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Short Review

The power of microbial life for the transformation towards a sustainable planet: key messages from the 2024 IUMS Congress in Florence, the city of the Renaissance

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Abstract

The 2024 International Union of Microbiological Societies Congress was held in Florence, the city of Renaissance. The theme was to increase the awareness of the power of microbial life, recognizing that it can lead the transformation towards a sustainable planet. The meeting gathered over 1400 experts from more than 90 countries and focused on the transformative potential of microbiology in addressing global challenges and aligning microbial science with the Sustainable Development Goals. Six roundtable discussions explored the pivotal role of microbiology in mitigating climate change, preparing for pandemics, producing sustainable energy, promoting a One Health approach, understanding microbiome dynamics, and developing data infrastructure. The discussions revealed that microbes are still overlooked agents in sustainable solutions. Expert panellists at the roundtables discussed microbial innovations

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in hydrogen and biofuel production, conversion of greenhouse gases, biomanufacturing, and soil restoration, the role of microbiome in immune health, the importance of cross-kingdom interactions, and the integration of food, environmental, and microbiomes under the One Health framework. Panels stressed the need for equitable access to vaccines, diagnostics, and data sharing, especially in the face of antimicrobial resistance. The importance of global collaboration, data repositories, and regulatory alignment, was repeatedly emphasized. The congress invited calls for the formation of an international microbiology coalition, need for interdisciplinary partnerships, increased investment in microbial technologies, updating of regulatory frameworks, and integration of microbiome science into public health and environmental policy. Microorganisms are the oldest architects of nature, able to build a sustainable future for the planet.

Keywords: IUMS, sustainable planet, microbial life, microbial innovations, One Health, SDGs

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Introduction

Florence is the city of the Renaissance, the historical period between AD 1450 and 1600 that marked the cultural transition from the Middle Ages to the modern era. During this period, Filippo Brunelleschi used revolutionary innovation to build the Dome of the Florentine Cathedral, and other giant artists like Piero della Francesca, Leonardo da Vinci, Michelangelo, Raffaello, and Botticelli, carved a new period in history where mankind became aware of the power of human innovation and ingenuity and left a legacy of scientific vision and incredible masterpieces of arts that we can still admire when walking around in the city of Florence.

The conference of the International Union of Microbiological Societies (IUMS) held in Florence on October 24–26, 2024, inspired by the testimonial of renaissance visible in every corner of the city, took the challenge to discuss whether mycology, virology and bacteriology, working together can usher a new era where microbiology becomes aware of the power of the microbial life, and can use it to impact climate change and microbial diversity, two fundamental problems which threaten the survival of the planet and of the organisms that live on it. The conference brought together a diverse range of scientists, policy makers, and institutional representatives to explore the transformative role of microbiology in addressing global challenges.

Following the plenary and sessions, six roundtable discussions during the meeting explored the environmental, clinical, agricultural, and biotechnological applications of microorganisms, highlighting their critical role in climate change mitigation, pandemic preparedness, sustainable energy production, and human and environmental health. Central to these discussions was the recognition that the complex communities of microbes are fundamental to sustaining life and achieving the United Nations Sustainable Development Goals (SDGs). The roundtables collectively emphasized that microorganisms are key enablers of sustainable solutions across multiple sectors, but their potential remains significantly underexploited, emphasizing the urgent need to raise awareness among policymakers, stakeholders, and the general public on the role of microbes in both environmental and clinical contexts.

The roundtables focused on how microbiology can help address climate change, pandemic preparedness, energy production, One Health, including microbiome and antimicrobial resistance (AMR), but also how to evolve the organization of data, repositories, and the challenge of taxonomy to handle the exponentially expanding diversity of the microbiological universe (Table 1 and Fig. 1). A summary of the discussions and of the recommendations that emerged during each of the round tables are reported below.

Climate change and microbe-driven sustainable solutions

Climate change is perhaps the most important problem humanity is facing today. The health of the planet is necessary for the sustainability of every form of life (Rappuoli et al. 2023). Microorganisms, which have been living on the planet for four billion years, gave origin to every form of life on earth, playing also a very important role in the production and consumption of greenhouse gases.

In spite of this, there is a lack of awareness that microbiology can contribute to mitigate climate change, even if during the last few years some papers have pointed out that microbiology has the potential to provide important contributions to the sustainability of the planet, to mitigate loss of biodiversity, and to achieve the SDGs of the United Nations (ASM 2022, Crowther et al. 2024). The 2024 IUMS congress in Florence was the first opportunity to discuss the role of microbes in climate change with the community of microbiology with over 1400 scientists coming from more than 90 countries. At the congress, a joint symposium organized by IUMS and the American Society of Microbiology (ASM) reported that IUMS and ASM had put together a Scientific Advisory Group (SAG) composed of 14 scientists expert in diverse disciplines of microbiology covering soil, water, energy, food health, and biodiversity, supported by experts in ethics and economy and that the SAG had almost completed its work to analyze and prioritize microbe-driven sustainable solutions. The conclusions of the SAG were published shortly after the IUMS meeting (Lennon et al. 2025, Rappuoli et al. 2025a, 2025b). During the panel discussion, there was complete support for the idea that microbes could provide important contributions to mitigate climate change. The overall message was that the scientific challenges are monumental, but not impossible. Liza Stein reported that it was already known how to reduce methane emissions and how carbon capture can be done. Similarly, it is already known how greenhouse gases and organic materials can be converted by microbes into energy, biofuels and used for biomanufacturing of high-value chemicals, bioplastics, and pharmaceuticals (Peixoto et al. 2024). Dilfuza Egamberdieva reported the challenges of producing food in soils with increasing water supply limitations and extreme environments, while meeting the goal of reducing the use of agrochemicals by 20% in the short term. The use of Biochar supplemented with microbes as biofertilizers was one of the proposals (Bolan et al. 2023). Others reported that there is an increasing soil desertification, which can be mitigated and possibly reversed by increasing microbial diversity. The example of Norway presented the approach, which has been able to eliminate the use of antibiotics in the cultivation of salmon and has developed a flourishing sustainable salmon economy.

Challenges for implementing microbe-driven sustainable solutions, mentioned at the panel discussion, were the absence of a collective voice of microbiologists around the world to build awareness and continue to engage with global leaders, the fact that microbe-driven solutions are not yet profitable commercially and not convenient for consumers, and restrictive legislations regarding the use of genetically modified organisms and the sharing of natural microbial resources.

Table 1. IUMS panel discussions.

Climate change and microbe-driven sustainable solutions	Pandemic preparedness	Energy	Empowering knowledge: material and data repositories	Multi-organismic interactions in the microbiome and self-sustainability of health	Food and environmental microbiomes: a One Health perspective
Moderators: Nguyen K. Nguyen, Rino Rappuoli *Panelists*: Dilfuza Egamberdieva, Lisa Stein, Amy Shurtleff	*Moderators*: Amy Shurtleff, Mariagrazia Pizza *Panelists*: Cristina Cassetti, Ursula Theuretzbacher, William Paul Duprex	*Moderator*: Iftach Yacoby *Panelists*: Tone Tonjum, Roberto Di Leonardo, Diethard Mattanovich, Gianluigi Cardinali	*Moderators*: Andrey Yurkov, Edward R.B. Moore *Panelists*: Jörg Overmann, D İpek Kurtböke, Irina S Druzhinina	Moderator: Duccio Cavalieri *Panelists*: Luisa Lanfranco, Paul Young, Marco Ventura	*Moderators*: Eliora Z Ron, Antonia Ricci *Panelists*: Carlotta De Filippo, Uri Gophna, Rachele De Giuseppe

However, scientists from Australia, Japan, Germany, supported by the others in the audience, raised their voice during the panel discussion and agreed to be willing to be involved in capturing the opportunities that are emerging for microbiologists. They suggested that the scientists working on similar problems should communicate and collaborate globally to solve problems more effectively and to raise the voice of microbiology to educate students, scientists from other disciplines such as chemistry, physics, economy, global society, and policy makers, including UNESCO and the United Nations. The conclusion was that the new revolutionary technologies provided a unique opportunity in history for microbes to shape again the sustainability of life on our planet. The 2024 Nobel Prize in chemistry to David Baker, Demis Hassabis, and John Jumper stated that artificial intelligence applied to protein design can benefit the environment by improving the efficiency of enzymes that capture carbon dioxide and methane, those that can break down plastics and convert agricultural waste into biofuels and improve food production by engineering nitrogenases to improve nitrogen fixation. Additionally, a huge reservoir of genes exists in the trillion species of microorganisms that populate our planet today, evolved for four billion years to survive with sustainable solutions on our planet.

Recommendations

Create an international coalition of microbiology. Represent microbiologists in global climate dialogues, policy-making, and public education initiatives.

Increase interdisciplinary collaboration. Encourage structured partnerships between microbiologists and experts in chemistry, physics, economics and policy to scale up microbial-based innovations.

Accelerate investment in microbial technologies. Provide funding mechanisms and incentives for the development of commercially viable microbial climate solutions such as bioplastics, biofertilizers, and biomanufacturing.

Update laws and regulatory frameworks. Work with governments and international organizations to reform laws that restrict the use of genetically modified or natural microbial organisms for sustainability purposes.

Support education and awareness campaigns. Launch global programmes to educate students, researchers and the public about the role of microbiology in environmental sustainability, with support from institutions such as UNESCO and the UN.

Harness AI and big data for microbial innovation. Encourage further research into AI-driven enzyme design, microbial genomics, and data sharing across countries to accelerate breakthroughs in sustainable microbial applications.

Pandemic preparedness

Emerging infections and pandemics are increasing in frequency and expanding in geography. This is due to the combined effects of climate change, urbanization, deforestation, pollution, abuse of antibiotics, and chemical fertilizers. The Covid-19 crisis demonstrated that there is an urgent need for a global collaborative plan to address how to monitor and prevent emerging pathogens and transmission of diseases from animals to humans (spillovers) and how to be ready to rapidly develop and equitably distribute vaccines, monoclonals, therapeutics, and diagnostics. An ongoing silent pandemic which is already causing millions of deaths every year is the global spread of AMR (GBD 2021 Antimicrobial Resistance Collaborators 2024). Multiple initiatives involving the Coalition for Epidemic

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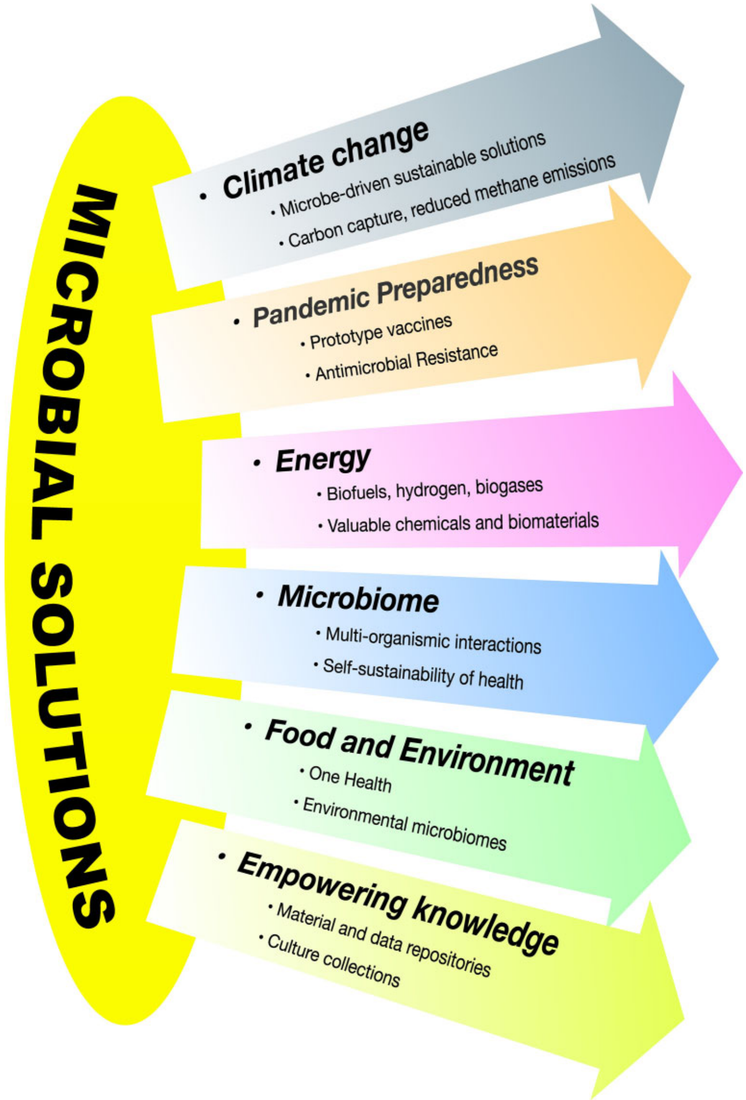

Figure 1. Schematic representation of the potential solutions that microbes can provide for a sustainable future of our planet.

Preparedness Innovations (CEPI; Saville et al. 2022), National Institutes of Health (NIH; Cassetti et al. 2023), Health Emergency Preparedness and Response Authority; https://health.ec.europa.eu/health-emergency-preparedness-and-response-hera_en), G7 and G20 are proposing to develop countermeasures such as diagnostics, therapeutics, prototype vaccines, and vaccine libraries to be ready to respond within 100 days from the identification of an emerging threat. Particular attention was devoted to building self-sustainable solutions for Africa and other low-income regions.

The roundtable opened with a discussion on pandemic preparedness funding initiatives that have been recently launched. The National Institute of Allergy and Infectious Diseases (NIAID) has developed the concept of 'prototype pathogens' and is funding the 'Revampp' program to promote basic and translational research on virus families that potentially could emerge as pandemic pathogens (https://www.niaid.nih.gov/research/vaccines-and-monoclonal-antibodies-pandemic-preparedness-revampp). The final goal is to develop vaccine and monoclonal antibody strategies for identified prototype pathogens that can be applied to closely related taxonomic members. The 100 days initiative by CEPI is supporting the generation of vaccine libraries to be ready for an emerging threat. Although these many initiatives have been launched, the coordination between the funders and the design of a global collaborative plan is still needed. Studies on viral transmission, pathogenesis, evolution, detection and identification of animal models are essential to face the next pandemics but the sharing of data and reagents among researchers is still problematic. The Nagoya Protocol (NP) and other national regulations for Access and Benefit Sharing (ABS) are hindering the sharing of genetic resources, including microbial isolates, between countries; many researchers from low- and middle-income countries have faced strict restrictions, due to their governments' policies and national priorities and it is often not legally possible to bypass these regulations. Scientific transparency, union and strong collaborative networks may help all laboratories in the world to obtain timely access to strains and reagents, share samples and data. WHO has established an international mechanism for the exchange of influenza material between designated international laboratories, operating under a specialized type of Material Transfer Agreement. This framework ensures the timely and equitable sharing of critical resources while addressing concerns related to access and benefit sharing. Such a mechanism could serve as a potential model for the exchange of other pathogens, facilitating global

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collaboration in pathogen surveillance, research, and preparedness. The agreement on the WHO pandemic accord achieved after the IUMS meeting represents a milestone in the field and addresses pathogen-sharing issues. The NIAID CREID network, consisting of NIH scientists (https://www.niaid.nih.gov/research/centers-research-emerging-infectious-diseases), can support the IUMS in promoting the sharing of research data, materials, samples, and strains.

IUMS may play an important role in reducing misinformation and vaccine hesitancy, with coordinated efforts in each microbiological society in promoting scientific education. Education will be critical to address effectively the global problems of our planet and influence policy makers in taking decisions at risk. It will be essential to connect different global crises, such as war, climate change, and political strife.

The Covid-19 pandemic was like a fast tsunami, while AMR develops and swells like a slow tide that can also overwhelm us (Moriel et al. 2024). Bacteria can become resistant to all antibiotics. Should resources be mobilized for AMR? At a recent UN General Assembly meeting, interest in AMR seemed to be resurgent. At the round table, the need for a holistic approach to fight AMR was emphasized, with the importance of new and better models and of multiple therapeutic and prophylactic approaches, such as vaccines, monoclonal antibodies, phages, CRISPR-CAS and, most importantly, the need of cooperative efforts.

Questions were raised about the political responses affecting economies and how incentivizing economic capabilities could be beneficial. It was emphasized that a new economic model is needed because pharmaceutical companies find it too costly to invest in discovery and development of new drugs. There is a need to address AMR and ensure economic sustainability. Combating AMR will be life insurance.

Recommendations

Strengthening global coordination. Health threats such as pandemics and AMR are increasing, but response efforts are fragmented. A unified global action plan is needed to align international organizations, funders, and national governments.

Facilitate equitable access and data sharing. Legal and logistical barriers, such as the NP, are slowing scientific progress. Expanding WHO-like frameworks can ensure fair and rapid access to genetic resources and materials.

Invest in holistic preparedness. COVID-19 highlighted gaps in preparedness. Investment in vaccine platforms, diagnostics, and treatments—especially in low-income regions—is essential for equitable and rapid responses to future threats.

Tackling AMR with urgency. AMR is a slow but deadly global crisis. Prioritize interdisciplinary research and innovation, including new antibiotics, alternative therapies, and preventive strategies such as vaccines and phage therapy.

Build public trust through education. Misinformation and vaccine hesitancy undermine global health efforts. Strengthen science communication and education to promote informed decision-making and public engagement.

Revisit economic incentives. Pharmaceutical investment in pandemic preparedness and AMR remains low. New economic models are needed to support innovation and ensure long-term sustainability.

Support resilience in low-resource settings. Global health security depends on building self-sustaining systems in vulnerable regions. Long-term investment in infrastructure, training, and access must be a priority.

Advance research on emerging pathogens. Programs such as the NIH and CEPI 100 Day Mission should be expanded to accelerate the discovery and development of countermeasures before the next outbreak.

Microbial solutions for energy production

Energy production by burning fossil fuels, such as petrol and coal, contributes to a large part of greenhouse gases. Microbial energy production offers a transformative foundation for sustainable, clean energy solutions and valuable chemical production. This innovative field holds the potential to redefine our energy and chemical landscapes, with models inspired by traditional, low-energy agriculture pointing the way forward. For instance, green algae cultivation can simultaneously produce hydrogen and nutrient-rich paste (with 50% of dry weight as protein), combining energy production with valuable byproducts for a truly sustainable impact (Grira et al. 2025). By embracing systems that minimize energy needs or utilize renewable sources, such as geothermal energy, microbial production is emerging as a practical, scalable path to clean energy.

One of the most exciting prospects of microbial activity is its ability to produce valuable chemicals. Instead of relying largely on fossil resources, microorganisms can generate essential compounds from renewable carbon sources, at best from CO_2 (Waltz 2024). This approach contributes to cleaner production cycles, although the energy required for carbon reduction needs to be provided by a smart integration of carbon sources (industrial off gas, agricultural, and municipal waste) with biotech production plants and energy grids.

The ability of microorganisms to convert biomass into energy opens exciting possibilities for localized, efficient energy systems. Locating production facilities near biomass sources, with customized technologies and microbial strains tailored to regional needs, enhances both sustainability and economic viability. Genetic improvements to microorganisms through classical genetics make this approach accessible worldwide, ensuring that even communities with limited access to technology can participate in a green energy future. The potential of genetically tailored microorganisms, however, should be leveraged, and microbiologists worldwide should raise awareness of the power and risk management of genome editing.

Microbial energy production is more than an energy alternative; it is a visionary pathway to store clean energy in biofuels and hydrogen, fostering renewable energy cycles. Algae, driven by the limitless energy of sunlight, present sustainable sources for biodiesel, while microbial biofuels unlock the potential for nearby, ample energy sources. Beyond energy, microbial biofuels serve as renewable resources for synthetic chemistry, helping shift reliance from oil to bioethanol and microbial lipids. With continued investment, microbial energy can fuel a new era of renewable, economically sustainable energy (Crowther et al. 2024).

This perspective highlights microbial energy as a key component in building a resilient, clean energy infrastructure, offering valuable chemicals and conserving energy for a brighter, sustainable future.

Recommendations:

Support Innovation: Advance microbial genome editing for optimized energy production.

Integrate microbial systems. Connect microbial technologies with industrial and municipal waste streams to enhance resource recovery and sustainability.

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Promote accessibility. Develop affordable, scalable technologies for adoption worldwide.

Encourage collaboration. Foster partnerships between scientists, policymakers, and industries.

Increase awareness. Educate stakeholders on the benefits of microbial energy. Advocate for sustainable practices and responsible genome editing.

Multiorganismic interactions in the microbiome and self-sustainability of health

The microbiome is essential for human and plant health and is involved in many processes, such as metabolism, nutrition, and immune system activation (Tomasulo et al. 2024). Emerging evidence implies that specific changes in the microbiome participate in the development of various diseases, including diabetes, liver diseases, tumours, and pathogen infections. The microbiome involves the interaction of different taxonomic kingdoms, including the cells of the host, the immune system of the host, fungi, protists, bacteria, archaea, and viruses. Recent studies suggest that mammals and their individual gut symbionts can have parallel evolutionary histories, as represented by their congruent phylogenies. These 'co-phylogenetic' patterns are signatures of ancient co-speciation events and illustrate the cohesiveness of the mammalian host-gut microbiome entity over evolutionary times. This conceptual framework applies to all multicellular organisms, which is the result of the evolution of the organismal genome, as well as of the genome of the microbes to which they provide an ecological niche. In this framework, every one of us is a walking hologenome, where microbiomes profoundly influence host fitness, yet the processes that drive the evolution of host-microbiome systems, including the interactions between the different components of the system are poorly understood. The first theme addressed was the Holobiont theory of Evolution, drawing a parallel between plants and humans (Rodrigo 2023).

The panel converged on the consensus that, in order to understand how the genes of the host shape the structure of the microbiome, the fitness of the host has to be considered as the result of multi-kingdom interactions and, while there is an extensive knowledge on the structure of the bacterial communities, the mutual relationships between bacterial communities and fungal, archaeal, and viral communities still lies in the heart of darkness and should be a major focus for future investigations.

Understanding cross-kingdom interactions is crucial for One Health approaches. In fact, the definition of a healthy microbiome depends on the cooperative interactions between commensal species and competitive interactions between commensals and pathogens. Commensal species compete with pathogens through several mechanisms, including the production of bacteriocins, antibiotics and also by directing the immune responses against the pathogen through the activation of trained immunity, an ability shown by yeasts, such as *Saccharomyces cerevisiae*. Viruses can also play a role in the activation of immune responses that decrease or increase the risk of other infections. In this framework, bacteriophages and phage therapy are viable tools to maintain or restore balanced communities of microbes that support normal functions in the body or environment, in addition to the use of probiotics.

The environment appears to be a major player in the transmission and dynamic nature of the host microbiomes. Evidence of interdependencies between the bacterial and fungal microbiome can be found in plants, in foods such as Kefir, and in the gut of ruminants, as well as humans. These cross-kingdom interactions include the role of the microbiome in immune training and immune maturation, from the childhood to the adulthood. The reduction of microbial exposure in the first 18 months of the child could, in fact, explain the rise in Non-Communicable Diseases in the globalized world. Examples on cooperative-competitive dynamics between bacteria, yeasts, and viruses in a one health perspective show how a healthy microbiome depends on a healthy environment where the environmental microbiomes serve as reservoirs of essential microbes for the self-sustainability of health of plants, animals, and humans (Sessitsch et al. 2023).

Recommendations

Advance research on cross-kingdom microbial interactions. Prioritize studies that investigate interactions between bacteria, fungi, viruses, and other microbiota to fully understand microbiome complexity and its influence on host fitness.

Embrace the holobiont and One Health Frameworks. Promote integrated approaches that consider the host and microbiome as co-evolving systems, incorporating environmental, animal, and human health into a unified research and health strategy.

Support microbiome-based therapies. Encourage the development of interventions such as probiotics, phage therapy, and microbial-based immune modulators to maintain or restore microbiome health.

Protect and restore environmental microbiomes. Safeguard environmental microbial diversity as a foundation for sustainable health. Early life exposure to rich microbiomes should be preserved to support immune development and resilience against disease.

Food and environmental microbiomes: a One Health perspective

Several aspects of microbiomes were discussed—the effect of nutrition and environment in health and disease and interactions between human animal and environmental microbiomes. Panellists reviewed studies of complex microbial communities (bacteria and fungi) in the human and animal body aimed at understanding the molecular factors that influence the host's immune response. Clearly, diet affects the composition of the intestinal microbiota and is influenced by the metabolism of key molecules on the intestinal microbial community and on health. Important factors in human nutrition are food globalization and fermented foods, which affect the gut microbiome and gut disorders. In this context, there was also a discussion on the addition of beneficial bacteria, which is achieved mainly by the consumption of fermented foods.

The discussion also focused on AMR in the human, agricultural and environmental microbiome (Lammie and Hughes 2016). Similarly to how zoonotic infections can give rise to epidemics and even pandemics, a major cause for AMR emergence is spillover of antibiotic resistance genes from bacteria that infect agriculturally important animals to those that infect humans. It is, therefore, not surprising that the recommendations regarding AMR that were presented in the United Nations General Assembly in September 2024, also included a 30% reduction in (inappropriate) antibiotic use in animals by applying new policies, such as elimination of the use of medically important antimicrobials for growth promotion, forbidding the use of the highest-priority antimicrobials for preventative treatment in animals, and requiring all antibiotics to be given exclusively under the guidance of a veterinary professional (WHO 2023).

Just like crowding in hospitals increases hospital-acquired infection and AMR transmission, crowded animal housing increases

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the risk of resistant infections in agriculture. Crowding of animals increases not just infection susceptibility, but also the chances of transmission of AMR between different bacterial strains. Therefore, better agricultural practices, not just veterinary practices, have become very important.

Another important One Health aspect is sometimes referred to as 'environmental health'. Environments that are highly polluted increase the relative abundance of multiresistant organisms due to co-resistance; AMR loci tend to also encode resistance to heavy metals and other environmental toxins. Thus, polluted ecosystems that are in proximity to humans or agricultural animals increase the risk for AMR transmission to medically important pathogens.

Recommendations

Increase public awareness on microbiomes. Promote educational campaigns on the role of microbiomes in food systems, gut health, and environmental sustainability.

Integrate microbiomes into policy frameworks. Encourage governments and international organizations to integrate human, animal, and environmental microbiomes into health and food system strategies.

Reduce inappropriate use of antibiotics in agriculture. Support the adoption of policies aimed at minimizing the misuse of antibiotics in agriculture to combat AMR.

Promote the One Health approach to AMR. Increase public understanding of AMR transmission pathways between agriculture, the environment and human health within the One Health framework.

Educate on fermented foods and sustainable practices: Raise community and consumer awareness of the benefits of fermented foods and the importance of sustainable food production.

Ensure access to reference micro-organisms. Recommend that organizations such as WHO, FAO, and EPPO facilitate access to reference material of pathogenic microorganisms for rapid identification in health, agriculture, and plant protection.

Simplify access and benefit-sharing policies for identification. Establish streamlined policies for access to microbial reference materials and associated data when used solely for identification and authentication purposes.

In conclusion, the scientific and technological capacity to capitalize on microbial power exists, but the future will depend on collective international action, supportive policies, inclusive economic models, and sustained investments.

Microorganisms, the ancient architects of life, are now essential partners in shaping a sustainable, resilient future.

Empowering knowledge: material and data repositories

Over the past century, advancements in microbiological research and techniques have significantly enhanced our understanding of microbial diversity, its vast potential for biotechnological applications, and its implications for animal and human health. The advent of DNA-based methods and, more recently, genome sequencing for microbial identification, has revolutionized our perception of microbial diversity (Locey and Lennon 2016). These approaches have uncovered an enormous range of previously uncultured and unrecognized microorganisms, often referred to as, 'microbial dark matter'. However, simply cataloging and naming this diversity is insufficient. The true challenge lies in the detailed characterization of these organisms. A thorough analysis of viable cultures is essential to bridge the gaps between genetic information and real-world ecological functions. The work towards understanding microbial roles in ecosystem processes, such as climate change mitigation, soil fertility enhancement, and other essential ecosystem services, represents some of the most exciting and innovative developments in microbiology.

The cultivation, purification, and characterization of microorganisms remain essential steps for unlocking their future potential. These efforts represent a significant investment, funded largely by taxpayers through public research initiatives. The costs associated with isolating, characterizing, and maintaining long-term microbial strains have been widely recognized (Jörg Overmann 2015) and are comparable across both developed and developing economies. Preserving microorganisms in culture collections safeguards this investment, creating a solid basis for future advancements. Importantly, the costs of strain preservation and maintenance are minimal compared to the expenses of initial isolation and characterization, underscoring the value of sustained investment in culture collections.

Culture collections are organized within national, regional (e.g. Europe, Asia, the Americas), and international networks, which facilitate the improvement of preservation techniques and quality standards (Kurtböke et al. 2019). At the international level, the World Federation for Culture Collections (WFCC), a federation under the IUMS, serves as a catalyst, connecting public research, the private sector, and governments. WFCC member collections play vital roles in the ex-situ conservation of microorganisms, which are often excluded from conventional conservation efforts. Beyond their core responsibilities of preserving microbial diversity and providing access to reference materials, they actively contribute to research, education activities, and policy development, reinforcing their importance in both scientific and societal contexts.

The availability of reference materials and associated data is crucial for modern science. Not only does this ensure scientific integrity and enable error detection, but data availability also facilitates the development of the global bioeconomy and advances health and medicine through interdisciplinary research, data reuse, and integration. In collaboration with the WFCC-MIRCEN World Data Center for Microorganisms, the WFCC plays an active role in global data sharing by collecting and providing information about culture collections worldwide, as well as an aggregated catalogue of microorganisms (Ma et al. 2019). Despite the clear importance of data integration (Schober et al. 2024), a standardized approach for microbial data has yet to be established.

The increasing use of culture-independent approaches is rapidly expanding the knowledge of novel lineages and the global diversity numbers. The growing body of evidence suggests that many prokaryotic organisms exhibit global distribution, more according to particular environmental niches than to geographic regions. Similarly, the dispersal of saprobic, nonhost-associated fungi may follow this pattern. This near-borderless distribution of microorganisms contrasts sharply with the constraints imposed by national ABS regulations, which complicate the collection and study of microorganisms in many parts of the world. The isolation, export, deposition, and access to microbial materials are now governed by various restrictions (Yurkov et al. 2019) under the Convention on Biological Diversity (CBD) and its supplementary agreement, NP. Two critical, yet often overlooked, aspects of CBD-NP legislation are particularly relevant for researchers. Regulations can apply retroactively, impacting materials collected before the enactment of specific national laws. These regulations formally apply to any biological material removed from its original habitat, including not just cultured strains but also

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environmental samples and herbarium specimens. Unlike many culture collections that routinely comply with ABS regulations, fungaria has yet to fully adapt to these regulatory frameworks. Large type collections, such as the Kew Herbarium with its 50 000 type specimens, will inevitably need to implement similar ABS protocols for their materials, including procedures for specimen exchange and loans.

Whole genome sequencing initiatives provide a solid foundation for the characterization and classification of microorganisms but also present new challenges for microbial systematics, especially with the increasing availability of genomic data and the ongoing discovery of microorganisms known solely from sequence data. The publication of names for organisms known only from sequences under the SeqCode (Hedlund et al. 2022) has altered the traditional approach to describing prokaryotic species. While naming uncultivable prokaryotes under the International Code of Nomenclature of Prokaryotes (ICNP) can and shall be improved in the future (Arahal et al. 2024), the application of the SeqCode to organisms that cannot be deposited in culture collections (Whitman et al. 2024) has been criticized for attempting to circumvent ABS legislations that refer to physical genetic resources but do not consider genetic data. However, physical intervention into a sample is required to obtain a nucleotide sequence. Digital Sequence Information (DSI), referring to genetic data, is the subject of ongoing discussions (Scholz et al. 2022) regarding whether it should be regulated similarly to physical genetic resources and what kind of ABS mechanism could be applied (Sett et al. 2024). Concerns about DSI focus on issues of fairness, equity, security, and governance. There is a fear that genetic data, once digitally accessible, could be exploited by companies or researchers without providing appropriate compensation or recognition to the source countries or communities that contributed to the biological material. Other concerns include potential conflicts over ownership and patents, as well as the lack of national regulatory oversight. While the deposition of physical cultures is typically overseen by culture collections, to ensure compliance with CBD-NP legislations and valid publication of prokaryotic names is regulated by the ICNP (Oren et al. 2023), the deposition of DSI and the formal publication of new taxa under the SeqCode currently fall outside any legal framework.

Collaborative efforts in discovering, describing, and preserving microbial biodiversity are crucial for advancing research and development. This includes facilitating access to reference materials, promoting their exchange to enhance availability, and sharing knowledge to ensure the safe preservation of microorganisms in their countries of origin. Currently, genome sequences derived from viable reference material dominate public databases, although contributions from fungaria (Royal Botanical Gardens Kew 2024) are expected to grow as DNA extraction and sequencing techniques continue to advance. However, major challenges remain, as highlighted by panel discussions, including the complex legal framework governing physical reference materials and their associated data, such as DSI. The volume of reference material and sequence data will inevitably increase, underscoring the need for clear policies and frameworks linked internationally to manage these resources responsibly.

Recommendations

Bridging the gap between genomic discovery and functional insights. Prioritize investment in the cultivation and functional characterization of microbes to translate genomic data into practical applications in health, agriculture, and biotechnology.

*Sustaining and strengthening culture collections***.** Ensure long-term funding and infrastructure support for microbial culture collections, which are essential for reproducible science and innovation.

*Simplify and harmonize ABS and DSI governance***.** Develop a unified international legal framework to address the complexity of ABS and DSI regulations, enabling equitable access while fostering scientific collaboration.

Standardise taxonomy and data sharing systems. Promote the adoption of global standards for microbial taxonomy and data interpretability to reduce confusion and facilitate the effective use of microbial resources across disciplines and borders.

Promoting global collaboration and access. Strengthen international partnerships between culture collections, data repositories and research institutions, with a focus on improving access, capacity building and equitable participation, particularly for low- and middle-income countries.

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