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Microbial Ecosystem Services for Sustainable Urbanization: A One Health Perspective

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Abstract
One Health is a concept and framework for addressing the interconnected nature of humans, animals and their environments to improve the health and wellbeing of all three, along with added social and financial benefits. On a microscopic level, the microbiota is a clear biological connector with strains shared across domains.This one health model attempts to reduce zoonotic diseases, antimicrobial resistance (AMR), and environmental degradation by increasing food security through ecosystem services, which are the benefits of natural processes (provisioning, regulating, supporting, and cultural services). To analyse synergies between One Health and ecosystem services for sustainable urbanization.This study synthesizes current knowledge on microbial ecosystem services within urban environments, explores their relevance to the One Health approach, and highlights emerging technologies and policy opportunities for integrating microbiome-based solutions into sustainable urbanization.
Keywords: Microbial, Ecosystem, Microbial Ecosystem, Sustainable Development, Urbanization, One Health, Microbial ecosystem services, Environmental health.

Introduction:

The collections of microbes and their genetic material in a particular environment are known as microbiomes. They are essential to health, ecosystem function, and the sustainability of agrifood systems and can be found in humans, animals, plants, soils, water, air, food, and constructed environments.

Ecosystem processes are fundamentally regulated by microorganisms, which include bacteria, fungus, archaea, protozoa, algae, and viruses. Despite being crucial to preserving human well-being and the health of the environment, their ecological roles are frequently unseen.

Important biological and ecological processes are actively regulated by these microbial populations. They support the development of the immune system, nutritional absorption, and metabolic control at the organismal level. Microbiomes affect growth performance, illness susceptibility, and feed efficiency in cattle systems. They aid in the uptake of nutrients, stress tolerance, and disease resistance in plants. Environmental microbiomes control organic matter decomposition, nutrient cycling, and other biogeochemical processes at the ecosystem level.

In addition to natural ecosystems, artificial environments and urban settings are also conducive to biodiversity. A wide variety of organisms, including people, live in urban environments, forming distinct ecosystems with their own biodiversity, dynamics, and interactions. Therefore, it is essential to comprehend biodiversity in different kinds of constructed settings in order to comprehend the ecosystem services that are linked to them.

Macro and microorganisms in these ecosystems are a part of a complex web of living things that depend on the abiotic environment and one another. Numerous ecosystem services that benefit not just the immediate participants but also ecosystems as a whole, including urban built environments, can result from these interactions, which can have cascading impacts. Numerous manmade environments, such as gardens, parks, and street trees, provide as habitats for a variety of plant, animal, and bacterial species. In semi-natural habitats, trees offer a variety of ecosystem services, such as stormwater attenuation, carbon sequestration, and improved air quality.

One of the key global trends of the twenty-first century is urbanization. By 2050, the United Nations projects that around 70% of the world's population will reside in cities. Rapid urban growth has led to biodiversity loss, pollution, habitat degradation, climatic vulnerability, and a rise in the introduction of infectious illnesses, despite the fact that cities play a major role in economic development and innovation.

Cities have developed into intricate socioecological systems as a result of globalization and urbanization. They have highly concentrated resources in the areas of health care, education, and the economy, but they are also subject to a variety of environmental and public risks, including heat waves, air pollution, infectious disease

outbreaks, and ecological degradation. There is a growing understanding that promoting health in metropolitan environments necessitates taking into account the welfare of people, animals, and the environment. The One Health concept, which emphasizes the necessity of coordinated actions across the human, animal, and environmental sectors to support their integrated and balanced growth, is strongly aligned with this viewpoint.The One Health idea has gradually broadened to include more issues, such as ecosystem services, climate adaption, and community equity, after initially concentrating on the prevention and control of zoonotic diseases and antimicrobial resistance. Promoting the interrelated well-being of people, animals, and ecosystems will now be greatly aided by incorporating the One Health approach into urban health agendas. The moment has come to integrate Urban One Health's theoretical underpinnings and practical approaches to address the interconnected problems of sustainability and health in urban areas. [1]

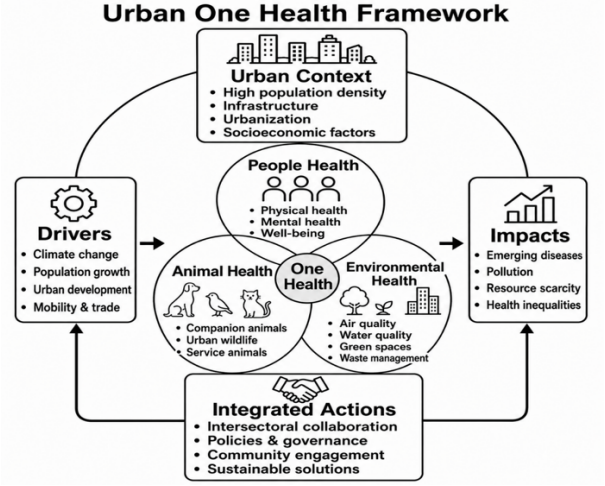


Figure 1: Urban One health Framework

Urban microbiomes

Human-animal-microbe interactions have changed as a result of urbanization, which has also created new health hazards by altering the variety, composition, and function of microbial communities. Urban microbiomes are made up of a variety of microbial communities found in environmental media, people, animals, and building environments. Together, they support essential ecosystem processes like the cycling of nutrients, the breakdown of organic matter, the degradation of pollutants, and the control of pathogenic organisms.5 Urban microbiomes typically show more complex spatial patterns and less variety than microbiomes found in natural settings. They assist human immunological modulation, control local microclimates, and improve urban ecological stability and resilience.Cross-species interactions in urban environments, on the other hand, facilitate microbial trade, disease persistence, and zoonotic pathogen spillover. Concurrently, dense populations and contaminated surroundings create selection pressures that hasten the growth and adaptability of pathogenic and antibiotic-resistant bacteria in urban areas, increasing the hazards to public health.

One of the biggest risks to ecological connectedness and biodiversity is urbanization. Degradation of ecosystems, isolated species populations, and reduced gene flow result from the fragmentation of habitats caused by urban growth. By connecting urban and peri-urban ecosystems through green corridors, urban parks, and integrated habitat zones, ecological networks in urban contexts (also known as urban ecological networks, or UEN) seek to lessen these effects. For instance, European programs like Natura 2000, which incorporates biodiversity conservation into highly inhabited areas, are examples of successful urban ecological networks. These networks frequently feature biodiversity corridors, such greenways or river ways, which serve as an example of how UENs can improve urban quality of life, promote connectivity, and solve habitat fragmentation. [2]

Objectives:

1. To identify the major microbial ecosystem services that contribute to sustainable urban ecosystems, including nutrient cycling, waste decomposition, bioremediation, and climate regulation.

2. To examine the role of microbial communities in maintaining environmental quality, biodiversity, and ecosystem resilience within urban environments.
3. To assess the Schematic representation of the One Health concept through Antimicrobial Resistance (AMR).
4. To analyze the challenges.

Review of Literature:

The realization that animal and ecological health are inextricably linked to human health gave rise to One Health. The necessity for integrated surveillance and response systems has historically been highlighted by zoonotic epidemics like avian influenza and rabies (Schneider et al., 2019). As a strategy framework for preventing and managing health risks at the human-animal-environment interface through interdisciplinary cooperation, One Health is now acknowledged worldwide (Couto &Brandespim, 2020). [3–4]

The World Health Organization (**WHO**), the World Organization for Animal Health (**WOAH**, formerly OIE), the Food and Agriculture Organization of the United Nations (**FAO**), and the United Nations Environment Programme (**UNEP**) formed the **One Health Quadripartite** in recognition of the need for interdisciplinary and multinational cooperation (Pitt & Gunn, 2024; Vors et al., 2024). [5]

The study, which was published in the *Journal of Environmental Chemical Engineering* (Elsevier), offers a thorough overview of the microbial environment concealed within treated tap water. It reveals the presence of antibiotic resistance genes (ARGs), such as **adeF** and **ermR**, which are linked to multidrug resistance, in addition to bacterial diversity.

Metagenomic sequencing enables researchers to decipher all of the microbial DNA found in water samples, as contrast to traditional culture-based testing that can only identify a portion of bacteria.

"This is the first time in India that metagenomic sequencing has been applied to public drinking-water systems to understand microbial ecology, antibiotic-resistance profiles and their environmental drivers," stated Dr. Vikas Kumar, the project's principle investigator and Scientist-E at ZSI.

"A variety of microorganisms can be found in even purified water. Temperature, pipeline conditions, and other distribution-system variables affect its composition. "Our results offer baseline information that is essential for incorporating microbial surveillance into national water safety initiatives," he continued.

"Water connects humans, animals, and the environment—the three pillars of Center's One Health Mission," stated Dr. Inderjeet Tyagi, a scientist at ZSI and co-supervisor of the study. The environmental-health evidence base required to include microbiome monitoring into One Health frameworks is provided by our study.

The researchers linked environmental exposure to clinical and agricultural antibiotic resistance by pointing out that ARGs in aquatic ecosystems can readily spread across One Health sectors. Additionally, the results are in line with national priorities under the National Action Plan on Antimicrobial Resistance (NAP-AMR), Swachh Bharat Mission, and Jal Jeevan Mission.

The method's potential was highlighted by Prof. Karthik Raman of IIT Madras: "We can detect thousands of microbial species and potential ARGs in a single sequencing run through metagenomic analysis." This encourages the creation of early warning systems for water-borne diseases and antibiotic resistance. [6]

Research Methodology:

The study was conducted as a pilot work under the aegis of The United Nations Educational, Scientific and Cultural Organization (UNESCO) for exploring innovative models for climate resilient health systems. Also described with the help of secondary data on peer-reviewed journal articles, books, reports from international organizations (e.g., WHO, UNEP, FAO), conference proceedings, and government publications. The study will follow the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency and reproducibility.

Result and Discussion:

Microbial Ecosystem Analysis

In many ecosystems, microorganisms are essential to activities like the cycling of nutrients, the breakdown of chemicals, the creation of biofuel, and the emission and consumption of greenhouse gases. In order to analyze the structure, dynamics, and stability of microbial ecosystems, as well as how they function and provide ecosystem services, we employ ecological models. For the benefit of both ecology and microbiology, microcosms are also effective instruments for testing ecological theories and model predictions under carefully regulated conditions at tiny geographical and temporal scales.

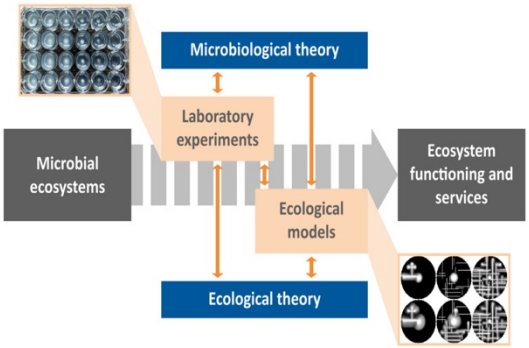


Figure 2: Microbial ecosystems are analysed with particular focus on their functioning and services. [7]

The Functions of Microbes in Environmental Systems Because they power vital biogeochemical processes that control ecosystem stability, microbes are essential to the upkeep of environmental systems. They have a major role in the decomposition of organic matter, the cycling of nutrients, and the transformation of important elements like carbon, phosphorus, and nitrogen (Siciliano et al., 2013). By improving soil fertility, cleaning water, and promoting biodiversity, these activities have a significant impact on both terrestrial and aquatic habitats and are essential to the health of ecosystems. Additionally, ecosystems can rebound from disruptions like pollution or climate change because microbial populations are resilient and adaptable to environmental perturbations (Bissett et al., 2013).Microbes control biogeochemical processes in aquatic systems that prevent eutrophication and preserve the health of aquatic ecosystems. The vital roles that microorganisms play in pelagic ecosystems, particularly in recycling nutrients and sustaining food webs, were highlighted by Cotner and Biddanda (2002). In a similar vein, terrestrial microbial communities improve soil fertility and structure, which supports plant health and productivity (Haferburg& Kothe, 2007). Sustainable farming methods are directly impacted by their interactions with plant roots through processes like phosphorus solubilization and nitrogen fixation.

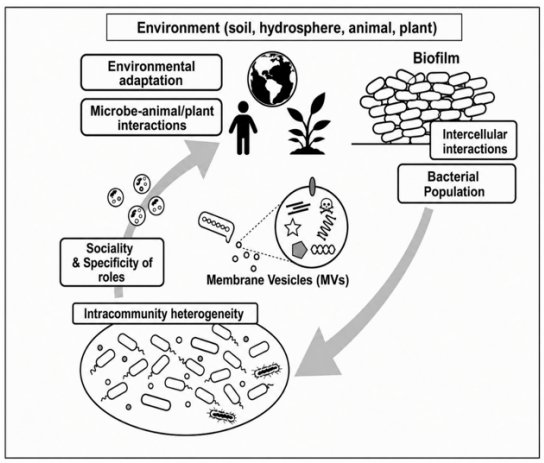
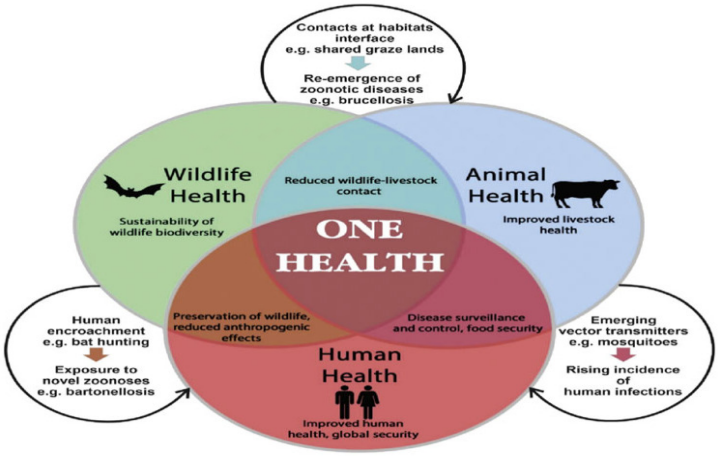


Figure 3: Microbial Interactions and Environmental Adaptation (Online Biology, 2018). [8]

The intricate interplay between bacteria and their surroundings is depicted in this figure. It displays important features such membrane vesicles, biofilm development, and environmental adaption. The illustration highlights the function of bacterial populations in preserving ecological balance by showing how they interact in a variety of environments, including soil, water, and living things.

One of the biggest dangers to world health is antimicrobial resistance (AMR), which makes it more difficult to treat infectious diseases in people, animals, and the environment. Drug-resistant bacterial infections were directly responsible for 1.27 million of the approximately 5 million deaths associated with AMR in 2019.

Bloodstream infections, pneumonia, TB, and intra-abdominal infections were among the diseases that resulted in treatment failure and caused these deaths. Low- and middle-income countries (LMICs) are disproportionately affected by these deaths, which are made worse by poor surveillance, restricted access to novel antibiotics, and inadequate healthcare infrastructure.More than 70% of these deaths were caused by resistance to widely used antibiotics, such as beta-lactams and fluoroquinolones, highlighting the critical need for coordinated action to tackle AMR. By 2050, AMR might cause up to 10 million deaths per year if current trends continue, which would have a significant impact on both public health and the world economy.



Schematic representation of the One Health concept [9].

AMR has long been associated with human and veterinary medicine, but it is also widely acknowledged as a serious environmental problem. The origin, evolution, and spread of antimicrobial-resistant bacteria (ARB) and ARGs are all facilitated by the natural environment, which also serves as a vital reservoir. The environment is now recognized as being crucial to the dynamics of AMR, which is consistent with the One-Health concept that highlights the interdependence of human, animal, and environmental health.

Environmental transmission pathways and ecological selection pressures that sustain resistance outside of host organisms are highlighted by the One-Health paradigm. The environment promotes resistance persistence, allows HGT amongst microbial communities, and makes it easier for AMR to move between compartments via soil, water, air, and biotic vectors.

Challenges:

There are a number of difficulties in operationalizing One Health strategies that are informed by microbiomes. Microbiomes are dynamic, complex, and context-specific, necessitating reliable and consistent methods for monitoring and characterisation.

There are still a lot of data gaps, especially in low- and middle-income nations. Furthermore, improved multidisciplinary cooperation and coordination across sectors, as well as the creation of common frameworks and indicators, are necessary to translate microbiome knowledge into policy and practice.

One Health's incorporation of microbiomes provides a route toward more robust and sustainable systems. Microbiome-informed techniques can increase food security, lower illness risk, and improve ecosystem function by addressing the underlying biological processes that link human, animal, plant, and environmental health. [10]

Conclusion:

Microorganisms operate in a variety of habitats, such as soils, sediments, aquatic systems, the atmosphere, and host-associated settings, and are essential drivers of ecosystem stability. Microbial assemblages function as ecosystem engineers that uphold ecological balance by stabilizing physical structures, controlling nutrient cycling, and preserving community resilience. Microbial diversity guarantees physiological stability and health in host-associated systems, including the human microbiome, underscoring the similarities between ambient and host ecosystems.

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