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Environmental Microbiomes and Health: A Narrative Review

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ABSTRACT

Environmental microbiomes are integral to ecosystem stability and human health, shaping immune development, disease resistance, and mental well-being. Microbial communities in soil, water, and air influence not only ecological processes such as nutrient cycling, carbon sequestration, and agricultural productivity but also human-associated microbiomes through direct and indirect exposure. Rapid urbanization, pollution, land-use changes, and climate change have disrupted microbial diversity, leading to increased risks of chronic inflammatory and infectious diseases. Soil microbiomes underpin crop yield and sustainable farming, while aquatic microbiomes regulate biogeochemical cycles and drinking water quality. The aerobiome remains less understood, though it significantly affects respiratory health. Urban microbiomes, often less diverse than rural counterparts, demonstrate homogenization linked to human activity. Technological advances in metagenomics, bioinformatics, and next-generation sequencing have accelerated our understanding of microbiome composition and function, but challenges persist in data interpretation, ethical considerations, and translation into policy. Conservation of microbial biodiversity and sustainable land-use practices are vital to preserving ecosystem services and preventing disease. This review synthesizes current evidence on environmental microbiomes, highlighting their role in health, ecosystem function, and future opportunities for research, conservation, and policy development.

Keywords: Environmental microbiomes, Human health, Biodiversity, Sustainable agriculture and Climate change.

INTRODUCTION

Environmental microbiomes strongly influence human immune function and affect a wide variety of diseases such as asthma, cancer and diabetes [1]. Since microbiomes have evolved over long timespans in constant association with the biosphere, numerous health mechanisms demand interactions between human biology and external microbiomes that become disrupted when human activities modify natural ecosystems and alter microbial community composition. Even in industrialized societies, humans typically still contact the outdoor environment directly or indirectly via urban green spaces that may act as reservoirs containing environmental microbiomes with the potential of modulating human-associated microbial communities, therefore promoting health. Urbanization causes reductions in both soil biodiversity and a generic microbiome composition associated with the Great Acceleration around the mid-20th century and has clear immediate consequences on ecological processes that support crop yield, and the overall construction of sustainable agricultural practices likely necessitates a thorough understanding of how environmental conditions affect microbial community organization. Metagenomics, bioinformatics tools and next-generation sequencing remain essential to knowledge advances throughout microbiome research for both basic and applied perspectives. Environmental microbiomes in soil, water and airborne can influence the health and wellbeing of people living in cities and, open areas. Perhaps the most studied environmental microbiomes are those associated with soil and their interaction with plants and crops; in particular, airborne microbiomes are less understood. As air masses move around and the "aerobiome" contains a mix of different potential sources such as soil, water bodies, vegetation and animals, temporal and spatial turnover is often subject to more rapid changes compared to soil or water. Other factors such as pollution and land use changes associated with urbanization further affect all microbiomes since chemical pollutants as well as physical disturbance may strongly modify the environmental characteristics that support specific microbiomes and their functions.

Understanding Microbiomes

The large variety of microbes found on the Earth's landforms, water, and atmosphere occupy specialized environmental niches and the habitats they occupy remain to be fully catalogued. This geographic environment–microbial–health axis, a further dimension along which the Earth's microbiota might be exploited safely, remains to be mapped. The concepts of microbiota and microbiome are now familiar [2]. Animals and plants harbour diverse microbial communities that provide specific functions and traits to their hosts. These communities are referred to as microbiota when the discussion concerns these ecological communities within a defined environment or microbiome when it concerns the collective genomes of the micro-organisms that the communities harbour. Different types of microbiomes can be identified [2]. These include those of vertebrate bodies, of naturally occurring environments such as soils and waters, and environments impacted by human activities such as agro-ecosystems and industrialized waters, or indoor and outdoor urban atmospheres. dRNA-phage-like replicons have much potential for new viral discovery and a widespread ability to infect a broad range of host bacteria[2].

Definition of Microbiomes

Microbial communities exist in every habitat on Earth, from deep-sea sediments to soil, rock, oceans, rivers, lakes, glaciers and air. A microbiota refers to the ecological community of symbiotic, commensal and pathogenic microorganisms that share our body space, as well as habitats in the wider environment, including soil, water and the atmosphere. Similarly, the term microbiome is applied not only to the collective genomes of our microbial symbionts but also to those of communities present in the wider environment [2]. Microbiomes show a wide diversity related to the characteristics of the environment; some common types include the soil microbiome, the marine microbiome, the airway microbiome and the urban microbiome. Urban and rural communities tend to host distinct bacteria that differ in structure and function. Low diversity urban communities demonstrate a homogenisation pattern with enhanced abundance of taxa associated with human activity, while high diversity rural communities are dominated by taxa associated with natural environmental sources and have similar community structure [2].

Types of Microbiomes

The microbiomes associated with microbial ecosystems have been categorized into several groups. Human microbiomes refer to the community of microbes that develop in and on the human body. Environmental microbiomes encompass microbial communities found in natural habitats such as soil, water, and air, collectively termed the environmental microbiome [1]. Similarly, built microbiomes are those within enclosed environments like homes, offices, public transportation systems, and hospitals. These divisions acknowledge the habitat specificity of microbial communities and provide a framework for studying their ecological roles and interactions with humans [2].

Microbiome Diversity

Microbiome diversity is a significant property of the microbiome in hosting ecosystems [1]. The diversity of the microbiome is highly influenced by the host's life activities, such as social interaction or metabolic, as well as by environmental conditions. Exploring the diversity of the human gut microbiome is important for understanding its diversity, and by understanding the genus of the human gut microbiome, knowledge of health and disease can be better attained. Scientists are studying the microbiome that populates the soil, the planet's open ocean, its rivers and lakes, and the polar ice caps. Scientists are mapping the human population of bacteria, viruses, protozoa, fungi, helminths, and mites on the skin, in the oral cavity, in the intestinal tract, in the respiratory tract, and on the urogenital tract [1, 2]. This enormous biodiversity constitutes the world's microbiome, which is currently undergoing extensive disturbance due to human alteration of environments. Relevant questions emerging include: How is this alteration affecting the planet's ecosystem services? How is it affecting the formation and spread of human, domestic animal, and wildlife pathogens? How is it affecting the development of the human immune system?

Environmental Microbiomes

Each unit of soil hosts millions of bacterial and fungal operational taxonomic units (OTUs) [1]. A similar scenario is also observed in water and air. Ocean water from any location, and irrespective of the depth, house roughly 20,000 bacterial and archaeal species. Coastal seawater microbial ecology is known to change markedly with distance from the land both for micro- and macro-organisms due to the terrestrial input of nutrients as well as microorganisms. Terrestrial streams flowing into oceans can carry a large and diverse proportion of terrestrial microbes and the impact of microorganisms can be genome-different at the regional scale. Urbanized areas feature a mix of environmental and human-associated organisms [1]. Indoor and outdoor air feature large concentrations of bacteria and fungi of environmental origin, and urbanization clearly alters the microbiota of airborne dust. In all three environmental matrices, urbanization tends to reduce microbial diversity and increases in the relative abundance of potential harmful microbial agents [1].

Soil Microbiomes

Soil microbiomes encompass the complete spectrum of microorganisms dwelling within soil habitats, including rhizosphere microbes encompassing bacteria, archaea, fungi, protists, and microfauna, as well as ecologically linked nonliving soil constituents [1]. Characterized by immense diversity, soil microbial communities vary from deeply isolated cave sediments with a singular microbial taxon to organic cranberry bogs harboring in excess of 30,000 taxa. In surface soils, approximately 10^9 bacterial and archaeal cells occupy each gram of dry material. Soil microbiomes play indispensable roles in global biogeochemical cycles and human well-being, collegially supporting agricultural productivity, pollutant degradation, and the provision of diverse ecosystem services [1]. Urban soils frequently experience truncation depletion of soil organic matter, diminished pore connectivity, loss of beneficial fungal symbionts, and associated microbial impoverishment leading to compromised ecosystem services. Such degradation is further aggravated by contamination and physical disturbance. Soil microbes simultaneously influence food, water, and air quality; fungi, as primary regulators of soil aggregation, control aerosolisation pathways, thereby mediating distribution of soil particles and associated microorganisms [3]. While pathogenic entities exist, the majority of soil microorganisms is nonpathogenic and may underpin human health through environmental exposure, particularly during early life stages contributing to immune system development and long-term immunoregulatory balance [1].

Water Microbiomes

Water microbiomes, diverse communities of microorganisms residing in aquatic environments, perform essential roles in regulating global element cycles, decomposing complex molecules, detoxifying hazardous substances, and providing nutrients [4]. Analysis of drinking water systems employing metagenomics has revealed complex bacterial communities influenced by temperature, stagnation, hydraulic conditions, and source water. These studies demonstrate microbial taxonomic shifts, biofilm structure alterations, and functional changes affecting water quality and ecosystem health. Combined metagenomics and bioinformatics approaches further detect differences in taxonomic and functional compositions of bottled waters [5]. Through interconnected biogeochemical cycles, water microbiomes contribute to the resilience, productivity, and service provision of aquatic ecosystems.

Air Microbiomes

Airborne microorganisms inhabit virtually every ecosystem on the planet and are deposited by gravity or precipitation on surfaces and plants they encounter. Their deposition varies according to particles carried on the air, wind velocity, terrain features, and the microbial community en route [6]. Technological advancements enable assessment of the structure, diversity, and function of the entire airborne microbial community at unprecedented resolution, enabling determination of the flux of microorganisms from industrial, transport, and surrounding land-use sources into urban air [6]. Innovative approaches are used to characterize airborne microbial communities inside and outside of the built environment, yielding insights into the interactions between humans, biodiverse environments, and the urban/industrial matrix ultimately governing human health and well-being. The atmosphere above the terrestrial surface contains enormous numbers of bacteria [6]. These microbes are often primary colonizers of volcanic ash and dust deposition and play an important role in reestablishing forest function after disturbance. Internal exposure to bacteria via inhalation must be considered in assessing the potential health threat of aerosolized biological agents. The healthy airway possesses a core microbial community dominated by Prevotella, Streptococcus, Veillonella, Corynebacterium, Haemophilus, Neisseria, and Actinobacteria [7]. This terminology encompasses the genetic material within an environmental niche.

Urban vs. Rural Microbiomes

The urban microbiome is a complex network of organisms that includes bacteria, viruses, and fungi, encompassing both life forms and their invaded surfaces. These microbiotic networks contain a distinct, large, yet diverse community of genes labeled as the urban metagenome. The metagenomics of built environments such as subways and hospitals are of great interest and significance due to the underside of infectious disease and the health management of citizens in their urban life. The characteristics of urban microbiomes, particularly the influences of cities on the composition of these metagenomic communities, have not been elucidated [6]. Microbes are abundant in the environment and capable of adapting to a wide range of habitats. Among them, certain species have adapted to live in urban ecosystems, which are habitat islands created by the human species. Urban areas influence the surrounding ecosystem in ways that affect animals, plants, and humans. Animals living in cities, such as pigeons and brown rats, exhibit physiological and behavioral adaptations that enable them to survive. Although the number and diversity of animals is usually lower in cities than in adjacent rural areas, certain pathogens can reach their highest prevalence in the urban environment. Thus, urbanization influences the ecology of microbes and the maintenance of pathogens in their differentiated environments of transmission [6, 7].

Human Health and Microbiomes

Environmental microbiomes influence human health by modulating immune function and contributing to the regulation of immune memory, which in turn protects against infections and chronic inflammatory diseases [1]. For instance, airborne microbes derived from soil and vegetation may benefit the lung microbiome and expose epithelial cells to microbial components and volatile organic compounds that enhance host resistance to respiratory infections [1]. By analogy, physiological exposure to environmental microbiomes may support immune regulation and contribute to mental health. Given the remote but growing literature on the role of environmental microbiomes in shaping lung and gut microbiomes, standard protocols for characterising environmental microbiomes should be established quickly, particularly because such environmental pathogens as Legionella or Mycobacterium are likely to induce public anxiety and hinder the acceptance of this approach [1, 6].

Impact on Immune System

Environmental microbiomes from air, drinking water, and soil have various impacts on human health. The immune system is regulated by microbial biodiversity in environmental reservoirs. The natural environment contains complex microbial populations, and humans are exposed to environmental microbiomes through drinking water, inhalation, and skin contact. These microbial assemblages inhabit soil, water, and the atmosphere, all of which can impact human health [8]. Increased exposure to biodiversity in its natural state may enhance immunoregulation and reduce the incidence of allergic and chronic inflammatory disorders. Complex interactions among the host, microbiotas, and environmental factors continuously influence the composition and function of the microbiome. Human microbiomes appear adapted to support health within the context of their natural environments [9].

Role in Disease Prevention

The functions of environmental microbiomes related to disease prevention have attracted widespread interest over recent decades. Modern agents have a capacity to protect against non-communicable diseases such as allergy, type [1] diabetes, some cancers, mental disorders, obesity, and more. Protective effects against numerous diseases and common diseases in human populations are presented in a table. Environmental contact with microbiomes forms physiological antispecies vaccines together with material served by other living organisms [1]. The relationship in disease prevention between environmental microbiomes and other species is widespread. Overuse of antiseptic products, antibiotics, vaccines, and inadequate (urban) nature contact can elevate risks of non-communicable diseases by reducing human contact with probiotics MRI MRS and MAD microbiomes and their metabolites [1].

Microbiomes and Mental Health

The types of microbiomes that a person is exposed to can influence human mental health and brain development. On the other hand, chronic stress can alter the composition of gut microbiomes and induce low-grade intestinal inflammation. It has been suggested that the gut–brain axis represents a complex network of communication between the gastrointestinal system and the brain, regulating cognitive and emotional functions [1]. The gut microbiome has emerged as a regulator of the gut–brain axis and behavior, and studies in animal models implicate gut microbiome dysbiosis in the etiology of neuropsychiatric disorders. Microbiomes are communities of microorganisms that form spatial patterns in their environments. Microbiomes exist in the air, land, and water. Studies have mainly compared rural and urban areas regarding the diversity of microbial communities in humans and the environment [1]. Evidence for the beneficial health roles of diverse environmental microbiomes is increasing. Human commensal microbiomes are partially derived from environmental sources and are crucial for proper immune training and regulation. Furthermore, exposure to diverse microbiomes mitigates disease development and promotes mental health. Current trends indicate that climate change, pollution, and particularly the loss of biodiversity negatively impact environmental microbiomes [1].

Environmental Factors Influencing Microbiomes

Environmental microbiomes are shaped by a combination of anthropogenic and natural factors, including those connected with climate change, pollution and land use [1]. Major biodiversity alterations, such as those resulting from fragmenting terrestrial habitats, fundamentally change these microbiomes and can accelerate disease transmission [1]. Communities from soil, water or air are particularly sensitive to extreme weather events such as floods and droughts. The increasing frequency and intensity of such episodes under anthropic global warming leads to higher microbial human and animal contamination risks from both potable and bathing waters. Pollution gradients also drive shifts in microbial communities from local to continental scales. Recent studies indicate that wild animals exposed to human activities or abundant tourist presence harbour altered faecal microbiota compared to less exposed ones, with impacts of microbiome disruption on immune status and host health [1].

Climate Change Effects

Climate change presents a significant challenge for microbes and microbiomes worldwide. Impacts on water resources, ice-free Arctic waters and sea-level rise, depletion of the ozone layer, and biogeochemical shifts all have the potential to influence the activities and distribution of microbes and the balance of their functions [10]. The worldwide emergence of novel fungal and bacterial pathogens may signal a substantial new risk to global health.

Microbes are often described as "rapidly adaptable and opportunistic" compared to a more "educated and slow" human race. Accordingly, climate exclusions are anticipated to shift worldwide as atmospheric and ocean conditions evolve, and current microbes depart from historical regions. Organisms and dispersal paths will eventually redefine the distribution of microbially mediated functions and the hosts and ecosystems receiving these services [10]. Geographical shifts of microbial taxa already appear well underway, both for terrestrial and marine microbes, with similarly rapid range extensions reasonably anticipated for microbially mediated processes.

Geographic ranges have expanded by several thousand kilometres for diverse fungal, oomycete, water mould, and bacterial pathogens of amphibians, fish, birds, and insects. The global expansion of tropical Vibrio pathogens is linked with increased risk of disease for millions of humans. Genetically defined populations of pathogenic marine vibrios expanded their distributions toward higher latitudes over 13 years, potentially to >40° latitude on both coasts of the United States [10].

Pollution and Microbial Communities

Pollution represents a dominant driver of human microbiome alterations, occurring both directly through the host and indirectly via the environmental reservoirs of microbial communities [11]. Chemical pollutants of terrestrial and aquatic origin modify the structure of soil and water microbiomes. These effects are especially evident for agricultural chemicals such as herbicides, fungicides and insecticides, a substantial share of which remains undiscovered and unregulated [12]. The structure of hosts from which microbes would subsequently colonise the human body likewise shifts in response to chemical exposure. Together, these transformations represent a pathway through which pollution limits the availability of key microbial inocula from the environment. Examination of human and animal microbiomes reveals that pollutants influence composition through a variety of mechanisms. Toxic effects can facilitate the preferential development of resistant taxa or the near extinction of highly sensitive microbes. Functional capacity can likewise become altered, especially for eutrophic environments exposed to high contaminant concentrations. Meta-omics analyses reveal that emerging pollutants are subject to microbial transformation and degradation in the body, which can generate toxic metabolites that subsequently interfere with the immune system [13]. The co-occurrence of pollution and associated toxic metabolites elicits pronounced ecological shifts: highly impacted microbiomes show limited diversity, impoverished network complexity, and truncated functional profiles, which translate to impaired ecosystem multifunctionality. The high eco-evolutionary turnover and functional redundancy of microbial communities challenge the assembly of robust models linking ecological structure with ecosystem functionality and host performance.

Land Use Changes

Land use changes alter the structure and functions of associated microbiomes [14]. Numerous studies have established how land use alterations influence the biological components of ecosystems through the effects on nutrient availability and on soil physicochemical properties. The exposure to agriculture, farming, composting, and building construction might affect microbial diversity [14].

Microbiomes in Agriculture

Soil microbiomes contain diverse communities of microorganisms. Many known soil microorganism species are plant-associated microorganisms and are used against plant pathogens. Microbial communities influence yield-improving traits of test plants [15]. Plant health is supported by agricultural soil microbiomes, and a specific body of knowledge currently advances solutions that support conservation and sustainable use of adaptive microbiomes as a nonconventional resource for crop production, growth enhancement, and natural disease suppression [15].

Soil Health and Crop Yield

Soil health plays a pivotal role in determining crop productivity, especially amid mounting concerns over feeding a growing global population. Microbial inoculants, such as plant growth-promoting bacteria (PGPB), have been broadly recognized for their capacity to enhance agricultural yields [14]. Mycorrhizal fungi and associated microbiomes influence aboveground plant community dynamics by facilitating direct and indirect interactions; for example, soil microbiota can either suppress or encourage arbuscular mycorrhizal fungi (AMF) activity, thereby affecting plant growth 16. Long-term field studies reveal complex and differential impacts of inorganic fertilization on soil bacterial and fungal richness, effects that can be moderated through organic amendments like manure, which maintain microbial diversity and support soil quality and crop yield. Overcoming challenges in harnessing these microbial insights is critical for translating biotechnological advances into practice; a comprehensive understanding of the soil microbiome's composition, diversity, and functional mechanisms is essential to optimizing soil health and sustaining crop production [14, 1, 2, 15].

Sustainable Farming Practices

Sustainable farming practices have been advocated as a strategy to reduce or reverse these trends, protecting commensal microbial communities, biodiversity, and promoting human and ecosystem health [2]. Large-scale agricultural monoculture emissions substantially influence both air-microbiome composition and soil microbial networks. Encouragingly, reversion to organic farming had only limited effects compared to the large differences caused by replacing monoculture by polyculture. Soil microbiomes are critical in supporting crop yield and sustainable farming practices that have the capacity to sustain food production with enhanced environmental quality [16]. Many benefits can be accrued from healthy and diverse soil microbiomes, which support crop growth by enhancing nutrient access and promoting nutrient cycling. Healthy soil microbiomes play a fundamental role in plant protection and confer resistance to pathogen invasion. A major challenge, therefore, is to manipulate these soil microbial communities and insert specific beneficial taxa to ensure the sustainability of both soil and food production.

Microbiomes and Biodiversity

The authors note that biodiversity loss severely impacts human health and global ecosystems. The human microbiome plays a crucial role in health, and human activities that disrupt ecosystems influence microbial diversity. Preservation of biodiversity is closely linked to maintaining healthy microbiomes, which support both human and planetary health [17]. Genetic and lifestyle factors, including diet, antibiotics, drugs, and exposure to environmental microbes, shape microbiota composition, thereby modulating host immune, metabolic, endocrine, and brain functions. Parental microbiotas exert health effects that span generations. Microbes are shared across humans, animals, and plants; consequently, terrestrial and aquatic microbial ecosystems affect the microbiota and health of all organisms. The preceding discussion underscores the association between microbial diversity and good health, emphasizing the importance of conserving environmental microbial ecosystems that are increasingly disturbed by anthropogenic activities [1].

Ecosystem Services

Microbiomes perform various ecosystem services, including regulating the speciation of elements, biodegradation of natural and synthetic materials, and carbon cycling. Recently, ecosystem services performed by the soil microbiomes have gained increasing prominence in light of their roles in sustainable agriculture and bioremediation [14]. Furthermore, substantial advances in soil microbiome research have also contributed to enhanced understanding of the microbial functions and have revealed the potential for manipulating and managing the soil microbiota. For more information on soil ecosystem services, see also "Microbiomes in Agriculture." Use of samples from environmental microbiomes (e.g., activated sludge) can facilitate the isolation of novel, valuable strains and enzymes [18]. Microbiomes in soil and ocean sediments contribute to the origin and preservation of cultural heritage materials, such as rock, fossil, and mummified human remains. Conversely, the detrimental impacts of microbiomes on cultural heritage materials have been recorded. A microbiome survey of mummified remains from geographically diverse locations (including Egypt, South Korea, the Italian Alps, Northern and Southern America) found not only shared microbial taxa but also a microbial association with the geographic origin, reflecting an ecological adaptation of the microbes. Understanding such microbial distributions in cultural heritage items can aid the formulation of better management strategies for their preservation [19].

Conservation Efforts

Conservation involves maintaining high-diversity environmental microbiomes, which have the highest potential to promote human health. Similar criteria used for protecting animal and plant communities can apply to environmental microbiomes, emphasizing the benefits of habitat complexity and connectivity for both environmental and human health [2]. Indigenous communities may benefit from their traditional, outdoor lifestyles that continuously expose them to rich environmental microbiomes. Urban populations evolving from rural backgrounds might maintain cultural practices promoting exposure to diverse microbiomes through diet or hobbies. However, defaulting to medical treatment without restoring access to diverse environmental microbiomes, such as through access to wilderness spaces, may not secure long-term health and well-being [2]. A global transition accelerator supporting research and outreach that combines microbial, ecosystem, social, and health perspectives is proposed to sustain the links between environmental microbiomes and health and to develop biodiversity-based interventions to help reduce non-communicable diseases [2].

Technological Advances in Microbiome Research

Microorganisms account for more than 60% of the Earth's biomass and support the growth of other living creatures through the cycling of carbon, nitrogen, and other key elements. The interaction between microorganisms and their hosts is fundamental, influencing health and the distribution of organisms [12].

Technological advances have enabled studies on the structure and function of complex microbial assemblages, revealing microbial diversity and functions in diverse environments, from the Arctic to the deep oceans and geothermal environments [18]. Moreover, molecular and synthetic-circuit strategies have also been established in recent years [19].

Metagenomics

Metagenomics characterizes the structure, function, and dynamics of microbiomes through genomic analysis. Conducted by the integrated use of computational, biochemical, and molecular tools, metagenomics studies the collective microbial genomes of microbiome consortia [20]. It elucidates the evolution of microbial communities based on the patterns of genes coded within metagenomes and leads to the identification and characterization of unculturable microorganisms active within the microbiome community. The information derived from metagenomics can thus establish and track the functional capacities of entire microbiomes [21]. Metagenomics integrates with other techniques to facilitate comprehensive, multifactorial characterizations of microbiomes, including targeted amplicon sequencing combined with DNA microarrays, metatranscriptomics and metaproteomics coupled to multiplex microarrays, or metabolomics, which synthesizes data from nuclear magnetic resonance and mass spectrometry. Technological advances, particularly in bioinformatics and next-generation sequencing permit the detailed study of microbial communities [22]. They enable a comprehensive analysis of interactions between microbiomes and their environments and support the development of hypotheses regarding their roles in various microbial activities. Cross-referencing relevant studies on the human microbiome in health and disease further informs investigations of environmental microbiomes.

Bioinformatics Tools

Experience-driven approaches informed by data collected from environmental microbiomes have increased capacity to mitigate associated risks and monitor remediation [23]. Metagenomic data can be used to associate microbial communities, gene expression, and metabolic signatures with possible sources (contaminated land, water, and air) and assess their impact on ecosystems and human health. Rapid advances in next-generation sequencing (NGS) technologies, such as whole-metagenome shotgun and amplicon sequencing, offer unprecedented opportunities to characterize the diversity and composition of known and unknown bacteria and archaea in the environment. This development promises novel insights into the detailed ecology and relationships between environmental and host-associated microbiomes [23].

Next-Generation Sequencing

Metagenomics became viable following the development of next-generation sequencing (NGS) techniques. Since the 2000s, the application of NGS to microbial ecology and metagenomics has transformed our approach to understanding the microbial world. Culture-independent methods have become commonplace and form the basis for a great deal of environmental microbial work [21]. NGS facilitates comprehensive examination of environmental microorganisms and uncovers microbial interactions with the environment. Capturing a sample of the genetic material present in an environment (the metagenome) provides detailed insights into the complex world of microbial ecology through whole-genome or targeted sequencing of microbial communities, also known as shotgun or amplicon sequencing [21]. Several NGS platforms are currently available. The Illumina platform (sequencing by synthesis) offers highly accurate, relatively short reads. Pyrosequencing (Roche 454) provides medium-length reads. The Ion Torrent platform uses semiconductor technology for medium-short reads. Third-generation sequencing platforms, such as Pacific Biosciences and Oxford Nanopore, generate longer reads. Platforms may be selected based on desired read length, throughput, run speed, and cost considerations. Different targets are used in NGS-based metagenomic studies, including the 16S rRNA gene (widely used to determine relative species abundances), crude metagenomes/whole genome sequencing, and mRNA. Counting and relating NGS reads to one another can be achieved using weighted or unweighted approaches. Bioinformatic analyses of raw sequencing data are also necessary [24]. Next-generation sequencing consists of multiple short DNA reads, and assembly is necessary for several downstream analyses within this field, including reference genome reconstruction, variant identification, transcriptomics, and metagenomics. From an algorithmic standpoint, assembly approaches and tools have historically been sets of intertwined heuristics composed of indexing, graph traversal, and error correction [19].

Challenges in Microbiome Research

Microbiomes are defined as microbial communities living in association with each other in a specific environment. Beyond the human gastrointestinal microbiome, others reside in soil, water, and air. How these community systems respond to climate change, biodiversity loss, and pollution remains poorly understood. Incorporating the perspectives of environmental and agricultural microbiomes is highly valuable for guiding society and policymakers [21]. Advances in metagenomics and bioinformatics, alongside developments in next-generation sequencing platforms, enable comprehensive research on microbial community composition, dynamics, and diversity, clarifying their influence on human health and ecosystem services [21]. The amount of information generated continues to expand; however, researchers must remain aware of problems related to data interpretation. Additionally, the ethical implications of microbiome research represent an unexplored territory. The complexity of the question discourages investigation. These challenges must be addressed before further progress can be achieved [22].

Data Interpretation Issues

Relating microbiome data to our current understanding of ecosystem–microbe–health interactions is a daunting task [25]. The inability of standard tools for modelling communities whose membership violates the principle of the independence of observations limits the development of mathematical models that can be used to describe system dynamics and provide mechanistic insight [26]. At best, an association is drawn between community differences and topical variables of interest. Because these associations are necessarily context-specific, microbiome information of future utility must be sustainable and the analyses reproducible [27].

Ethical Considerations

The ongoing shift in indoor and outdoor micro-environments renders it more important than ever for people to understand the relationships between environmental microbiomes and human health, and to identify general principles that underlie these relationships across a wide variety of settings. It is therefore important to address ethical considerations associated with the acquisition, analysis, sharing, and application of data on environmental microbiomes [28]. Ethical considerations in the field of microbiome research reached awareness only recently [29]. The emergence of microbiome ethics represents a natural development within the broader fields of bioethics, environmental ethics, and food ethics. The potential of improved microbiomes to reduce the use of chemical pesticides and chemical fertilizers lends support for the inclusion of microbiomes in discussions of the ethics of sustainability. Because food-associated microbiomes can promote the production of high-fat, high-sugar, and/or high-salt foods, microbiome ethics in food should also consider the positive societal effects of restraining the negative influence of food-associated microbiomes on diet and public health Morbidity and mortality resulting from overweight and obesity already place a substantial economic burden on healthcare systems. Interventions in the human microbiome deserving ethical discussion include fecal transplants and the informed consent required for human subjects in microbiome screening [29]. The most urgent emerging topic of microbiome ethics revolves around microbiome-targeted interventions as promising solutions to the loss of wildlife biodiversity caused by habitat degradation, destruction, and fragmentation, urbanization, and climate change. Such interventions encompass 'rewilding' the environmental microbiome, facilitating detoxification and bioremediation, increasing host resilience to stress, and ultimately guiding ecological adaptation, evolutionary rescue, and species migration. Their ethical evaluation takes into account the inevitable complex interplay between multiple sites and scales, and a necessary discussion on the relative priority of preservation of wildlife biodiversity versus human interests and integrity [28, 29].

Future Directions in Microbiome Studies

The significance of microbiomes in governing environmental and human health fosters the emergence of research foci towards interdisciplinary strategies [2]. Designing microbiome-readjusting practices necessitates profound comprehension of the mechanisms through which microorganisms affect human physiology, macroorganism functioning, and, ultimately, the balance of the entire Earth system [2]. The multidisciplinary endeavor towards the dissemination of beneficial microorganisms in the context of climate change and biodiversity loss explores distinct research areas: (1) incentive measures for the preservation of jobs related to the protection of natural habitats and therefore to the persistence of species, both macro- and microorganisms, in their healthy state; (2) multidisciplinary research on the dispersal of beneficial microorganisms, while accounting for environmental particularities and natural routes; (3) developing open access policies for microbiome data, in order to build the basis for artificial intelligence approaches, support bioinformed social agreements, and therefore help societies to live in a coordinated manner on a planet where beneficial microorganisms are consciously disseminated. With these agendas, tailored regulations and practices, grounded within transdisciplinary and participatory frameworks where governments, scientists, and civil society interact, have the capacity to guarantee not only the dissemination of beneficial microorganisms but also the preservation of soil and air quality, biodiversity, and, ultimately, Earth's health. More generally, the knowledge-gathering, spread, and sharing processes promoted in these endeavors represent the foundations on which the general-purpose knowledge that regulates the functioning of experimental, observational, and theoretical microbiome studies can be built [2].

Interdisciplinary Approaches

It is suggested that a comprehensive understanding of microbiomes requires a multi-disciplinary approach integrating health sciences, ecological, evolutionary, and habitat research [1]. Environmental microbiomes thereby represent priority targets and indicators important for monitoring biodiversity and ecosystem services, and thus enable much-enhanced precision. The interconnectedness of environment, plants, animals, and humans consequently lends itself to interdisciplinary research focusing on the health of all these individual players [1]. This perspective complements the individuals-only approach by including the wider environment and its effects on all the living components. Development of innovative monitoring methods facilitating the rapid acquisition of high-quality data may furthermore provide leverage for improving evidence-based policies [1].

Policy Implications

Microbiomes are crucial for the health of plants, animals, and people and the ecosystems that sustain them. Microbiomes support trees, coral, and natural ecosystems; group living in humans, social animals, and some plants; and crop and animal productivity in agriculture [1]. Microbiomes are of economic importance for, among others, public health, agriculture, forestry, fisheries, food, aquaculture, and the food and beverages industry [2]. They play a critical role in carbon fixation and the nitrogen and phosphorus cycles.

CONCLUSION

Environmental microbiomes serve as essential mediators between ecosystems and human health, regulating immune responses, protecting against disease, and maintaining ecological balance. Soil, water, and air microbiomes each provide crucial services ranging from food security to respiratory health, yet all are increasingly threatened by pollution, climate change, and biodiversity loss. Urbanization reduces microbial diversity, increasing exposure to pathogenic taxa, while sustainable farming and conservation practices help preserve beneficial microbiomes. Technological innovations in sequencing and bioinformatics offer new insights into microbiome diversity and function, but significant challenges remain in interpretation, ethical application, and integration into public health frameworks. Preserving microbial biodiversity is not only vital for ecosystem resilience but also for long-term human well-being. Future strategies must prioritize interdisciplinary research, conservation of environmental microbiomes, and policies that safeguard microbial diversity as a cornerstone of sustainable development and global health.

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