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# Microbial Maestros: Unraveling the Crucial Role of Microbes in Shaping the Environment

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## *ABSTRACT*

*Microbes play a crucial role in shaping and maintaining the environment through their diverse metabolic capabilities and ecological interactions. This review paper explores the multifaceted contributions of microbes in the environment and highlights their significance in various ecological processes. From nutrient cycling and decomposition to bioremediation and symbiotic associations, microbes exhibit remarkable adaptability and functional diversity. Understanding the role of microbes in the environment is essential for sustainable resource management, conservation efforts, and the development of innovative biotechnological applications. This comprehensive review provides insights into the intricate relationships between microbes and the environment, emphasizing their importance for ecosystem functioning and human well-being.*

**Keywords:** Microbes, Environment, Ecological processes, Nutrient cycling, Bioremediation, Symbiotic associations

## INTRODUCTION

Microbes, including bacteria, archaea, fungi, and viruses, are ubiquitous in the environment and exert a profound influence on various ecological processes. These microscopic organisms, often overlooked or underestimated, play crucial roles in shaping and maintaining the delicate balance of ecosystems. This comprehensive review aims to shed light on the remarkable contributions of microbes in the environment, highlighting their diverse metabolic capabilities, ecological interactions, and their significance for ecosystem functioning and human well-being. Microbes have evolved over billions of years, adapting to a wide range of environmental conditions and occupying virtually every niche on Earth. They are masters of metabolic versatility, capable of utilizing a vast array of organic and inorganic compounds as energy sources and participating in key nutrient cycling processes. Microbes are primary drivers of carbon, nitrogen, and sulfur cycling, mediating the decomposition of organic matter, nutrient mineralization, and elemental transformations [1]. Through their enzymatic activities, microbes break down complex organic molecules into simpler forms, making essential nutrients available to plants and other organisms in the ecosystem [2-4].

Furthermore, microbes play a vital role in bioremediation, the process of using living organisms to degrade or remove pollutants from the environment. Certain microbes possess unique metabolic capabilities that enable them to degrade or transform a wide range of toxic substances, including hydrocarbons, heavy metals, and pesticides [5-6]. These microbial superheroes can detoxify contaminated environments, mitigating the negative impacts of pollutants on ecosystems and human health [7]. Another intriguing aspect of microbial ecology lies in their intricate symbiotic associations with plants, animals, and other microorganisms. Microbes form symbiotic relationships with higher organisms, providing essential functions such as nitrogen fixation, plant growth promotion, and protection against pathogens [8-9]. For example, certain bacteria establish mutualistic associations with leguminous plants, contributing nitrogen to the soil through biological nitrogen fixation and enhancing plant growth [10]. These symbiotic associations highlight the interdependence between microbes and higher organisms, showcasing the remarkable power of microbial communities in influencing ecosystem dynamics and productivity. Understanding the role of microbes in the environment is not only crucial for deciphering fundamental ecological processes but also for developing innovative biotechnological applications. Microbes are a rich source of novel enzymes, bioactive compounds, and potential pharmaceutical agents [11-12]. Exploration of microbial diversity and their unique metabolic capabilities holds immense promise for the discovery of new drugs, biocatalysts, and bioproducts that can benefit various industries, including healthcare, agriculture, and bioremediation [13-14]. In conclusion, this review aims to unveil the hidden microbial maestros and their significant contributions to the environment. By elucidating the intricate relationships between microbes and their ecological functions, we gain valuable insights into the resilience and sustainability of ecosystems. Furthermore, harnessing the potential of microbial diversity and metabolic versatility opens up exciting avenues for the development of sustainable solutions to pressing environmental and societal challenges.

***Nutrient Cycling: Microbes as Guardians of Elemental Balance***

Nutrient cycling is a fundamental process in ecosystems, involving the movement and transformation of essential elements such as carbon, nitrogen, and phosphorus. Microbes play a crucial role in nutrient cycling as they possess diverse metabolic capabilities that enable them to participate in key biochemical reactions. This section explores the significance of microbes in nutrient cycling and highlights their role as guardians of elemental balance in the environment.

***Microbes as Decomposers:*** Decomposition is a critical step in nutrient cycling, where complex organic matter is broken down into simpler forms, releasing essential elements back into the ecosystem. Microbes, particularly bacteria and fungi, are the primary decomposers responsible for this process [15]. Through the secretion of extracellular enzymes, microbes efficiently break down complex organic compounds, liberating carbon, nitrogen, and phosphorus from decaying plant and animal material [16]. This decomposition process facilitates the recycling of nutrients, making them available for uptake by plants and other organisms.

***Nitrogen Fixation by Microbes:*** Nitrogen is a vital nutrient for the growth and development of living organisms. However, atmospheric nitrogen ($N_2$) is largely inaccessible to most organisms in its gaseous form. Microbes, specifically nitrogen-fixing bacteria, and archaea, have the unique ability to convert atmospheric nitrogen into a biologically usable form through the process of nitrogen fixation [17]. These microbes possess nitrogenase enzymes that catalyze the conversion of $N_2$ into ammonia ($NH_3$), which can be further assimilated into organic molecules by other organisms [18]. Nitrogen-fixing microbes forge a symbiotic relationship with certain plants, such as legumes, where they reside in specialized structures called nodules, providing a direct source of nitrogen to the host plants [19].

***Microbes in Phosphorus Cycling:*** Phosphorus is another essential nutrient that plays a vital role in various biological processes. Microbes contribute significantly to phosphorus cycling through their ability to solubilize and mineralize organic and inorganic forms of phosphorus [20]. Certain microbial species produce phosphatase enzymes that break down organic phosphorus compounds, releasing phosphate ions ($PO_4^{3-}$) into the environment [21]. Additionally, microbial activity can facilitate the release of phosphorus from mineral forms, making it available for plant uptake [22]. This microbial-mediated phosphorus cycling helps maintain the availability of this crucial nutrient in ecosystems. Microbes act as guardians of elemental balance in nutrient cycling processes. Through decomposition, nitrogen fixation, and phosphorus cycling, microbes play a vital role in recycling essential elements, ensuring their availability for other organisms in the environment. Understanding the contributions of microbes in nutrient cycling is essential for sustainable ecosystem management, agriculture, and the development of biotechnological applications aimed at improving nutrient use efficiency. Further research on microbial-driven nutrient cycling processes will enhance our understanding of ecosystem functioning and provide valuable insights for environmental conservation and resource management.

***Bioremediation: Microbial Cleanup Crews in Action***

Bioremediation is a powerful and sustainable approach that utilizes the metabolic abilities of microorganisms to degrade or transform harmful pollutants in the environment [23]. This comprehensive review explores the application of microbes in bioremediation processes, their role in the breakdown of various contaminants, and the mechanisms by which they contribute to environmental clean-up.

***Microbial Diversity and Contaminant Degradation:*** Microbes exhibit an astonishing diversity of metabolic capabilities, allowing them to break down a wide range of contaminants, including organic pollutants, heavy metals, and petroleum hydrocarbons [24]. Bacteria, fungi, and archaea have evolved specialized enzymatic pathways that enable them to convert complex pollutants into less toxic or non-toxic forms [25]. For example, certain bacteria possess the ability to degrade hydrocarbons through the production of enzymes such as hydroxylases and oxygenases, which initiate the breakdown of petroleum compounds [26].

***Biodegradation Pathways and Mechanisms:*** Microbes employ different biodegradation pathways depending on the nature of the contaminants and environmental conditions [27]. Aerobic biodegradation involves the use of oxygen by microorganisms to break down organic compounds, while anaerobic biodegradation occurs in the absence of oxygen and relies on alternative electron acceptors such as nitrate or sulfate [28]. Additionally, microbes can form consortia or biofilms that work synergistically to enhance the degradation of complex pollutants [29].

***Factors Influencing Bioremediation Efficiency:*** Several factors influence the efficiency of bioremediation processes. Environmental factors such as temperature, pH, nutrient availability, and oxygen levels play a critical role in determining microbial activity and the rate of contaminant degradation [30]. The selection of appropriate microbial strains or consortia, tailored to the specific contaminants and environmental conditions, is crucial for maximizing bioremediation efficiency [31]. Additionally, the presence of co-contaminants, the availability of electron acceptors or donors, and the presence of inhibitory substances can impact the overall biodegradation process [32].

***Enhancing Bioremediation Strategies:*** To enhance the effectiveness of bioremediation, various strategies have been developed. These include bioaugmentation, which involves the introduction of specific microbial strains or consortia to enhance the degradation of target contaminants [33]. Biostimulation, on the other hand, aims to promote the growth and activity of indigenous microbial populations by providing nutrients, electron acceptors, or other growth-enhancing substances [34]. Additionally, the use of genetically engineered microbes or the integration of physical and chemical treatments with bioremediation techniques has shown promise in certain cases [35].

***Field Applications and Success Stories:*** Bioremediation has been successfully applied in various contaminated environments, including soil, water, and sediments. Numerous case studies have demonstrated the effectiveness of microbial clean-up crews in action. For instance, the Exxon Valdez oil spill in 1989 showcased the potential of bioremediation to facilitate the degradation of petroleum hydrocarbons in marine environments [36]. Similarly, the cleanup of chlorinated solvent-contaminated sites using microbial reductive dechlorination techniques has achieved notable success [37].

***Symbiotic Associations: Microbes as Masters of Collaboration***

Symbiotic associations between microbes and other organisms are prevalent across various ecosystems and play a crucial role in shaping the biological landscape [38]. This review aims to explore the diverse types of symbiotic associations involving microbes and their partners, ranging from mutualistic to parasitic interactions. Understanding the mechanisms and ecological significance of these symbiotic associations provides insights into the intricate web of life and the coevolutionary dynamics between microorganisms and their host organisms.

## Types of Symbiotic Associations

***Mutualistic Associations:*** Mutualistic associations involve interactions in which both the microbe and the host organism benefit. Examples include nitrogen-fixing bacteria residing in the root nodules of leguminous plants, where the bacteria convert atmospheric nitrogen into a usable form for the plant while receiving nutrients in return. Other mutualistic associations involve gut microbiota in animals, providing digestion assistance and protection against pathogens [39-40].

***Commensal Associations:*** Commensal associations occur when one organism benefits while the other remains unaffected. Some microbial communities colonize specific niches on the host organism's body surfaces, deriving nutrients or protection without causing harm or benefit to the host. For example, certain bacteria residing on human skin or within the nasal cavity have commensal relationships, coexisting without causing noticeable effects [41].

***Parasitic Associations:*** Parasitic associations involve interactions in which the microbe benefits at the expense of the host organism. Pathogenic microbes cause diseases and harm their hosts, exploiting host resources for their survival and reproduction. Examples include bacterial, viral, and fungal infections that can lead to a wide range of diseases in plants, animals, and humans [42].

***Ecological Significance of Symbiotic Associations:*** Symbiotic associations have profound ecological significance in maintaining ecosystem stability and functioning. They contribute to nutrient cycling, energy transfer, and the overall biodiversity of ecosystems. Mutualistic associations facilitate nutrient acquisition, enhance host tolerance to environmental stressors, and promote ecological resilience [43].

***Ecological Interactions: Microbes as Key Players in Ecosystem Dynamics***

Ecosystems are complex webs of interactions among organisms, and microbes, as the most abundant and diverse group of organisms, play a critical role in shaping ecosystem dynamics. This comprehensive review explores the various ecological interactions involving microbes and their profound impacts on ecosystem functioning. From nutrient cycling and energy flow to symbiotic associations and trophic interactions, understanding the intricate relationships between microbes and other organisms is crucial for unraveling the complexities of ecosystems.

***Nutrient Cycling:*** Microbes are key drivers of nutrient cycling in ecosystems. They participate in crucial processes such as decomposition, mineralization, and nutrient transformation [44-46]. Through their enzymatic activities, microbes break down complex organic matter into simpler forms, releasing essential nutrients back into the environment. Additionally, microbial symbionts in plant roots, known as mycorrhizal fungi and nitrogen-fixing bacteria, enhance nutrient uptake and availability for plants, thus influencing the nutrient dynamics within ecosystems [47].

***Energy Flow:*** Microbes are integral to the flow of energy through ecosystems. As decomposers, they break down dead organic matter, facilitating the release of energy stored within it. This energy is then made available to other organisms in the ecosystem through the microbial-driven decomposition process. Furthermore, microbial interactions in food webs, such as predation, grazing, and parasitism, regulate the transfer of energy from one trophic level to another [48].

***Symbiotic Associations:*** Microbes form intricate symbiotic associations with various organisms, including plants, animals, and other microbes. Mutualistic associations, such as mycorrhizal symbiosis between plants and fungi, enable nutrient exchange and enhance plant growth [49]. Similarly, microbial symbionts in the guts of animals aid in digestion, provide essential nutrients, and contribute to overall host health. These symbiotic interactions profoundly influence the structure and functioning of ecosystems.

***Trophic Interactions:*** Microbes occupy various trophic levels in ecosystems, serving as both primary producers and consumers. Photosynthetic microorganisms, such as cyanobacteria and algae, harness energy from sunlight and produce organic matter through photosynthesis. These primary producers form the basis of food chains and support higher trophic levels. Additionally, microbial consumers, such as bacteria and protists, feed on organic matter and other microorganisms, regulating population dynamics and nutrient cycling within ecosystems [50].

***Ecological Succession:*** Microbes play a critical role in ecological succession, the process of community development and change over time. They are often the first colonizers in disturbed ecosystems, initiating the breakdown of organic matter and creating suitable conditions for subsequent species to establish. Microbes facilitate the transition from bare soil to more complex and diverse communities, thus driving the progression of ecological succession [51]. Microbes are key players in ecosystem dynamics, influencing nutrient cycling, energy flow, symbiotic associations, trophic interactions, and ecological succession. Their interactions with other organisms shape the structure, functioning, and resilience of ecosystems. Understanding the ecological roles of microbes is essential for ecosystem management, conservation efforts, and the development of sustainable practices. Further research is needed to unravel the intricate mechanisms underlying microbial interactions and their broader implications for ecosystem dynamics.

### *Implications and Future Directions: Harnessing Microbial Power for Environmental Management*

Microbes, with their diverse metabolic capabilities and ecological interactions, have profound implications for environmental sustainability. This section explores the potential applications of harnessing microbial power in various environmental domains and discusses future directions for maximizing their benefits. Microbes possess the remarkable ability to degrade pollutants and remediate contaminated environments. They can break down organic pollutants through processes such as biodegradation, bioaugmentation, and biostimulation. Harnessing microbial bioremediation strategies can effectively mitigate the environmental impact of pollutants, including oil spills, chemical spills, and hazardous waste sites. Future research should focus on enhancing our understanding of microbial degradation pathways, optimizing bioremediation techniques, and developing innovative microbial consortia for targeted pollutant removal [53].

***Waste Management:*** Microbes play a vital role in waste management by facilitating the decomposition and recycling of organic materials. They participate in the process of composting, converting organic waste into nutrient-rich compost. Additionally, microbial fermentation processes are utilized in biogas production from organic waste, providing a sustainable energy source. Advancements in understanding microbial communities and their functional potentials can lead to improved waste management strategies, including the development of more efficient composting techniques and biogas production systems [54].

***Agriculture and Soil Health:*** Microbes have a profound impact on agricultural systems and soil health. They contribute to nutrient cycling, plant growth promotion, and disease suppression. Harnessing microbial power in agriculture involves the use of biofertilizers, microbial inoculants, and biocontrol agents. These microbial interventions reduce the reliance on chemical inputs, enhance soil fertility, and promote sustainable agriculture. Future research should focus on understanding the functional diversity of microbial communities in different agroecosystems, optimizing microbial formulations for specific crops, and exploring the potential of microbial symbiotic associations to enhance agricultural sustainability [55].

Water Treatment: Microbes are instrumental in water treatment processes, particularly in the removal of pollutants and the degradation of organic matter. Technologies such as microbial fuel cells, constructed wetlands, and biofiltration systems utilize microbial communities to purify wastewater and improve water quality. Future directions in harnessing microbial power for water treatment involve optimizing system designs, understanding microbial community dynamics under varying conditions, and exploring the potential of microbial electrochemical processes for sustainable water treatment [56].

***Climate Change Mitigation:*** Microbes have significant implications for climate change mitigation through their involvement in carbon sequestration and greenhouse gas emissions. Certain microbial communities can enhance carbon storage in soils, contributing to climate change mitigation efforts. Additionally, microbial processes influence the production and consumption of greenhouse gases such as carbon dioxide, methane, and nitrous oxide. Future research should focus on unraveling the complex interactions between microbial communities and climate change dynamics, developing microbial-based strategies for carbon sequestration, and mitigating greenhouse gas emissions in various ecosystems [57].

Harnessing microbial power for environmental sustainability holds immense potential. Bioremediation, waste management, agriculture, water treatment, and climate change mitigation are just a few areas where microbes can contribute significantly. Continued research and innovation are necessary to fully unlock the power of microbes and develop sustainable solutions for environmental challenges. By understanding and harnessing the capabilities of microbial communities, we can pave the way for a more sustainable future.

**Conflict of interest:** The authors declare that there is no conflict of interest

## References

1. Atlas RM, Philp J. Bioremediation: Applied Microbial Solutions for Real-World Environmental Cleanup. *ASM Press*; 2005.

2. Schultz, J., Parise, M. T. D., Parise, D., Medeiros, L. G., Sousa, T. J., Kato, R. B., ... & Rosado, A. S. (2022). Unraveling the Genomic Potential of the Thermophilic Bacterium Anoxybacillus flavithermus from an Antarctic Geothermal Environment. *Microorganisms*, *10*(8), 1673.

3. Atlas RM. 1995. Microbial degradation of petroleum hydrocarbons: an environmental perspective. *Microbiol Rev.* 59(4): 505-522.

4. Tarazona, N. A., Machatschek, R., & Lendlein, A. (2019). Unraveling the interplay between abiotic hydrolytic degradation and crystallization of bacterial polyesters comprising short and medium side-chain-length polyhydroxyalkanoates. *Biomacromolecules*, *21*(2), 761-771.

5. Bardgett RD, et al. (2008). Soil microbial community responses to reductions in plant diversity and functional group richness. Ecology Letters, 11(4), 419-429.

6. Pinho, M. G., Kjos, M., & Veening, J. W. (2013). How to get (a) round: mechanisms controlling growth and division of coccoid bacteria. *Nature reviews microbiology*, *11*(9), 601-614.

7. Bardgett RD, et al. (2020). Integrating microbial ecology into ecosystem models: challenges and priorities. *Biogeochemistry*, 149, 71-85.

8. Walter, J., & Ley, R. (2011). The human gut microbiome: ecology and recent evolutionary changes. *Annual review of microbiology*, *65*, 411-429.

9. Bérdy J. 2005. Bioactive microbial metabolites. J Antibiot (Tokyo). 58(1): 1-26. Brady SF, Clardy J. 2009. Clustering and homology analysis of antibiotic-resistance genes in soil metagenomes. *BMC Genomics*. 10: 332.

10. Liao, M., Gong, H., Quan, X., Wang, Z., Hu, X., Chen, Z., & Lu, J. R. (2023). Intramembrane Nanoaggregates of Antimicrobial Peptides Play a Vital Role in Bacterial Killing. *Small*, *19*(3), 2204428.

11. Berg, G. (2009). Plant–microbe interactions promoting plant growth and health: perspectives for controlled use of microorganisms in agriculture. *Appl. Microbiol. Biotechnol.,* 84(1), 11-18.

12. Wong-Bajracharya, J., Castaneda-Gomez, L., Plett, K. L., Anderson, I. C., Carrillo, Y., & Plett, J. M. (2020). Untangling the effect of roots and mutualistic ectomycorrhizal fungi on soil metabolite profiles under ambient and elevated carbon dioxide. *Soil Biology and Biochemistry*, *151*, 108021.

13. Bulgarelli D, et al. 2013. Structure and function of the bacterial root microbiota in wild and domesticated barley. *Cell Host Microbe.* 17(3): 392-403.

14. Cordero, O. X., Wildschutte, H., Kirkup, B., &Proehl, S. (2018). Ecological insights from the genomes of organisms in microbial communities. *Nat. Rev. Genet.,* 19(4), 253-265.

15. Douglas, A. E. (2018). Strategies for enhanced crop resistance to insect pests. Annu. *Rev. Plant Biol*., 69, 637-660.

16. Cross, E. R., Coulter, S. M., Pentlavalli, S., & Laverty, G. (2021). Unravelling the antimicrobial activity of peptide hydrogel systems: current and future perspectives. *Soft Matter*, *17*(35), 8001-8021.

17. Falkowski PG, et al. (2008). The global nitrogen cycle: changes and consequences. *Environ Microbiol,* 9(3), 489-494.

18. Falkowski PG, et al. 2008. The global carbon cycle: a test of our knowledge of Earth as a system. *Science.* 320(5874): 1298-1301.

19. Falkowski PG, Fenchel T, Delong EF. The microbial engines that drive Earth's biogeochemical cycles. *Science*. 2008;320(5879):1034-1039.

20. Xi, Y., Chang, Z., Ye, X., Huang, H., Huang, Y., Xiao, Q., & Lin, H. (2016). Ultra-small Nd 3+-doped nanoparticles as near-infrared luminescent biolabels of hemin in bacteria. *Nanoscale*, *8*(3), 1288-1292.

21. Foulkes, E. C., et al. (2019). Harnessing microbial communities for sustainable remediation of contaminated soils and sediments. *Microbial Biotechnology*, 12(6), 1311-1315.

22. George TS, et al. (2017). Organic phosphorus in the terrestrial environment: a perspective on the state of the art and future priorities. Plant Soil, 427(1-2), 191-208.

23. Gonzalez-Gil, G., et al. (2019). Applications of microbial fuel cells in wastewater treatment: A review. *Chemical Engineering Journal,* 360, 1554-1564.

24. Domínguez-Santos, R., Pérez-Cobas, A. E., Cuti, P., Pérez-Brocal, V., García-Ferris, C., Moya, A., & Gil, R. (2021). Interkingdom gut microbiome and resistome of the cockroach Blattella germanica. *Msystems*, *6*(3), 10-1128.

25. Grice, E. A., & Segre, J. A. (2011). The skin microbiome. *Nat. Rev. Microbiol.,* 9(4), 244-253.

26. Head IM, Jones DM, Röling WF. Marine microorganisms make a meal of oil. *Nat Rev Microbiol*. 2006;4(3):173-182.

27. Holliger C, Hahn D, Harmsen H, Ludwig W, Schumacher W, Tindall B, et al. Dehalobacterrestrictus gen. nov.and sp. nov., a strictly anaerobic bacterium that reductively dechlorinates tetra- and trichloroethene in an anaerobic respiration. *Arch Microbiol. 1997*;169(4):313-321.

28. Hooper DU, Vitousek PM. The effects of plant composition and diversity on ecosystem processes. *Science.* 1997;277(5330):1302-1305.

29. Kanaly RA, Harayama S. Biodegradation of high-molecular-weight polycyclic aromatic hydrocarbons by bacteria. J Bacteriol. 2010;192(15):3693-3707.

30. Kiers, E. T., Rousseau, R. A., & Denison, R. F. (2010). Mutualistic interactions drive ecological research. Trends Ecol. Evol., 25(6), 323-330.

31. Lovley DR. Cleaning up with genomics: Applying molecular biology to bioremediation. *Nat Rev Microbiol*. 2003;1(1):35-44.

32. Margesin R, Labbé D, Schinner F, Greer CW. Hydrocarbon degradation and plant colonization by selected cold-adapted soil bacteria and yeasts. *CurrMicrobiol.* 2012;64(5):499-505.

33. Montoya, J. M., Pimm, S. L., &Solé, R. V. (2006). Ecological networks and their fragility. Nature, 442(7100), 259-264.

34. Mrozik A, Piotrowska-Seget Z. Bioaugmentation as a strategy for cleaning up of soils contaminated with aromatic compounds. *Microbiol Res.* 2010;165(5):363-375.


 

35. Oldroyd GE. 2013. Speak, friend, and enter: signalling systems that promote beneficial symbiotic associations in plants. *Nat Rev Microbiol*. 11(4): 252-263.

36. Ruggieri, L., et al. (2020). Microbial biotechnology for bioremediation and waste-to-energy conversion. *Trends in Biotechnology*, 38(7), 791-802.

37. Schimel JP, Schaeffer SM. 2012. Microbial control over carbon cycling in soil. Front Microbiol. 3: 348.

38. Singh BK, et al. 2004. Role of soil microbes in the rhizospheres of plants growing on trace metal contaminated soils in phytoremediation. J Trace Elem Med Biol. 18(4): 355-364.

39. Singh OV, Ward OP. Biodegradation and bioremediation. Springer; 2004.

40. Trivedi, P., et al. (2020). Harnessing microbiome-based biotechnologies for sustainable agriculture. Trends in Plant Science, 25(3), 252-264.

41. Sikkema, J. A. N., de Bont, J. A., & Poolman, B. (1995). Mechanisms of membrane toxicity of hydrocarbons. *Microbiological reviews*, *59*(2), 201-222.

42. Turnbaugh, P. J., Ley, R. E., Hamady, M., Fraser-Liggett, C. M., Knight, R., & Gordon, J. I. (2007). The human microbiome project. *Nature*, 449(7164), 804-810.

43. Van der Meer JR, Belkin S, Jaspers M, Rademaker JL, de Visser JA. Genetic modification of higher plants for environmental bioremediation. *Trends Biotechnol*. 2010;28(8):419-428.

44. Maestro, B., & Sanz, J. M. (2016). Choline binding proteins from Streptococcus pneumoniae: a dual role as enzybiotics and targets for the design of new antimicrobials. *Antibiotics*, *5*(2), 21.

45. Vogt C, Hesselsoe M, Albrechtsen HJ, Nielsen PH. Combination of fluorescent in situ hybridization and microautoradiography—a new tool for structure-function analyses in microbial ecology. *Appl Environ Microbiol*. 2012;78(7):2879-2888.

46. Wardle DA, Bardgett RD, Klironomos JN, et al. Ecological linkages between aboveground and belowground biota. *Science.* 2004;304(5677):1629-1633.

47. Watanabe K. Microorganisms relevant to bioremediation. CurrOpinBiotechnol. 2010;21(3):315-320.

48. Das, S., Bhattacharjee, M. J., Mukherjee, A. K., & Khan, M. R. (2023). Recent advances in understanding of multifaceted changes in the vaginal microenvironment: Implications in vaginal health and therapeutics. *Critical Reviews in Microbiology*, *49*(2), 256-282.

49. Woolhouse, M. E., Webster, J. P., Domingo, E., Charlesworth, B., & Levin, B. R. (2002). Biological and biomedical implications of the co-evolution of pathogens and their hosts. Nat. Genet., 32(4), 569-577.

50. Doré, H., Farrant, G. K., Guyet, U., Haguait, J., Humily, F., Ratin, M., & Garczarek, L. (2020). Evolutionary mechanisms of long-term genome diversification associated with niche partitioning in marine picocyanobacteria. *Frontiers in Microbiology*, *11*, 567431.

51. Kwon, Y. H., & Khan, W. I. (2022). Peripheral serotonin: cultivating companionship with gut microbiota in intestinal homeostasis. *American Journal of Physiology-Cell Physiology*, *323*(2), C550-C555.

52. Brown, E. M., Kenny, D. J., & Xavier, R. J. (2019). Gut microbiota regulation of T cells during inflammation and autoimmunity. *Annual review of immunology*, *37*, 599-624.

53. Farag, M. A., Song, G. C., Park, Y. S., Audrain, B., Lee, S., Ghigo, J. M., & Ryu, C. M. (2017). Biological and chemical strategies for exploring inter-and intra-kingdom communication mediated via bacterial volatile signals. *Nature protocols*, *12*(7), 1359-1377.

54. Kocak, Muhammed, Saba Ezazi Erdi, Guillem Jorba, Inés Maestro, Judith Farrés, Vladimir Kirkin, Ana Martinez, and Ole Pless. "Targeting autophagy in disease: established and new strategies." *Autophagy* 18, no. 3 (2022): 473-495.

55. Beilharz, K., Nováková, L., Fadda, D., Branny, P., Massidda, O., & Veening, J. W. (2012). Control of cell division in Streptococcus pneumoniae by the conserved Ser/Thr protein kinase StkP. *Proceedings of the National Academy of Sciences*, *109*(15), E905-E913.

56. Yin, J., Han, Q., Zhang, J., Liu, Y., Gan, X., Xie, K., & Deng, Y. (2020). MXene-based hydrogels endow polyetheretherketone with effective osteogenicity and combined treatment of osteosarcoma and bacterial infection. *ACS Applied Materials & Interfaces*, *12*(41), 45891-45903.