneficial and pathogenic microorganisms. Frontiers in Plant Science, 15, 1481110.

[12]. Chaparro, J. M., Sheflin, A. M., Manter, D. K., & Vivanco, J. M. (2012). Manipulating the soil microbiome to increase soil health and plant fertility. Biology and Fertility of Soils, 48, 489-499.

[13]. Chatterji, T., & Kumar, S. (2022). Biofilm in remediation of pollutants. In S. Kumar & M. Z. Hashmi (Eds.), Biological approaches to controlling pollutants (Chapter 20). Woodhead Publishing.

[14]. Chen, L., Feng, Q., Li, C., Wei, Y., Zhao, Y., Feng, Y., ... & Li, H. (2017). Impacts of aquaculture wastewater irrigation on soil microbial functional diversity and community structure in arid regions. Scientific Reports, 7(1), 11193.

[15]. Chen, W., Modi, D., & Picot, A. (2023). Soil and phytomicrobiome for plant disease suppression and management under climate change: A review. Plants, 12(14), 2736.

[16]. Chen, W., Modi, D., & Picot, A. (2023). Soil and Phytomicrobiome for Plant Disease Suppression and Management under Climate Change: A Review. Plants, 12(14), 2736.

[17]. Deng, X., Zhang, N., Shen, Z., Zhu, C., Liu, H., Xu, Z., ... & Salles, J. F. (2021). Soil microbiome manipulation triggers direct and possible indirect suppression against Ralstonia solanacearum and Fusarium oxysporum. npj Biofilms and Microbiomes, 7(1), 33.

[18]. Desai, S. A., Patel, V. P., Bhosle, K., Nagare, S., Thombare, K., Hashem, A., ... & Parray, J. A. (2024). Microbiome and Ecosystem Approaches. In Progress in Soil Microbiome Research (pp. 37-52). Cham: Springer Nature Switzerland.

[19]. Dini-Andreote, F., Kowalchuk, G. A., Prosser, J. I., & Raaijmakers, J. M. (2021). Towards meaningful scales in ecosystem microbiome research. Environmental microbiology.

[20]. Dubey, A., Malla, M. A., Khan, F., Chowdhary, K., Yadav, S., Kumar, A., ... & Khan, M. L. (2019). Soil microbiome: a key player for conservation of soil health under changing climate. Biodiversity and Conservation, 28, 2405-2429.

[21]. Dufossé, L., & Tiwari, P. (2024). Emerging trends and advances in the socioeconomic applications of beneficial microbes. Frontiers in Microbiology, 15, 1523569.

[22]. Dzvene, A. R., & Chiduza, C. (2024). Application of Biofertilizers for Enhancing Beneficial Microbiomes in Push–Pull Cropping Systems: A Review. Bacteria, 3(4), 271-286.

[23]. Enyejo, J. O., Fajana, O. P., Jok, I. S., Ihejirika, C. J., Awotiwon, B. O., & Olola, T. M. (2024). Digital Twin Technology, Predictive Analytics, and Sustainable Project Management in Global Supply Chains for Risk Mitigation, Optimization, and Carbon Footprint Reduction through Green Initiatives. *International Journal of Innovative Science and Research Technology*, Volume 9, Issue 11, November– 2024. ISSN No:-2456-2165. https://doi.org/10.38124/ijisrt/IJISRT24NOV1344

[24]. Enyejo, L. A., Adewoye, M. B. & Ugochukwu, U. N. (2024). Interpreting Federated Learning (FL) Models on Edge Devices by Enhancing Model Explainability with Computational Geometry and Advanced Database Architectures. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*. Vol. 10 No. 6 (2024): November-December doi : https://doi.org/10.32628/CSEIT24106185

[25]. Fouladi, F., Bailey, M. J., Patterson, W. B., Sioda, M., Blakley, I. C., Fodor, A. A., ... & Alderete, T. L. (2020). Air pollution exposure is associated with the gut microbiome as revealed by shotgun metagenomic sequencing. Environment international, 138, 105604.

[26]. Franchitti, E., Caredda, C., Anedda, E., & Traversi, D. (2022). Urban aerobiome and effects on human health: A systematic review and missing evidence. Atmosphere, 13(7), 1148.

[27]. Gandolfi, I., Canedoli, C., Rosatelli, A., Covino, S., Cappelletti, D., Sebastiani, B., ... & Franzetti, A. (2024). Microbiomes of urban trees: unveiling contributions to atmospheric pollution mitigation. Frontiers in Microbiology, 15, 1470376.

[28]. Gill, A. S., Purnell, K., Palmer, M. I., Stein, J., & McGuire, K. L. (2020). Microbial composition and functional diversity differ across urban green infrastructure types. Frontiers in Microbiology, 11, 912.

[29]. Glodowska, Martyna & Woźniak, Małgorzata. (2019). Changes in Soil Microbial Activity and Community Composition as a Result of Selected Agricultural Practices. Agricultural Sciences. 10. 330-351. 10.4236/as.2019.103028.

[30]. Gomes, M. P. (2024). Climate Change and Aquatic Phytoremediation of Contaminants: Exploring the Future of Contaminant Removal. Phyton (0031-9457), 93(9).

[31]. Gupta, V. K., Ali, I., Saleh, T. A., Nayak, A., & Agarwal, S. (2012). Chemical treatment technologies for waste-water recycling—an overview. Rsc Advances, 2(16), 6380-6388.

[32]. Hartmann, M., Six, J. (2023). Soil structure and microbiome functions in agroecosystems. Nat Rev Earth Environ 4, 4–18.

[33]. Huffnagle, G., Dickson, R. & Lukacs, N. (2016). The respiratory tract microbiome and lung inflammation: a two-way street. Mucosal Immunol 10, 299–306 (2017).

[34]. Ibokette, A. I. Ogundare, T. O., Anyebe, A. P., Alao, F. O., Odeh, I. I. & Okafor, F. C. (2024). Mitigating Maritime Cybersecurity Risks Using AI-Based Intrusion Detection Systems and Network Automation During Extreme Environmental Conditions. *International Journal of Scientific Research and Modern Technology (IJSRMT)*. Volume 3, Issue 10, 2024. DOI: 10.38124/ijsrmt.v3i10.73.

[35]. Idoko, D. O., Agaba, J. A., Nduka, I., Badu, S. G., Ijiga, A. C. & Okereke, E. K, (2024). The role of HSE risk assessments in mitigating occupational hazards and infectious disease spread: A public health review. *Open Access Research Journal of Biology and Pharmacy*, 2024, 11(02), 011–030. https://oarjbp.com/content/role-hse-risk-assessments-mitigating-occupational-hazards-and-infectious-disease-spread.

[36]. Idoko, D. O., Danso, M. O., Olola T. M, Manuel, H. N. N., & Ibokette, A. I. (2024). Evaluating the ecological impact of fisheries management strategies in Georgia, USA: A review on current practices and future directions. *Magna Scientia Advanced Biology and Pharmacy*, 2024, 12(02), 023–045. https://doi.org/10.30574/msabp.2024.12.2.0041

[37]. Idowu, O. S., Idoko, D. O, Ogundipe, S. O., & Mensah, E. (2025). Optimizing SDS-PAGE for Accurate Protein Characterization in Nutritional Research and Food Quality Assessment. *International Journal of Innovative Science and Research Technology* Volume 10, Issue 1, ISSN No:-2456-2165 https://doi.org/10.5281/zenodo.14744563

[38]. Ijiga, A. C., Abutu E. P., Idoko, P. I., Ezebuka, C. I., Harry, K. D., Ukatu, I. E., & Agbo, D. O. (2024). Technological innovations in mitigating winter health challenges in New York City, USA. *International Journal of Science and Research Archive*, 2024, 11(01), 535–551.· https://ijsra.net/sites/default/files/IJSRA-2024-0078.pdf

[39]. Ijiga, A. C., Enyejo, L. A., Odeyemi, M. O., Olatunde, T. I., Olajide, F. I & Daniel, D. O. (2024). Integrating community-based partnerships for enhanced health outcomes: A collaborative model with healthcare providers, clinics, and pharmacies across the USA. *Open Access Research Journal of Biology and Pharmacy*, 2024, 10(02), 081–104. https://oarjbp.com/content/integrating-community-based-partnerships-enhanced-health-outcomes-collaborative-model

[40]. Jeong, S. W., & Choi, Y. J. (2020). Extremophilic microorganisms for the treatment of toxic pollutants in the environment. Molecules, 25(21), 4916.

[41]. Jok, I. S., & Ijiga, A. C. (2024). The Economic and Environmental Impact of Pressure Washing Services on Urban Infrastructure Maintenance and its Role in a Circular Economy. International Journal of Innovative Science and Research

Technology. Volume 9, Issue 11, November– 2024. ISSN No:-2456-2165. https://doi.org/10.38124/ijisrt/IJISRT24NOV1508
[42]. Kasozi, N., Abraham, B., Kaiser, H., & Wilhelmi, B. (2021). The complex microbiome in aquaponics: significance of the bacterial ecosystem. Annals of Microbiology, 71, 1-13.
[43]. Kumari, A., Dash, M., Singh, S. K., Jagadesh, M., Mathpal, B., Mishra, P. K., ... & Verma, K. K. (2023). Soil microbes: a natural solution for mitigating the impact of climate change. Environmental Monitoring and Assessment, 195(12), 1436.
[44]. Li, J., Wu, L., Zhou, Y., Xie, Y., Lu, F., Chang, F., ... & Cheng, M. (2024). Kobresia humilis via root-released flavonoids recruit Bacillus for promoted growth. Microbiological Research, 287, 127866.
[45]. Lorgen-Ritchie, M., Webster, T. U., McMurtrie, J., Bass, D., Tyler, C. R., Rowley, A., & Martin, S. A. M. (2023). Microbiomes in the context of developing sustainable intensified aquaculture.
[46]. Martin-Pozas, T., Cuezva, S., Fernandez-Cortes, A., Cañaveras, J. C., Benavente, D., Jurado, V., ... & Sanchez-Moral, S. (2022). Role of subterranean microbiota in the carbon cycle and greenhouse gas dynamics. Science of the Total Environment, 831, 154921.
[47]. Michael, I. A., Olade, A. D., Idoko, D. O., Yiga, V., & Galadima, D. (2025). Exploring Microbial Diversity in Air and Water and their Role in Enhancing Agricultural Resilience and Urban Ecosystem Health.
[48]. Mills, J. G., Bissett, A., Gellie, N. J., Lowe, A. J., Selway, C. A., Thomas, T., ... & Breed, M. F. (2020). Revegetation of urban green space rewilds soil microbiotas with implications for human health and urban design. Restoration Ecology, 28, S322-S334.
[49]. Mishra, S., Hora, S., Mishra, R., & Kanaujia, P. K. (2022). Bioremediation-based microorganisms to break down pollutants decelerate due to climate change. In Plant Stress Mitigators: Action and Application (pp. 125-143). Singapore: Springer Nature Singapore.
[50]. Nabavi-Pelesaraei, A., Mohammadkashi, N., Naderloo, L., Abbasi, M., & Chau, K. W. (2022). Principal of environmental life cycle assessment for medical waste during COVID-19 outbreak to support sustainable development goals. Science of the Total Environment, 827, 154416.
[51]. Naylor, D., Sadler, N., Bhattacharjee, A., Graham, E. B., Anderton, C. R., McClure, R., ... & Jansson, J. K. (2020). Soil microbiomes under climate change and implications for carbon cycling. Annual Review of Environment and Resources, 45(1), 29-59.
[52]. Olmo, R., Wetzels, S. U., Armanhi, J. S. L., Arruda, P., Berg, G., Cernava, T., ... & Wagner, M. (2022). Microbiome research as an effective driver of success stories in agrifood systems–a selection of case studies. Frontiers in Microbiology, 13, 834622.
[53]. Onuh, J. E., Idoko, I. P., Igbede, M. A., Olajide, F. I., Ukaegbu, C., & Olatunde, T. I. (2024). Harnessing synergy between biomedical and electrical engineering: A comparative analysis of healthcare advancement in Nigeria and the USA. **World Journal of Advanced Engineering Technology and Sciences**, 11(2), 628-649.
[54]. Prasad, S., Malav, L. C., Choudhary, J., Kannojiya, S., Kundu, M., Kumar, S., & Yadav, A. N. (2021). Soil microbiomes for healthy nutrient recycling. Current trends in microbial biotechnology for sustainable agriculture, 1-21.
[55]. Qin, N., Liang, P., Wu, C., Wang, G., Xu, Q., Xiong, X., ... & Zhu, T. F. (2020). Longitudinal survey of microbiome associated with particulate matter in a megacity. Genome biology, 21, 1-11.
[56]. Roberts, D. P., & Mattoo, A. K. (2018). Sustainable agriculture—Enhancing environmental benefits, food nutritional quality and building crop resilience to abiotic and biotic stresses. Agriculture, 8(1), 8.
[57]. Robinson, J. M., Redvers, N., Camargo, A., Bosch, C. A., Breed, M. F., Brenner, L. A., ... & Ishaq, S. L. (2022). Twenty important research questions in microbial exposure and social equity. Msystems, 7(1), e01240-21.
[58]. Robinson, J., Watkins, H., Man, I., Liddicoat, C., Cameron, R., Parker, B., ... & Meagher, L. (2021). Microbiome-inspired green infrastructure (MIGI): a bioscience roadmap for urban ecosystem health.
[59]. Ruiz, A., Scicchitano, D., Palladino, G., Nanetti, E., Candela, M., Furones, D., ... & Andree, K. B. (2023). Microbiome study of a coupled aquaponic system: unveiling the independency of bacterial communities and their beneficial influences among different compartments. Scientific Reports, 13(1), 19704.
[60]. Sarkar, M., & Gupta, J. (2024). Biotechnological Interventions to Mitigate the Influence of Climate Alterations on Ecosystem Viability and Human Well-Being. In Unraveling New Frontiers and Advances in Bioinformatics (pp. 387-407). Singapore: Springer Nature Singapore.
[61]. Schweitzer, M., Kögl, I., Wassermann, B., Abdelfattah, A., Wicaksono, W. A., & Berg, G. (2024). Urban air quality affects the apple microbiome assembly. Environmental Research, 262(1).
[62]. Shiels, P. G., Painer, J., Natterson-Horowitz, B., Johnson, R. J., Miranda, J. J., & Stenvinkel, P. (2021). Manipulating the exposome to enable better ageing. Biochemical Journal, 478(14), 2889-2898.
[63]. Singh, A. K., Srivastava, A. K., Johri, P., Dwivedi, M., Kaushal, R. S., Trivedi, M., ... & Lakhanpal, S. (2025). Odyssey of environmental and microbial interventions in maize crop improvement. Frontiers in Plant Science, 15, 1428475.
[64]. Siqueira, G. P., Araújo, D. A., de Faria, L. V., Ramos, D. L., Matias, T. A., Richter, E. M., ... & Muñoz, R. A. (2023). A novel 3D-printed graphite/polylactic acid sensor for the electrochemical determination of 2, 4, 6-trinitrotoluene residues in environmental waters. Chemosphere, 340, 139796.

[65]. Sun, X., Liddicoat, C., Tiunov, A., Wang, B., Zhang, Y., Lu, C., ... & Zhu, Y. G. (2023). Harnessing soil biodiversity to promote human health in cities. npj Urban sustainability, 3(1), 5.

[66]. Toor, M. D., Ur Rehman, M., Abid, J., Nath, D., Ullah, I., Basit, A., ... & Mohamed, H. I. (2024). Microbial Ecosystems as Guardians of Food Security and Water Resources in the Era of Climate Change. Water, Air, & Soil Pollution, 235(11), 741.

[67]. Trevathan-Tackett, S. M., Sherman, C. D., Huggett, M. J., Campbell, A. H., Laverock, B., Hurtado-McCormick, V., ... & Macreadie, P. I. (2019). A horizon scan of priorities for coastal marine microbiome research. Nature ecology & evolution, 3(11), 1509-1520.

[68]. VectorMine. (n.d.). Soil food web and nutrient cycling as plant biological cycle outline diagram

[69]. Vlasselaer, L., De Coninck, B., Lievens, B., & De Clercq, T. (2024). Uncovering the interplay between Phytophthora cryptogea and hydroponic lettuce: Insights from microbial communities and cultivar diversity.

[70]. Wu, L., Ning, D., Zhang, B., Li, Y., Zhang, P., Shan, X., ... & Zhou, J. (2019). Global diversity and biogeography of bacterial communities in wastewater treatment plants. Nature microbiology, 4(7), 1183-1195.

[71]. Wyss Institute. (2020). Microbiomes could hold keys to improving life as we know it [Infographic].

[72]. Zhang, Y., & Liu, W. T. (2019). The application of molecular tools to study the drinking water microbiome–Current understanding and future needs. Critical Reviews in Environmental Science and Technology, 49(13), 1188-1235.

[73]. Zhou, Y., Yang, Z., Liu, J., Li, X., Wang, X., Dai, C., ... & Li, X. (2023). Crop rotation and native microbiome inoculation restore soil capacity to suppress a root disease. Nature Communications, 14(1), 8126.