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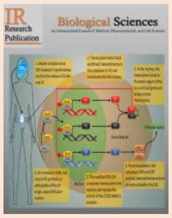

Environmental Epidemiology Reimagined: Soil Microbes as Indicators of Public Health Risks

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ABSTRACT

This study explores the potential of soil microbiomes as indicators of public health risks, emphasizing the complex interplay between soil microbial communities and human health outcomes. Soil microorganisms are critical components of ecosystems, influencing both beneficial functions, such as nutrient cycling and plant health, and harmful effects, including the presence of pathogens and antimicrobial resistance genes that can pose risks to human populations. The study investigates how anthropogenic factors—such as urbanization, agriculture, and climate change—affect soil microbial diversity, which in turn impacts public health. The integration of advanced biotechnological tools, such as metagenomics, machine learning, and biosensors, is explored as a means of enhancing the detection and monitoring of soil health risks. The study also highlights the current gaps in research linking soil microbial dynamics to human health outcomes and calls for interdisciplinary approaches to bridge these gaps. Findings from this research suggest that soil microbiomes have significant potential to serve as bioindicators of public health risks, offering a new avenue for improving health surveillance and informing policy recommendations. The study concludes with a call to action for further research, improved monitoring strategies, and the incorporation of soil health into public health frameworks to address the global health challenges posed by environmental changes.

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Introduction

Soil microbiomes comprise bacteria, fungi, archaea, viruses, and other microorganisms that perform vital ecosystem functions. They are essential not only for sustaining plant and soil health but also for indirectly influencing human well-being. For instance, soil microorganisms are sources of antibiotics, such as penicillin and streptomycin, which revolutionized medicine (1). However, the misuse of antibiotics has led to the evolution of antimicrobial resistance (AMR), with soil acting as a hotspot for resistance gene proliferation (2). Furthermore, soil contamination from pesticides, industrial pollutants, and pathogens can adversely affect human health by entering the food chain or contaminating water supplies. Public health risks, such as outbreaks of zoonotic diseases, are often linked to environmental reservoirs. Soil, being a dynamic interface between humans, animals, and ecosystems, provides a unique vantage point for studying these interactions. For example, soil disturbances from urbanization or agriculture can lead to the release of pathogenic microorganisms or pollutants, increasing exposure risks for surrounding communities (3).

Environmental epidemiology seeks to understand how environmental factors influence human health outcomes. Soil microbes, as mediators of both beneficial and harmful processes, are emerging as key players in this field. Beneficial soil microbes, such as those involved in nitrogen fixation and carbon cycling, support food production and environmental sustainability. On the other hand, harmful microorganisms, such as Clostridium tetani or Bacillus anthracis, pose direct risks to public health through soilborne infections (4). Moreover, soil microbes can serve as bioindicators, reflecting environmental changes and potential health risks. For instance, the presence of antibiotic resistance genes (ARGs) in agricultural soils may signal high levels of antibiotic use in nearby livestock farming (5). Similarly, soil microbial diversity—or lack thereof—can be used to assess the health of ecosystems impacted by pollutants, deforestation, or climate change. By studying these microbial dynamics, researchers can predict potential public health crises, such as the emergence of resistant pathogens or zoonotic disease outbreaks.

This study presents a novel perspective by explicitly integrating soil microbiome data into public health frameworks, a critical linkage that remains underexplored in existing literature. By examining the intersection of soil microbial ecology with global health challenges such as antimicrobial resistance (AMR), zoonotic disease transmission, and environmentally mediated infections, the review advances current discourse on how environmental microbiomes shape human health. Recent insights into soil-pathogen interactions and microbial shifts due to anthropogenic pressures underscore the urgency of this integration. The study explores the potential of soil microbiomes as indicators of public health risks, identifies the roles soil microorganisms play in both ecosystem and human health, and analyzes how microbial dynamics respond to factors such as urbanization, agriculture, and climate change. It also highlights emerging biotechnological tools such as metagenomics and biosensors for monitoring and mitigating soil-related health risks. Furthermore, the study identifies research gaps and proposes actionable recommendations to enhance the role of soil microbiomes in disease surveillance and prevention. However, this work contributes to the growing field of environmental epidemiology and promotes the inclusion of soil health as a foundational element of public health strategy within the broader planetary health framework.

Soil Microbial Communities: An Overview

Soil microbial communities are among the most diverse and complex biological systems on Earth. Comprising bacteria, fungi, archaea, viruses, and protozoa, these microorganisms are critical for maintaining soil health and ecosystem functionality. Soil microbes play a pivotal role in biogeochemical cycles, supporting plant growth and resilience, and influencing environmental quality. The diversity and functionality of these communities are shaped by soil physicochemical properties, land use patterns, and environmental factors, which can either enhance their beneficial roles or amplify their risks to public health.

Diversity and function of soil microbes

Soil microbial diversity is vast, with a single gram of soil estimated to contain billions of microorganisms and thousands of species (6). These microorganisms contribute to essential ecological processes, such as organic matter decomposition, nutrient cycling (e.g., nitrogen fixation and phosphorus solubilization), and the regulation of greenhouse gas emissions. Soil microbial communities are highly dynamic, adapting to environmental conditions and external pressures like climate change, pollution, and agricultural practices. For example, nitrogen-fixing bacteria like Rhizobium and Azotobacter form symbiotic relationships with plants, enhancing soil fertility (7). The functional diversity of soil microbes is equally critical. Functional traits, such as enzyme production, organic matter degradation, and biofilm formation, enable soil microbes to mediate nutrient availability and pathogen suppression. However, disruptions to soil microbial diversity, often caused by land-use changes or pollution, can impair these functions, leading to ecological imbalances and increased vulnerability to disease outbreaks.

Beneficial roles of soil microorganisms

Soil microorganisms provide numerous ecosystem services that directly or indirectly benefit human and environmental health. They are critical for nutrient cycling, decomposing organic matter into simpler compounds, which replenish soil fertility and support plant growth (8). Mycorrhizal fungi, for instance, enhance water and nutrient uptake in plants, promoting agricultural productivity and resilience to environmental stressors. In addition to ecosystem services, soil microbes are a source of bioactive compounds, including antibiotics, enzymes, and other secondary metabolites. Streptomyces, a genus of soil bacteria, has been instrumental in producing life-saving antibiotics like streptomycin and tetracycline (9). Furthermore, soil microbes contribute to bioremediation by breaking down pollutants such as hydrocarbons and pesticides, reducing environmental contamination and associated public health risks.

Soil microbes as reservoirs of pathogens and resistance genes

While soil microbes offer numerous benefits, they can also act as reservoirs of pathogenic organisms and antimicrobial resistance genes (ARGs). Pathogenic microbes, including Clostridium tetani, Bacillus anthracis, and Mycobacterium ulcerans, persist in soils and pose risks to human and animal health through direct contact or environmental pathways (10). For instance, outbreaks of tetanus and anthrax are often linked to soil contamination in agricultural or flood-prone areas. Moreover, soils are recognized as critical reservoirs for ARGs, contributing to the global antimicrobial resistance crisis. Agricultural soils, particularly those exposed to manure and wastewater, harbor elevated levels of ARGs due to the overuse of antibiotics in livestock farming (11). These resistance genes can transfer between soil microbes and human pathogens, exacerbating the challenge of treating infectious diseases. Addressing the dual role of soil microbes as beneficial agents and potential health risks is crucial for sustainable public health and environmental management.

Drivers of Soil Microbial Shifts

Soil microbial communities are highly dynamic and responsive to various environmental and anthropogenic influences. Shifts in these microbial communities are driven by multiple factors, including urbanization, industrial activities, agricultural practices, and climate change. Understanding the drivers of soil microbial shifts is critical for predicting the impacts on ecosystem services, public health, and the sustainability of agricultural systems. These shifts can influence soil fertility, pathogen dynamics, and the proliferation of antimicrobial resistance genes, which in turn affect public health outcomes.

Urbanization and industrial activities

Urbanization and industrial activities significantly affect soil microbial communities through land disturbance, pollution, and the introduction of novel chemicals and materials. Urbanization often involves soil compaction, construction, and the sealing of land surfaces with concrete, which limits microbial diversity and alters soil structure (12). In urban environments, the concentration of pollutants such as heavy metals, chemicals, and waste materials can also disrupt microbial function and composition. For example, industrial runoff containing petroleum hydrocarbons can lead to soil contamination, which negatively impacts microbial populations essential for nutrient cycling and degradation of organic matter (13). Industrial activities also introduce synthetic chemicals, such as plastics and solvents, into the soil environment, which may either support or hinder the growth of specific microbial species. Some microbes may adapt to these pollutants, forming specialized communities that can degrade or transform these substances, but this can also lead to the accumulation of resistance genes. In addition, the increase in urban and industrialized areas fosters the spread of pathogenic microorganisms due to contaminated waste systems, wastewater, and runoff (14). These environmental stresses on soil microbial communities can have significant implications for human health, such as increased exposure to resistant pathogens or soilborne infections.

Comparative impacts of organic and conventional farming on soil microbiomes and public health

Organic and conventional farming practices have distinct impacts on soil microbial communities, which in turn influence public health outcomes. Organic farming, characterized by the use of natural fertilizers, compost, and minimal synthetic inputs, generally promotes higher microbial diversity and activity (15). This enhanced microbial richness supports beneficial functions such as nutrient cycling, pathogen suppression, and resilience to environmental stressors (16). In contrast, conventional farming, which relies heavily on synthetic fertilizers, pesticides, and monoculture cropping, has been shown to reduce microbial diversity and disrupt soil ecological balance (17). Soils under conventional farming also tend to harbor higher concentrations of antimicrobial resistance (AMR) genes, partly due to the overuse of agrochemicals and antibiotics in agriculture (18). By altering the structure and function of soil microbiota, these contrasting agricultural systems can influence the emergence and spread of soilborne pathogens and AMR, underlining the need to integrate soil health into public health frameworks (19).

Climate change and environmental stressors

Climate change is an increasingly important driver of soil microbial shifts. Rising temperatures, altered precipitation patterns, and more frequent extreme weather events can directly affect microbial populations and their functions. Temperature changes can influence microbial metabolism, growth rates, and community composition, favoring thermophilic or drought-tolerant species while potentially reducing the abundance of mesophilic organisms (20). Changes in precipitation patterns, such as prolonged droughts or heavy rainfall, can alter soil moisture, which is critical for microbial activity. Drought conditions can reduce microbial biomass, while flooding can lead to anaerobic conditions, favoring the growth of harmful bacteria such as Clostridium species or pathogens that thrive in low-oxygen environments (21). In addition to direct climate-related changes, environmental stressors such as air pollution and UV radiation can also influence soil microbial communities. For example, increased atmospheric CO2 concentrations and ground-level ozone can impact microbial processes such as nitrogen cycling and the breakdown of organic matter (22). Furthermore, shifts in microbial communities induced by climate change can exacerbate the spread of diseases, particularly in agricultural settings where soilborne pathogens may thrive under changing conditions. Understanding the impacts of climate change on soil microbial communities is essential for developing strategies to mitigate public health risks, particularly those related to infectious diseases and antimicrobial resistance. Figure 1 below highlights the key factors driving shifts in soil microbial communities: urbanization, industrial activities, agricultural practices, land use changes, and climate change. These drivers impact microbial diversity, nutrient cycling, and pathogen dynamics, influencing ecosystem health and public well-being. Urbanization causes soil contamination and compaction, while agriculture disrupts microbial balance through fertilizers and pesticides. Climate change further alters conditions, fostering pathogen growth and resistance. Understanding these drivers is essential for addressing health risks linked to antimicrobial resistance and soilborne diseases. Climate change is altering soil microbial communities, leading to increased abundance of thermophilic bacteria like Thermus and Geobacillus, which thrive in warmer soils (23). Warming also reduces the fungal-to-bacterial ratio and promotes pathogenic microbes such as Fusarium and Phytophthora, increasing disease risks (24). Moreover, heat affects nitrogen-cycling microbes like Nitrosomonas, impacting soil fertility and emissions (25). These shifts highlight the need for climate-adaptive soil management in public health planning.

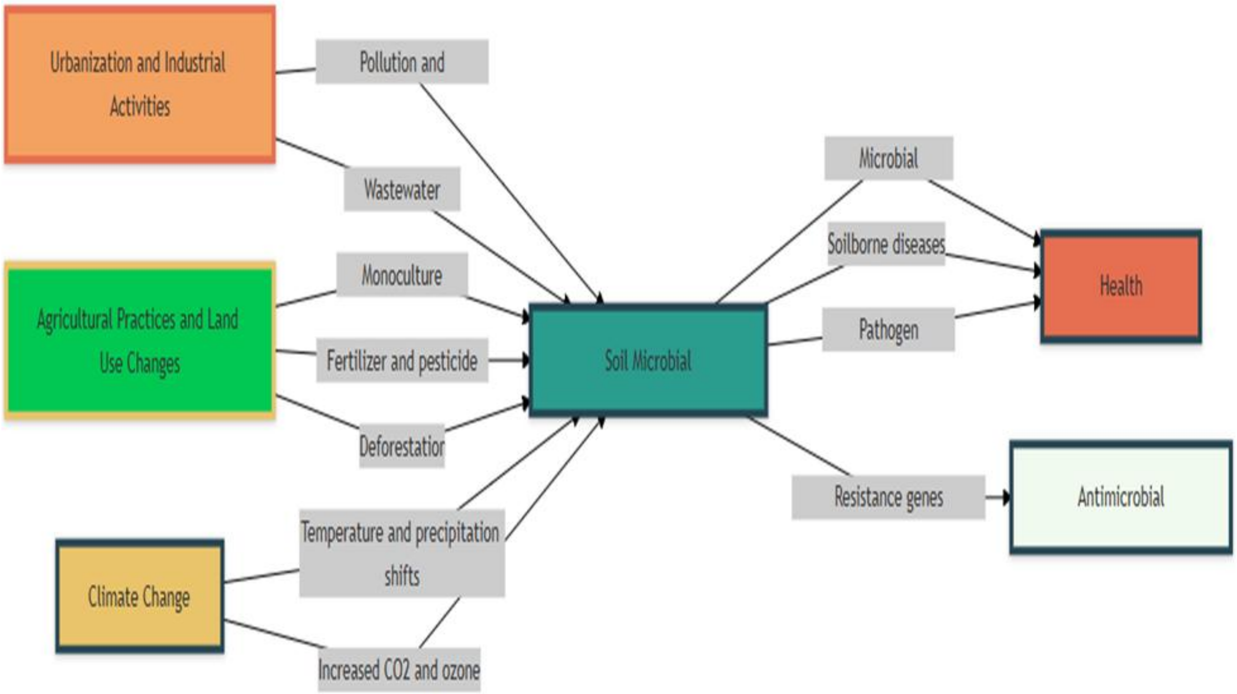

Figure 1. Drivers of Soil Microbial Shifts: A Complex Interaction Framework.

Soil Microbes as Bioindicators of Public Health Risks

Soil microbes, as integral components of the soil ecosystem, can serve as effective bioindicators of public health risks. The diversity, composition, and abundance of microbial communities in soil reflect the health of the environment and can provide valuable insights into potential health hazards. Soil microbial populations are influenced by a variety of factors, including land use, pollution, climate change, and agricultural practices, which can either promote or inhibit the growth of pathogenic organisms and antimicrobial resistance genes. By monitoring these microbial communities, scientists can assess risks to human health, including exposure to infectious diseases, antibiotic-resistant pathogens, and environmental contaminants. Therefore, soil microbes hold considerable promise as early warning systems for potential public health threats, helping to mitigate disease outbreaks and guide public health interventions.

Linking soil microbial diversity to human health outcomes

Soil microbial diversity plays a pivotal role in shaping the health of ecosystems and can directly impact human health outcomes. Diverse soil microbial communities are essential for maintaining soil fertility, plant health, and ecosystem services, which are vital for food production and human well-being (26). Changes in soil microbial diversity, often caused by anthropogenic activities such as agriculture, urbanization, or pollution, can lead to disruptions in ecosystem functioning and increase the risk of disease transmission. A decrease in microbial diversity has been linked to poorer soil health, reduced resistance to pathogens, and compromised food safety (27). Emerging research also suggests that the loss of soil microbial diversity may be associated with an increase in human health conditions such as allergies, asthma, and autoimmune diseases. Soil microbes, particularly those in agricultural and rural environments, are thought to play a protective role by helping to train the immune system and preventing overreactions to harmless substances (28). This connection, known as the "hygiene hypothesis," suggests that a loss of exposure to diverse environmental microbes, including those from soil, may contribute to the rise in chronic diseases in developed societies. Monitoring and maintaining microbial diversity in soil could, therefore, have significant implications for public health, particularly in mitigating the rising incidence of immunological disorders.

Soil microbial pathways for disease transmission

Soil microbes can serve as vectors for disease transmission, directly influencing public health through environmental exposure. Pathogenic microorganisms, including bacteria, viruses, and parasites, can survive and proliferate in soil, where they may be transferred to humans through direct contact, consumption of contaminated water or food, or through inhalation of dust particles (29). For example, Clostridium tetani, the bacterium responsible for tetanus, can persist in soil and cause infections through wounds. Similarly, soilborne pathogens such as Bacillus anthracis (anthrax) and Leptospira species (which cause leptospirosis) are capable of surviving in soil for extended periods, creating a risk for agricultural workers, veterinarians, and individuals living in affected areas (30).

In addition to direct transmission, soil microbes can play a role in the spread of waterborne diseases. For instance, fecal contamination of soil and water sources can lead to the presence of pathogenic microorganisms such as Escherichia coli, Salmonella, and Campylobacter, which are common causes of gastrointestinal infections. These pathogens can be spread through soil particles that contaminate water supplies, leading to outbreaks of waterborne diseases. In regions with inadequate sanitation and waste management infrastructure, the risk of such diseases is heightened. Therefore, understanding the soil microbial pathways for disease transmission is critical for developing effective public health strategies to reduce exposure and mitigate disease outbreaks.

Antimicrobial resistance genes in soil and public health implications

The presence of antimicrobial resistance genes (ARGs) in soil has become a significant public health concern, as these genes can be transferred between soil microorganisms and human pathogens. Agricultural practices, particularly the use of antibiotics in livestock farming, have led to the accumulation of ARGs in the soil (31). Manure and wastewater from farms often contain high concentrations of antibiotics and resistant bacteria, which can contribute to the proliferation of ARGs in the soil environment. These resistance genes can then spread to soilborne pathogens, such as Salmonella and Escherichia coli, which may eventually infect humans through contaminated food, water, or direct contact. Soil microbes act as reservoirs and vectors for the spread of ARGs, which can be transferred through horizontal gene transfer, a process in which bacteria exchange genetic material, including resistance traits (32). The presence of ARGs in soil may lead to the development of "superbugs" that are resistant to multiple classes of antibiotics, making infections more difficult to treat and increasing the burden on public health systems. Furthermore, the presence of ARGs in environmental settings, including soils, raises concerns about the spread of resistance to community-acquired infections, particularly in vulnerable populations. Given the potential for ARGs to exacerbate the global antimicrobial resistance crisis, it is crucial to monitor and mitigate the spread of resistance genes in soil ecosystems to protect both environmental and public health.

Predictive soil microbiome monitoring for disease outbreak prevention

Soil monitoring offers a practical and proactive approach to predicting and preventing disease outbreaks. By routinely analyzing soil microbial communities, particularly the presence of pathogens, antimicrobial resistance (AMR) genes, or shifts in microbial diversity, public health officials can identify early warning signals of potential health threats. For instance, detecting increased levels of Escherichia coli, Salmonella, or AMR-related genes in agricultural or urban soils may indicate a heightened risk of foodborne or waterborne disease transmission (33). Such insights enable targeted interventions, such as improved sanitation, regulation of agrochemical use, or public health advisories in high-risk zones. Integrating real-time soil biosensor data into health surveillance systems can further enhance early detection and response strategies, ultimately reducing the burden of environmentally linked diseases (34).

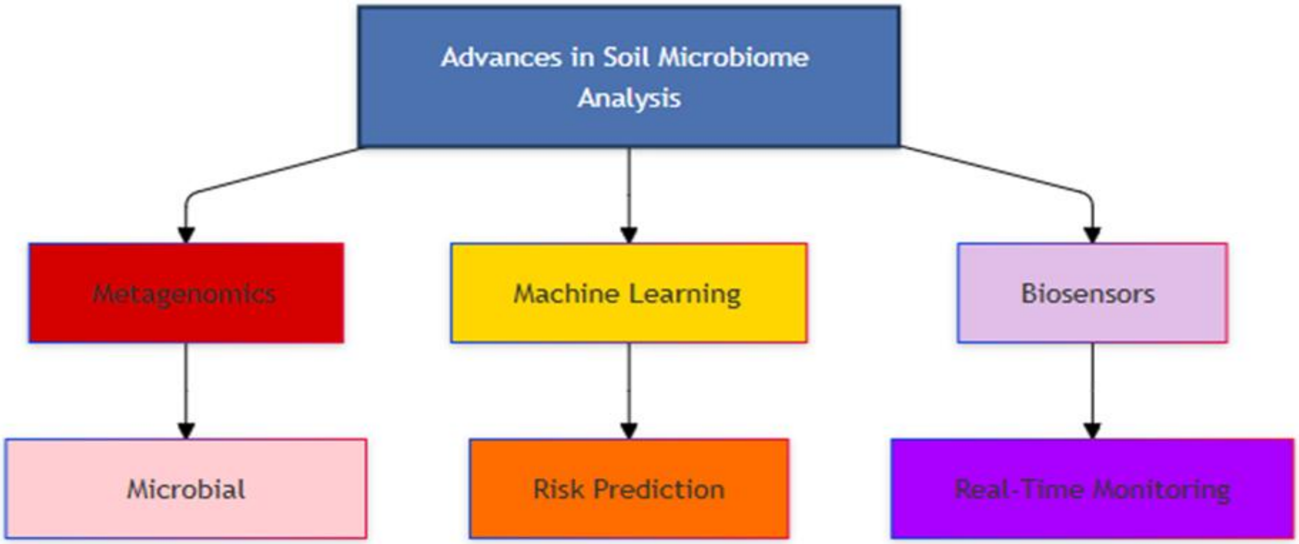

Figure 2. Advances in Soil Microbiome Analysis: Interconnected Tools and Techniques.

Advances in Soil Microbiome Analysis

Advances in soil microbiome analysis have revolutionized our understanding of microbial communities in soil and their roles in environmental and public health. Historically, studying soil microbes was limited by cultivation techniques, which only allowed for the analysis of a small fraction of microbial diversity. However, with the development of molecular techniques, including metagenomics and high-throughput sequencing, researchers can now explore the entire microbial community in soil samples without the need for culturing organisms. These technologies have led to significant breakthroughs in understanding how soil microbial communities influence soil health, disease transmission, and ecosystem functioning. Furthermore, the integration of machine learning and biosensor technologies has enhanced our ability to predict and monitor soil health in real-time, providing valuable insights for public health risk assessments. These advancements have paved the way for a more comprehensive understanding of soil microbiomes, their impact on human health, and the development of novel biotechnological solutions for monitoring and mitigating public health risks.

Metagenomics and soil microbial profiling

Metagenomics, a powerful tool for analyzing genetic material directly from environmental samples, has transformed the study of soil microbiomes. Traditional methods of microbial profiling, such as culturing and microscopy, were limited by the inability to detect unculturable microorganisms, which represent a substantial portion of the microbial community. Metagenomic sequencing bypasses these limitations by allowing for the extraction and sequencing of DNA from entire soil samples, providing a comprehensive snapshot of microbial diversity (35). This approach enables the identification of a wide range of microbial species, including bacteria, fungi, archaea, and viruses, that might play important roles in soil health and disease dynamics. Soil microbial profiling using metagenomics has provided valuable insights into the functions and dynamics of microbial communities under different environmental conditions. For instance, metagenomic analysis has revealed how soil microbiomes respond to factors such as land use change, pollution, and climate change, offering a better understanding of their role in ecosystem services, such as nutrient cycling, plant health, and disease suppression (36). Furthermore, metagenomics can be used to identify specific microorganisms associated with health risks, such as pathogens or antimicrobial-resistant bacteria, making it an essential tool for environmental epidemiology. By identifying microbial taxa and functional genes linked to disease transmission, researchers can assess public health risks more effectively and design interventions to mitigate these threats.

Machine learning in soil microbial risk prediction

Machine learning (ML) has emerged as a powerful tool for predicting soil microbial risks and understanding the complex interactions between soil microorganisms and public health outcomes. ML algorithms can analyze large and complex datasets derived from soil microbiome profiling, identifying patterns and correlations that might be difficult to detect through traditional statistical methods. By integrating metagenomic data, environmental variables (such as climate and land use), and public health data, ML models can predict the likelihood of disease outbreaks, soil contamination, or antimicrobial resistance transmission linked to soil microbial communities (37). One of the key applications of ML in soil microbiome analysis is the identification of microbial risk factors associated with disease transmission. For example, ML algorithms have been used to predict the presence of pathogenic bacteria in soil, linking microbial community changes to outbreaks of waterborne diseases or zoonotic infections. These models can also identify early warning signs of antimicrobial resistance in soil environments, helping to predict the spread of resistance genes and their potential impact on public health. By applying predictive models to large-scale soil health monitoring, researchers can identify areas at high risk for microbial contamination and recommend targeted interventions to reduce exposure.

Biosensors for real-time soil health monitoring

Biosensors have gained significant attention for their potential to provide real-time monitoring of soil health, including microbial communities and pathogens. These sensors are designed to detect specific biological or chemical markers in soil, such as microbial metabolites, toxins, or pathogens, providing immediate feedback on the condition of the soil environment. Biosensors can be deployed in the field to monitor changes in soil microbial populations or detect the presence of harmful microorganisms that may pose a risk to public health (38). Recent developments in biosensor technology have led to the creation of highly sensitive and specific devices capable of detecting microbial contaminants, including soilborne pathogens such as Salmonella, Escherichia coli, and Clostridium difficile (39). These biosensors can provide valuable data on microbial diversity, metabolic activity, and environmental stressors in real-time, facilitating rapid decision-making for land management, agricultural practices, and public health monitoring. For instance, biosensors can be used in conjunction with other tools, such as metagenomics and machine learning, to enhance the prediction and monitoring of microbial health risks in soils. By enabling continuous, on-site soil health monitoring, biosensors offer a promising approach to preventing the spread of infectious diseases, antimicrobial resistance, and other public health threats linked to soil microbes. Figure 2 below highlights the interplay between cutting-edge tools in soil microbiome research—metagenomics, machine learning, and biosensors. It showcases how these advancements collectively enhance our understanding of microbial diversity, functional gene analysis, real-time monitoring, and predictive risk assessments, fostering novel solutions for public and environmental health challenges.

Limitations of current analytical tools in soil microbiome surveillance

Despite the transformative potential of advanced analytical tools like metagenomics in studying soil microbiomes, several limitations persist. One key challenge is the inherent bias toward dominant microbial species, which can obscure the detection of rare but potentially significant taxa involved in health-related functions or pathogen emergence (40). Furthermore, metagenomic approaches often lack resolution at the strain level, making it difficult to distinguish pathogenic strains from their non-pathogenic relatives. Functional inference from metagenomic data is also limited by incomplete reference databases, which hampers accurate annotation of microbial genes and pathways (41). Furthermore, high sequencing costs and complex data analysis requirements can limit accessibility in low-resource settings, restricting widespread implementation for real-time public health surveillance.

Integrating Soil Microbiome Data into Public Health Frameworks

Integrating soil microbiome data into public health frameworks is a critical step in advancing our understanding of how soil environments affect human health. The growing recognition of soil microbes as pivotal players in ecosystem dynamics and disease transmission has spurred efforts to incorporate microbial data into public health surveillance systems. Traditional public health frameworks often overlook the influence of environmental microbiomes on human health outcomes, but emerging research is highlighting the need to broaden these frameworks to include soil health. By integrating soil microbiome data, we can better predict and mitigate potential health risks, such as the spread of zoonotic diseases, antimicrobial resistance, and foodborne illnesses, which often originate in the soil environment. The integration process involves developing cross-disciplinary models that link microbial community dynamics to health outcomes, providing valuable insights for disease prevention, early detection, and intervention. This requires collaboration between environmental scientists, epidemiologists, policymakers, and public health professionals to ensure that microbial data is effectively utilized in public health decision-making. Furthermore, it necessitates the development of standardized methods for soil sample collection, microbial analysis, and risk assessment to ensure data consistency and comparability across studies and regions (42).

Development of predictive models for health surveillance

The development of predictive models for health surveillance that incorporate soil microbiome data is an essential step toward improving public health outcomes. Predictive models leverage soil microbial data to forecast potential health risks, such as the emergence of infectious diseases, antimicrobial resistance (AMR), or the spread of soilborne pathogens. These models typically rely on machine learning algorithms and statistical tools that analyze large datasets, identifying patterns and correlations between soil microbial composition and public health data. For instance, by integrating data on soilborne pathogens and environmental conditions with public health records, researchers can predict the likelihood of disease outbreaks, identify high-risk areas, and implement timely interventions (43). Recent advances in artificial intelligence (AI) and machine learning (ML) have significantly enhanced the accuracy and predictive power of these models. For example, AI algorithms can analyze complex relationships between microbial diversity, soil conditions, and climate variables, generating forecasts that support preventive measures. Predictive models have also been used to track the spread of AMR genes in soil, providing early warning signals for potential public health threats. These models have the potential to revolutionize public health surveillance by enabling real-time monitoring of soil health and its link to disease transmission, ultimately leading to more proactive public health strategies (44).

Policy recommendations for soil health and public safety

Policy recommendations that link soil health to public safety are crucial for preventing health risks associated with soilborne pathogens, pollutants, and antimicrobial resistance. Governments and regulatory bodies need to recognize the importance of soil microbiomes in shaping human health outcomes, particularly in the context of urbanization, agriculture, and climate change. Policymakers should advocate for the incorporation of soil health assessments into national health strategies, particularly in regions where soil contamination and microbial risks are prevalent. Recommendations include the implementation of soil monitoring programs that regularly assess microbial diversity and health, as well as policies aimed at reducing soil pollution and managing land use changes. Furthermore, there is a need for regulations that control the use of antibiotics and other chemicals in agriculture, which can contribute to the development of antimicrobial resistance in soil microbial communities (45). Public health guidelines should also address the safe use of biosensors for soil microbial monitoring and the incorporation of microbiome data into health surveillance systems. For example, the establishment of soil health standards, supported by research, can guide land management practices that promote beneficial microbial communities and reduce exposure to harmful pathogens. The integration of soil microbiome data into public health policies can also help to address issues related to food security and nutrition. For instance, soil microbiomes play a critical role in enhancing crop health and productivity, which directly affects human nutrition. Policies that promote sustainable agricultural practices, such as crop rotation, organic farming, and soil conservation, can help to maintain healthy soil microbiomes and prevent diseases that may affect both crops and human populations (46).

Case studies: successful integration of soil microbial data

Several successful case studies demonstrate the potential benefits of integrating soil microbial data into public health frameworks. One such example is the use of soil microbial data to predict outbreaks of waterborne diseases. In a study conducted in rural India, researchers combined soil microbial analysis with water quality monitoring to identify the presence of pathogens such as Escherichia coli and Vibrio cholerae in soil, which was directly linked to an increase in waterborne diseases in local populations (47). By incorporating microbial data into public health surveillance, authorities were able to identify hotspots for disease transmission and implement targeted water purification efforts, ultimately reducing the incidence of cholera and other waterborne diseases. In another case, researchers in the United States investigated the role of soilborne pathogens in foodborne outbreaks, particularly those linked to produce contamination. By analyzing the soil microbiome and its connection to foodborne illness outbreaks, they were able to develop predictive models that helped identify high-risk regions and provide recommendations for safer farming practices (48). These case studies highlight the importance of integrating soil microbial data into public health frameworks to enhance early warning systems and improve public health outcomes. Moreover, the successful integration of biosensors into public health surveillance systems in European countries has enabled real-time monitoring of soil health, identifying microbial contamination, and allowing for prompt action. This integration has helped improve disease control and prevent the spread of pathogens in agricultural regions, benefiting both public health and food safety (49). These case studies underscore the importance of interdisciplinary collaboration and the potential of soil microbiome data in safeguarding public health.

Research Gaps and Future Directions

The growing recognition of soil microbiomes as crucial components of both environmental health and public health presents a wealth of opportunities for research and innovation. However, significant gaps in our understanding still exist, particularly regarding the complex relationships between soil microbial communities and human health outcomes. Addressing these gaps requires a concerted effort from researchers, policymakers, and healthcare professionals to explore uncharted territories and implement novel biotechnological tools that can aid in the study of soil microbes.

Unexplored soil microbial pathways and health risks

Although research on soil microbiomes has grown substantially, key microbial pathways linking soil ecosystems to human health remain poorly understood. Soilborne pathogens such as Salmonella, Escherichia coli, and Clostridium species are known contributors to foodborne illnesses. However, the exact routes of their persistence, mobilization, and human exposure, especially through the food chain and water systems, require deeper investigation (50). One critical but underexplored domain is the soil microbiome-gut microbiome axis. Emerging evidence suggests that frequent environmental exposure to soil microbes through ingestion of unwashed produce, physical contact with soil during childhood, or inhalation of dust can influence the composition and function of the human gut microbiome (51). This interface may modulate immune system development, allergic responses, and even neuroinflammatory pathways. These findings indicate a vital role for environmental microbes in shaping human health and disease susceptibility.

In addition, chronic exposure to soil pollutants and pathogens may contribute to the development of non-communicable diseases such as certain cancers, autoimmune disorders, or cardiovascular conditions. While these associations remain speculative, limited mechanistic evidence points to a need for further exploration. Another pressing knowledge gap involves the poorly defined pathways through which soil microbiomes facilitate the spread of antimicrobial resistance (AMR). Although it is well established that soil acts as a major reservoir for resistance genes, the specific transmission routes into clinical and community settings, whether through crops, water, or livestock, are not fully delineated (52). Addressing these gaps requires interdisciplinary research that integrates metagenomics, exposomics, and longitudinal human microbiome studies to trace microbial pathways from the environment to human hosts. Advancing our understanding of these mechanisms is essential for designing public health interventions that consider environmental microbial exposures.

Advancing biotechnological tools for soil microbial studies

Advancements in biotechnological tools offer the potential to significantly improve our ability to study and monitor soil microbiomes. While traditional culture-based methods of soil microbial analysis have provided foundational insights, these techniques are often limited in their ability to detect and characterize the full spectrum of microbial life present in the soil. Recent breakthroughs in metagenomics, which allow for the comprehensive sequencing of all microbial DNA in a given sample, have opened up new avenues for soil microbiome research (53). However, challenges remain in refining these technologies to allow for more precise identification of microorganisms and their functional roles within complex soil ecosystems. One promising avenue for future research is the development of biosensors for real-time monitoring of soil microbial health. These devices would enable the rapid detection of pathogens, AMR genes, or other health-related markers in the soil, facilitating early warning systems and more effective public health responses (53). The integration of machine learning algorithms with metagenomic and biosensor data could further enhance the predictive capacity of these tools, enabling more accurate assessments of microbial risks associated with soil contamination and environmental change. Moreover, the application of CRISPR-based gene editing techniques could play a significant role in understanding soil microbial function and disease transmission. By targeting specific genes in soil microbes, researchers could study microbial behavior and interactions in unprecedented detail. This technology could also help develop strategies for mitigating harmful microbial activity in the soil, such as reducing the presence of pathogenic organisms or limiting the spread of AMR genes (54).

Advanced tools such as metagenomics offer powerful insights into soil microbial communities, yet their widespread adoption is limited by significant cost and accessibility barriers, particularly in low-resource settings. High-throughput sequencing platforms, bioinformatics infrastructure, and skilled personnel are often lacking in many developing regions, restricting local researchers' ability to conduct in-depth soil microbiome studies. Furthermore, the costs of reagents, data storage, and computational tools further limit routine surveillance or integration into public health programs. These disparities highlight the need for more affordable, scalable technologies and capacity-building initiatives to ensure equitable access to cutting-edge microbial analysis (55).

Bridging soil health and global public health goals

As the world grapples with issues like climate change, urbanization, and the increasing burden of infectious diseases, there is an urgent need to bridge soil health with global public health goals. Soil health, often overlooked in global health frameworks, plays a crucial role in food security, water safety, and disease prevention. There is a growing recognition that sustainable soil management practices can contribute to broader global health objectives, including the United Nations Sustainable Development Goals (SDGs), such as Zero Hunger (SDG 2), Clean Water and Sanitation (SDG 6), and Good Health and Well-Being (SDG 3). Integrating soil health into global public health initiatives requires a holistic approach that recognizes the interdependence between soil ecosystems and human health. This involves interdisciplinary collaboration between environmental scientists, public health professionals, and policymakers to develop integrated strategies for improving both soil health and human well-being. For instance, sustainable agricultural practices that promote soil biodiversity could reduce the risk of soilborne diseases and enhance food security, while also supporting the health of nearby communities by preventing contamination of water supplies (56). Moreover, there is a need to advocate for soil health policies that account for both ecological and public health outcomes. This includes developing regulations that mitigate the effects of industrial activities, urbanization, and intensive farming practices that degrade soil health. Public health strategies must also incorporate soil microbiome monitoring as part of their surveillance systems, ensuring that soil-related risks are considered in disease prevention and control programs (57). Future research should focus on building a strong evidence base linking soil microbial health to public health outcomes. This evidence could drive the adoption of policies that integrate soil microbiome management into global health frameworks, ensuring a more sustainable and health-focused approach to land use and environmental stewardship.

Conclusion

The study highlights the dual role of soil microbial communities in both ecosystem and human health. While soil microbes support soil fertility and plant health, they also act as reservoirs for pathogens and antimicrobial resistance (AMR) genes, which can directly impact human health. Environmental changes such as urbanization, agricultural practices, and climate change are shifting soil microbial composition, potentially escalating public health risks. The application of advanced technologies, including metagenomics and biosensors, offers valuable tools for monitoring these microbial risks, although challenges persist in understanding the complexities of microbial pathways and their links to human diseases. The research reveals a correlation between soil microbial diversity and human health outcomes, positioning soil microbiomes as potential bioindicators of public health risks. However, significant knowledge gaps remain, particularly concerning the long-term health effects of exposure to soilborne pathogens and the mechanisms by which soil microbes influence chronic diseases. The study calls for more targeted research and the integration of soil health monitoring into public health strategies. The findings emphasize the importance of the soil microbiome in environmental epidemiology, urging a paradigm shift in how environmental factors are considered in public health research. Soil microbes have the potential to act as early warning systems for emerging health threats, suggesting that environmental health surveillance systems should include soil health data. Incorporating soil microbiome monitoring into public health frameworks can provide insights into the prevention of infectious diseases, chronic conditions, and the spread of AMR. Integrating soil microbial data into epidemiological models can improve understanding of how environmental factors, such as soil quality, influence human health. To address the identified research gaps, interdisciplinary collaboration among environmental scientists, microbiologists, public health experts, epidemiologists, and policymakers is crucial. Investment in advanced biotechnological tools, such as metagenomic sequencing, biosensors, and machine learning models, is essential to improve soil health monitoring. Public health policies must also evolve to incorporate soil health as a key determinant of well-being, ensuring comprehensive strategies to mitigate soil contamination, reduce AMR, and protect public health from environmental threats.

Contribution of authors

- Fiddausi Umar Musa conceptualized the study, particularly focusing on the integration of soil microbiome data into public health frameworks. She contributed significantly to drafting and revising sections on soil microbes as bioindicators of public health risks and future research directions.
- Tijani Abiola Tajudeen analyzed the impact of urbanization, industrial activities, and land use changes on soil microbial communities. He provided insights into the drivers of microbial shifts and their implications for public health.
- Olaitan Lateefat Salam reviewed advancements in molecular tools such as metagenomics for soil microbial profiling. She contributed to the discussion on the role of microbial diversity in ecosystem health and disease transmission.
- Idowu Afeez Temitope focused on the link between antimicrobial resistance genes in soil and public health risks. He contributed to the development of case studies demonstrating the integration of soil microbiome data into health surveillance frameworks.
- Miracle Uwa Livinus explored the beneficial roles of soil microorganisms and their pathways for disease suppression. She provided insights into the potential of soil microbiomes to serve as indicators of ecosystem health.
- Abdulhakeem Idris Abdulhakeem contributed to the analysis of climate change and environmental stressors affecting soil microbial diversity. He emphasized their effects on pathogen dynamics and disease risks.
- Ishola Jonathan Adekunle evaluated policy recommendations for enhancing soil health and mitigating public health risks. He provided critical feedback on integrating microbial data into health policies.
- Musa Ojeba Innocent reviewed advancements in predictive modeling and machine learning for soil microbial risk prediction. He provided key inputs on integrating multi-omics data into public health research.
- Mustapha Abdulsalam addressed challenges in soil microbiome research, particularly in data limitations and model scalability. He contributed to sections on research gaps, future directions, and biotechnological advancements for soil microbial studies.

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Conflict of Interest

The authors declared no conflict of interest in the manuscript.

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References

1. Cook MA, Wright GD. The past, present, and future of antibiotics. Sci Transl Med. 2022;14(657):eabo7793.
2. Gao FZ, He LY, Chen X, Chen JL, Yi X, He LX, Ying GG. Swine farm groundwater is a hidden hotspot for antibiotic-resistant pathogenic Acinetobacter. ISME Commun. 2023;3(1):34.
3. Jamshed A, Birkmann J, Rana IA, McMillan JM. The relevance of city size to the vulnerability of surrounding rural areas: An empirical study of flooding in Pakistan. Int J Disaster Risk Reduct. 2020;48:101601.
4. Tong DQ, Gill TE, Sprigg WA, Van Pelt RS, Baklanov AA, Barker BM, Vimic AV. Health and safety effects of airborne soil dust in the Americas and beyond. Rev Geophys. 2023;61(2):e2021RG000763.
5. Wu J, Wang J, Li Z, Guo S, Li K, Xu P, Zou J. Antibiotics and antibiotic resistance genes

in agricultural soils: A systematic analysis. Crit Rev Environ Sci Technol. 2023;53(7):847–64.

6. Innocent MO, Mustapha A, Abdulsalam M, Livinus MU, Samuel JO, Elelu SA, Muhammad AS. Soil microbes and soil contamination. In: Soil Microbiome in Green Technology Sustainability. Cham: Springer Nature Switzerland; 2024. p. 3–35.
7. Aasfar A, Bargaz A, Yaakoubi K, Hilali A, Bennis I, Zeroual Y, Meftah Kadmiri I. Nitrogen-fixing Azotobacter species as potential soil biological enhancers for crop nutrition and yield stability. Front Microbiol. 2021;12:628379.
8. Timsina J. Can organic sources of nutrients increase crop yields to meet global food demand? Agronomy. 2018;8(10):214.
9. Bottalico L, Charitos IA, Potenza MA, Montagnani M, Santacroce L. The war against bacteria, from the past to present and beyond. Expert Rev Anti Infect Ther. 2022;20(5):681–706.
10. Samaddar S, Karp DS, Schmidt R, Devarajan N, McGarvey JA, Pires AF, Scow K. Role of soil in the regulation of human and plant pathogens: Soils' contributions to people. Philos Trans R Soc Lond B Biol Sci. 2021;376(1834):20200179.
11. Abdulsalam M, Musa IO, Livinus MU, Elelu SA, Ibrahim GO, Salami OL, Pal SK. Blue bioeconomy and biomedical innovation. In: Marine Bioprospecting for Sustainable Blue-Bioeconomy. Cham: Springer Nature Switzerland; 2024. p. 143–57.
12. Sandil S, Kumar R. Soil contamination from construction projects. In: Ecological and Health Effects of Building Materials. Amsterdam: Elsevier; 2022. p. 205–44.
13. Raza T, Qadir MF, Khan KS, Eash NS, Yousuf M, Chatterjee S, Oetting JN. Unrevealing the potential of microbes in the decomposition of organic matter and the release of carbon in the ecosystem. J Environ Manage. 2023;344:118529.
14. Onyedikachi UB, Mukah FE. Water contamination by industrial processes and sustainable management strategies. In: Water Crises and Sustainable Management in the Global South. Singapore: Springer Nature Singapore; 2024. p. 181–210.
15. Abdulsalam M. Exploring the therapeutic promise of cationic antibacterial peptides. Biol Sci. 2024;4(3):692–700.
16. Tripathi S, Srivastava P, Devi RS, Bhadouria R. Influence of synthetic fertilizers and pesticides on soil health and soil microbiology. In: Agrochemicals Detection, Treatment and Remediation. Oxford: Butterworth-Heinemann; 2020. p. 25–54.
17. Musa IO, Samuel JO, Adams M, Abdulsalam M, Nathaniel V, Maude AM, Tiamiyu AGT. Soil erosion, mineral depletion and regeneration. In: Prospects for Soil Regeneration and Its Impact on Environmental Protection. Cham: Springer Nature Switzerland; 2024. p. 159–72.
18. Gwadabe HA, Elelu SA, Innocent MO, Ibrahim GO, Adekunle IJ, Abdulsalam M. Exploring local-to-global win-win strategies for infectious disease control: Enhancing human health and sustainability. Biol Sci. 2025;5(1):850–64.
19. Abdulsalam M, Innocent MO, Livinus MU, Danjuma FA, Temitope IA, Adekunle IJ. Hydroxychloroquine and azithromycin in treating emerging viral infections: Efficacy, safety, and mechanisms in monkeypox and influenza A (H5N1). Biol Sci. 2025;5(1):865–77.
20. Etesami H. Enhancing soil microbiome resilience: The mitigating role of silicon against environmental stresses. Front Agron. 2024;6:1465165.
21. Abdulsalam M, Fari HI, Tiamiyu BB, O LS. Optimizing α-amylase production from locally isolated Aspergillus sp. using selected agro waste as substrate. Biosci Biotechnol Res Commun. 2022;15(3):424–30.
22. Wang Q, Wang D, Agathokleous E, Cheng C, Shang B, Feng Z. Soil microbial community involved in nitrogen cycling in rice fields treated with antiozonant under ambient ozone. Appl Environ Microbiol. 2023;89(4):e00180-23.
23. Abdulsalam M, Innocent MO, Livinus MU, Abdulhakeem AI, Danjuma FA, Khadijah A, Adekunle IJ. Community health and vulnerability. In: The Interplay of Pesticides and Climate Change: Environmental Dynamics and Challenges. Cham: Springer Nature Switzerland; 2025. p. 443–67.
24. Livinus MU, Bala SZ, Abdulsalam M, Innocent MO, Hassan M, Yusuf K, Ali GM. Activities, pollution and climate change. Wetl Ecosyst Conserv Strateg Policy Manag Appl. 2025;12:107.
25. Bala A, Elelu SA, Ibrahim GO, Temitope IA, Livinus MU, Yasir AM, Abdulsalam M. Peptide-based approaches for biomolecule encapsulation, storage, and preservation: A comprehensive review. Biol Sci. 2025;5(2):916–31.
26. Tiamiyu BB, Lateef AA, Ajadi I, Adeyemi SB, Owolabi PO, Sagaya Q, Abdulsalam M, Mustapha OT. Bioclimatic modeling of current geographic distribution and future range shifts of selected edible mushrooms in Nigeria. Sahel J Life Sci FUDMA. 2024;2(1):51–61.
27. Musa IO, Samuel JO, Adams M, Abdulsalam

M, Abdulazeez M, Muhammad MS, Akande SA. Natural contaminant of infant food: Case study. In: Emerging Contaminants in Food and Food Products. Boca Raton: CRC Press; 2024. p. 151–61.

28. Livinus MU, Bala SZ, Abdulsalam M, Innocent MO, Hassan M, Kini P. Natural occurrences of soil dilapidation. In: Prospects for Soil Regeneration and Its Impact on Environmental Protection. Cham: Springer Nature Switzerland; 2024. p. 205–23.
29. Zuri G, Karanasiou A, Lacorte S. Microplastics: Human exposure assessment through air, water, and food. Environ Int. 2023;179:108150.
30. Musa IO, Isibor PO, Samuel JO, Mustapha A, Mustapha A, Akande S, Adeniji H. Introduction to nanotoxicology. In: Environmental Nanotoxicology: Combatting the Minute Contaminants. Cham: Springer Nature Switzerland; 2024. p. 1–22.
31. Abdulsalam M, Tiamiyu BB, Abdulrazaq I, Salam OL. Comparative antimicrobial properties of a consortium of Nauclea latifolia Sm. and Ocimum gratissimum L. extracts with their CuO nanoparticle multiplexes. Biol Sci. 2023;3(1):386–93.
32. Arnold BJ, Huang IT, Hanage WP. Horizontal gene transfer and adaptive evolution in bacteria. Nat Rev Microbiol. 2022;20(4):206–18.
33. Abdullah AA, Elelu SA, Innocent MO, Ibrahim GO, Tajudeen TA, Abdulrasheed U, Abdulsalam M. Advances in mushroom chitosan biorefinery and its applications in food engineering: A sustainable approach to food preservation and quality enhancement. Biol Sci. 2025;5(1):837–49.
34. Ahmed AA, Yusuf UA, Fadlallah ZH, Innocent MO, Abdulsalam M. Developing an omics-driven computational framework for next-generation microbiome therapeutics. Biol Sci. 2024;4(4):810–21.
35. Abdulsalam M, Salihu AT, Usman HY, Usman MY. Protein biosynthesis in microorganisms: Mechanisms, regulation, and biotechnological applications. World J Adv Res Rev. 2024;21(1):869–81.
36. Abdulsalam M, Fatima ZYU, Hasiya UA, Ummulkhuthum AT, Aisha WN, Muhammad FY. Deciphering the genetic code: Mechanisms, evolution, and implications for biotechnology. World J Adv Res Rev. 2024;21(1):858–68.
37. Saheed YK, Balogun BF, Odunayo BJ, Abdulsalam M. Microarray gene expression data classification via Wilcoxon sign rank sum and novel Grey Wolf optimized ensemble-learning models. IEEE/ACM Trans Comput Biol Bioinform. 2023;20(6):3575–87.
38. Livinus MU, Bala SZ, Abdulsalam M, Innocent MO, Hassan M, Elelu SA, Kini P. Role of microbes in soil food webs and vegetation development. In: Soil Microbiome in Green Technology Sustainability. Cham: Springer Nature Switzerland; 2024. p. 107–32.
39. Wang H, Huang J, Jiang X. Perspectives on using a competitive exclusion approach to control Listeria monocytogenes in biological soil amendments of animal origin (BSAAO): A review. Appl Microbiol. 2023;3(3):786–804.
40. Saheed YK, Abdulganiyu OH, Abdulsalam M, Mustapha M, Olivier MM, Majikumna KU. A hybrid ant colony optimization for Parkinson’s disease classification based on synthetic minority oversampling and adaptive synthetic techniques. In: 2024 5th International Conference on Data Analytics for Business and Industry (ICDABI). IEEE; 2024. p. 16–23.
41. Muhammad FA, Elelu SA, Ibrahim GO, Temitope IA, Livinus MU, Avoswahi AH, Abdulsalam M. Artificial intelligence meets vascular health: Identifying molecules for precision repair of barrier dysfunctions. Biol Sci. 2025;5(2):932–46.
42. Durlik I, Miller T, Kostecka E, Tuński T. Artificial intelligence in maritime transportation: A comprehensive review of safety and risk management applications. Appl Sci. 2024;14(18):8420.
43. Saheed YK, Salau-Ibrahim TT, Abdulsalam M, Adeniji IA, Balogun BF. Modified bi-directional long short-term memory and hyperparameter tuning of supervised machine learning models for cardiovascular heart disease prediction in the mobile cloud environment. Biomed Signal Process Control. 2024;94:106319.
44. Musa IO, Ijah UJJ, Abioye OP, Abdulsalam M, Pal SK, Abamhekhelu IA, Akande SA. Phytoremediation of heavy metal-contaminated soil. In: Eco-Restoration of Polluted Environment. Boca Raton: CRC Press; 2024. p. 35–52.
45. Abdulsalam M, Hamisu AA, Ahmad AM, Wakili FB, Annu FS, Garba MM. Microbiome dynamics and strategic management strategies: Exploring synergies between integrative medicine modalities and microbial balance. Biol Sci. 2024;4(3):725–35.
46. Livinus MU, Bala SZ, Abdulsalam M, Musa IO, Hassan M, Kini P. Marine genetic resources of blue economy. In: Marine Bioprospecting for Sustainable Blue-Bioeconomy. Cham: Springer Nature

Switzerland; 2024. p. 159–80.

47. Tulchinsky TH. John Snow, cholera, the Broad Street pump; waterborne diseases then and now. In: Case Studies in Public Health. 2018. p. 77.
48. SS VC, Hareendran A, Albaaji GF. Precision farming for sustainability: An agricultural intelligence model. Comput Electron Agric. 2024;226:109386.
49. Ristaino JB, Anderson PK, Bebber DP, Brauman KA, Cunniffe NJ, Fedoroff NV, et al. The persistent threat of emerging plant disease pandemics to global food security. Proc Natl Acad Sci USA. 2021;118(23):e2022239118.
50. Flandroy L, Poutahidis T, Berg G, Clarke G, Dao MC, Decaestecker E, Rook G. The impact of human activities and lifestyles on the interlinked microbiota and health of humans and ecosystems. Sci Total Environ. 2018;627:1018–30.
51. Abdulsalam M, Innocent MO, Livinus MU, Elelu SA, Ibrahim GO, Lateefat SO, Muhammad AS. Future research of soil microbiomes and green technology innovation for a better tomorrow. In: Soil Microbiome in Green Technology Sustainability. Cham: Springer Nature Switzerland; 2024. p. 569–85.
52. Mijač S, Banić I, Genc AM, Lipej M, Turkalj M. The effects of environmental exposure on epigenetic modifications in allergic diseases. Medicina. 2024;60(1):110.
53. Rajguru B, Shri M, Bhatt VD. Exploring microbial diversity in the rhizosphere: A comprehensive review of metagenomic approaches and their applications. 3 Biotech. 2024;14(10):224.
54. Singh S, Sharma P, Pal N, Sarma DK, Tiwari R, Kumar M. Holistic One Health surveillance framework: Synergizing environmental, animal, and human determinants for enhanced infectious disease management. ACS Infect Dis. 2024;10(3):808–26.
55. Lawal TO, Abdulsalam M, Aliyu M, Sundararajan S. Economic and environmental implications of sustainable agricultural practices in arid regions: A cross-disciplinary analysis of plant science, management, and economics. Int J Membr Sci. 2023;10(3):3100–14.
56. Abdulsalam M, Elelu SA, Innocent MO, Ibrahim GO, Livinus MU, Lateefat SO, Muhammad AS. Women empowerment in environmental conservation. In: Prospects for Soil Regeneration and Its Impact on Environmental Protection. Cham: Springer Nature Switzerland; 2024. p. 351–70.
57. Muhammed A, Aminu BM, Musa IO, Abdulsalam M, Isma’il R, Gimba YM, Moses EO. Blue economy in Nigeria and the African continent. In: Marine Bioprospecting for Sustainable Blue-Bioeconomy. Cham: Springer Nature Switzerland; 2024. p. 355–70.