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Review

Scientists' call to action: Microbes, planetary health, and the Sustainable Development Goals

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SUMMARY

Microorganisms, including bacteria, archaea, viruses, fungi, and protists, are essential to life on Earth and the functioning of the biosphere. Here, we discuss the key roles of microorganisms in achieving the United Nations Sustainable Development Goals (SDGs), highlighting recent and emerging advances in microbial research and technology that can facilitate our transition toward a sustainable future. Given the central role of microorganisms in the biochemical processing of elements, synthesizing new materials, supporting human health, and facilitating life in managed and natural landscapes, microbial research and technologies are directly or indirectly relevant for achieving each of the SDGs. More importantly, the ubiquitous and global role of microbes means that they present new opportunities for synergistically accelerating progress toward multiple sustainability goals. By effectively managing microbial health, we can achieve solutions that address multiple sustainability targets ranging from climate and human health to food and energy production. Emerging international policy frameworks should reflect the vital importance of microorganisms in achieving a sustainable future.

INTRODUCTION

The emergence of microorganisms more than three billion years ago[1] has fundamentally shaped the planet, enabling the existence of all other life forms. Today, microorganisms are the most diverse organisms on Earth[2,3] (Figure 1), estimated to represent over 99% of all species.[3] They inhabit almost every environment, from deep ocean trenches to human guts. The unique catalytic capacity of microorganisms means that they are central to the cycling of most of the major elements (including H, C, N, P, O, and S) essential to life on Earth.[8] Just as the human microbiome is critical to the functioning of individuals, the global microbiome is central to the functioning of the planetary system.

In 2012, the United Nations Sustainable Development Goals (SDGs)[9] were proposed to provide an overarching framework to move toward a sustainable future on our planet. Yet, although microbial activity is fundamental to sustaining all life, the role of microorganisms is not explicitly represented in the high-level policy documentation aimed at achieving these goals. Across the 560 official multilateral treaties of the UN Secretary-General,[10] explicit mentions of microorganisms or associated solutions are largely absent. Unlike other forms of life, including plants and animals, the lack of microbial representation may stem from their ubiquitous and inconspicuous nature. However, an ever-expanding field of research shows how different microbial groups perform different functions, and the effective management of microbial communities can provide solutions for improving various aspects of life, from human health[11] to energy[12] or food production.[13] In addition, promoting microbial health can help address global threats like climate change,[14,15] biodiversity loss,[16] pathogen emergence,[17] pandemic outbreaks,[18] food insecurity,[13] and increasing societal inequalities.[19] And yet, until now, few financial or regulatory policies recognize the need to incentivize the deployment of microbial solutions or the targeted microbial research that is needed to address our international sustainability targets.

Over the last decade, several studies have highlighted the need to consider microorganisms and associated technologies for achieving different SDGs (see Timmis et al.[20] and articles therein; Akinsemolu[21]). Here, we build on these perspectives to provide an overview of the potential for integrating microbial technologies into all of these sustainable agendas. Recognizing that microorganisms are directly or indirectly associated with every one of SDGs, we review the key overarching areas where emerging microbial technologies have begun to provide tangible solutions that can contribute to achieving a sustainable future (Figure 2). In addition, by clustering these microbial processes into seven overarching areas, we identify tangible synergies that reveal where microbial innovation can help in accelerating multiple "Global Goals" in tandem. By reviewing and highlighting the fundamental role of microorganisms in achieving the SDGs, we hope to encourage the explicit consideration of microorganisms in international sustainability planning and policy agreements.

NURTURING HEALTH AND ADDRESSING DISEASE

SDGs: 1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 16

Good human health is a necessary precondition for many societal functions, including education (Goal 4), employment and economic prosperity (Goal 8), community well-being and peace (see Anand et al.[19]) (Goals 11 and 16), and equality (Goals 5 and 10). Health is prejudiced by many factors, including poverty (Goal 1), malnutrition (Goal 2), environmental pollution (Goals 6 and 12), limited access to clean water and healthcare (Goals 3 and 6), and conflicts, especially those leading to the displacement of peoples and the rise in refugee camps (Goal 16). As acknowledged by the One Health concept,[22] health is also directly linked to environmental reservoirs of pathogens and antibiotic resistance genes and implicitly dependent on a diverse range of flora and fauna, natural and managed environments, and the food and other products derived from them.[23,24] Yet, despite the highly integrated nature of health within the SDGs, there exists a broad range of microbial technologies that can specifically target many of the greatest direct threats to human health.

Microbial technologies provide barriers to risks posed by infectious and toxic agents in the environment. They include, for example, wastewater treatment and processes for purification of drinking water (e.g., facilitated by membrane biofilm reactors), which can remove harmful biological and chemical agents.[25,26]

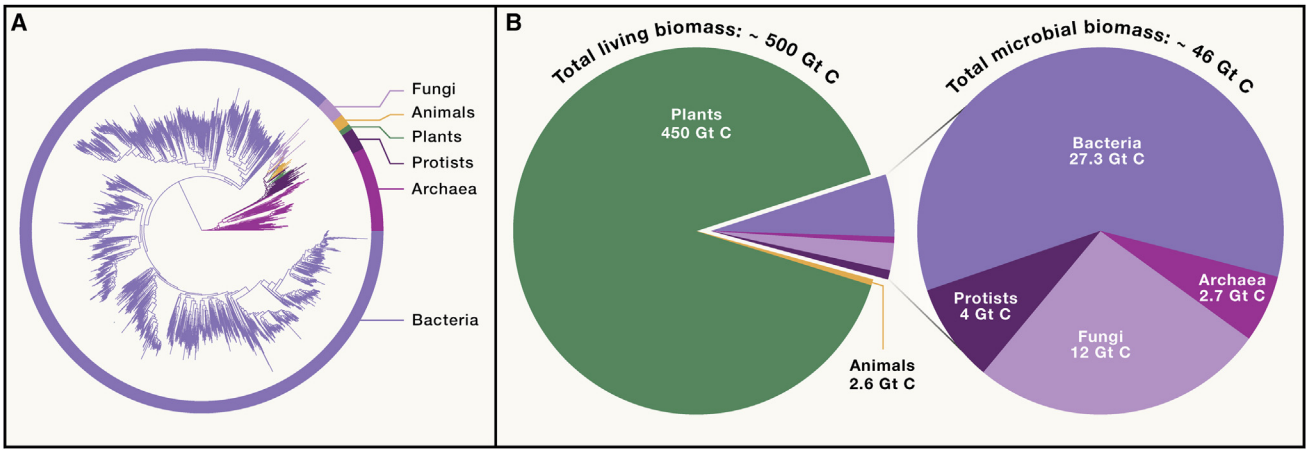

Figure 1. Microbial contribution to the tree of life and to global living biomass

(A) Microbes represent the overwhelming majority of phylogenetic diversity in both prokaryotic and eukaryotic realms.

(B) Microbes account for ~46 Gt C of living biomass, the largest proportion after plants. Data are from Hug et al.[4] for (A) and Bar-On et al.[5] for (B), with bacteria and archaea estimates for (B) updated based on Bar-On and Milo.[6] These data do not include the substantial viral diversity and biomass on Earth, which remain insufficiently quantified to include.[7]

Wastewater treatment also now affords near real-time surveillance of pathogens in community wastewater,[27] inactivation of emerging pollutants (e.g., phthalates[28]) and antimicrobial resistant pathogens,[29] recovery and recycling of resources like nitrogen and phosphorus, and conversion of waste carbon into methane as an energy source[30] (Goals 6 and 7). Deployment of these technologies in communities lacking clean water is key in reducing inequalities (Goals 5 and 10). Moreover, vector control, such as the insertion of microorganisms into arthropod vectors (e.g., mosquitoes) to prevent reproductive cycles,[31,32] can reduce the risk of pathogen transmission (Goal 3).

As well as being used for risk prevention, microbial technologies are central in addressing countless health challenges. They are the basis of vaccines and many pharmaceuticals that reduce the incidence, severity, and mortality of infectious and secondary non-infectious diseases, such as cancers (Goals 3, 5, and 10). Bacteria are being developed to image tumors[33] and, along with bacterial minicells[34] and bacterial membrane vesicles,[35] are being designed to deliver toxins and other compounds to tumors.[33] While antibiotics have saved countless lives, their inappropriate use in healthcare and animal husbandry has selected and promoted the spread of multi-drug-resistant organisms, which has become a pressing contemporary global health crisis.[36] Of particular concern are the multi-resistant ESKAPE pathogens (see De Oliveira et al.[37]), especially in hospital settings. Pathogenic biofilms are also particularly challenging as slow-growing or dormant microbes can be phenotypically antibiotic resistant, resulting in rapid biofilm re-establishment post-treatment.[38] Potential therapies include conjugation-based delivery systems for antimicrobial toxins[39] and CRISPR-Cas-based approaches that can either destroy target pathogens or their antimicrobial resistance.[40,41] In addition to the search for new or modified antimicrobials and anti-virulence therapeutics,[38,42,43] pathogens of microbes such as bacteriophages[44] and bacterivorous bacteria like *Bdellovibrio* are being explored. However, although phage therapy is relatively affordable and lends itself to use in lower-income settings (Goals 3 and 10), its development as a therapy is still in the early stages.[45] Moreover, expanding lateral flow diagnostic tests to new target conditions is particularly compelling, as these tests are crucial in monitoring and managing rapidly emerging infections, can be used independently of, and hence reduce the burden on, health services,[46] and can be manufactured at a fraction of the cost of accessing and maintaining healthcare and diagnostic infrastructure[46] (Goals 3, 5, 9, and 10).

Among the most promising targets for novel and holistic health interventions are the innovations in human microbiome technology. Microbiota have been identified in niches across the human body and even *de novo* tumor environments.[11,47] Gut microbiota are essential for normal development of the immune, metabolic, and nervous systems,[48–50] and are involved in many processes regulating central, but also distal, bodily functions, e.g., via the gut-brain[51] or gut-skeletal muscle[52] axes. Balanced and healthy gut microbiota are essential for healthy gut physiology, including resistance to infection, metabolizing foods, producing vitamins and amino acids, and degrading non-digestible carbohydrates (Goals 2 and 3). However, microbiota and their metabolites have been implicated in a range of disorders, such as atherosclerosis, cancer, and depression.[53,54] In addition, by metabolizing endo- or xenobiotic entities, microbiota control the impact of such compounds on the host, including the effectiveness of health interventions like chemotherapy or vaccination.[55] The substantial recent interest in developing microbiota-targeting interventions that address cancer; disorders of the metabolic, (neuro-)muscular, and respiratory systems; and skeletal, dermatological, and communicable diseases attests to the promise of managing many diseases by microbiota modulation.[56] Yet, significant challenges exist for pertinent innovation (and regulation) due to the significant variability in microbiota composition within and across individuals, ill-understood microbial behaviors in different micro-environments, and varying treatment responses.[56] A case exemplifying the long timelines for the

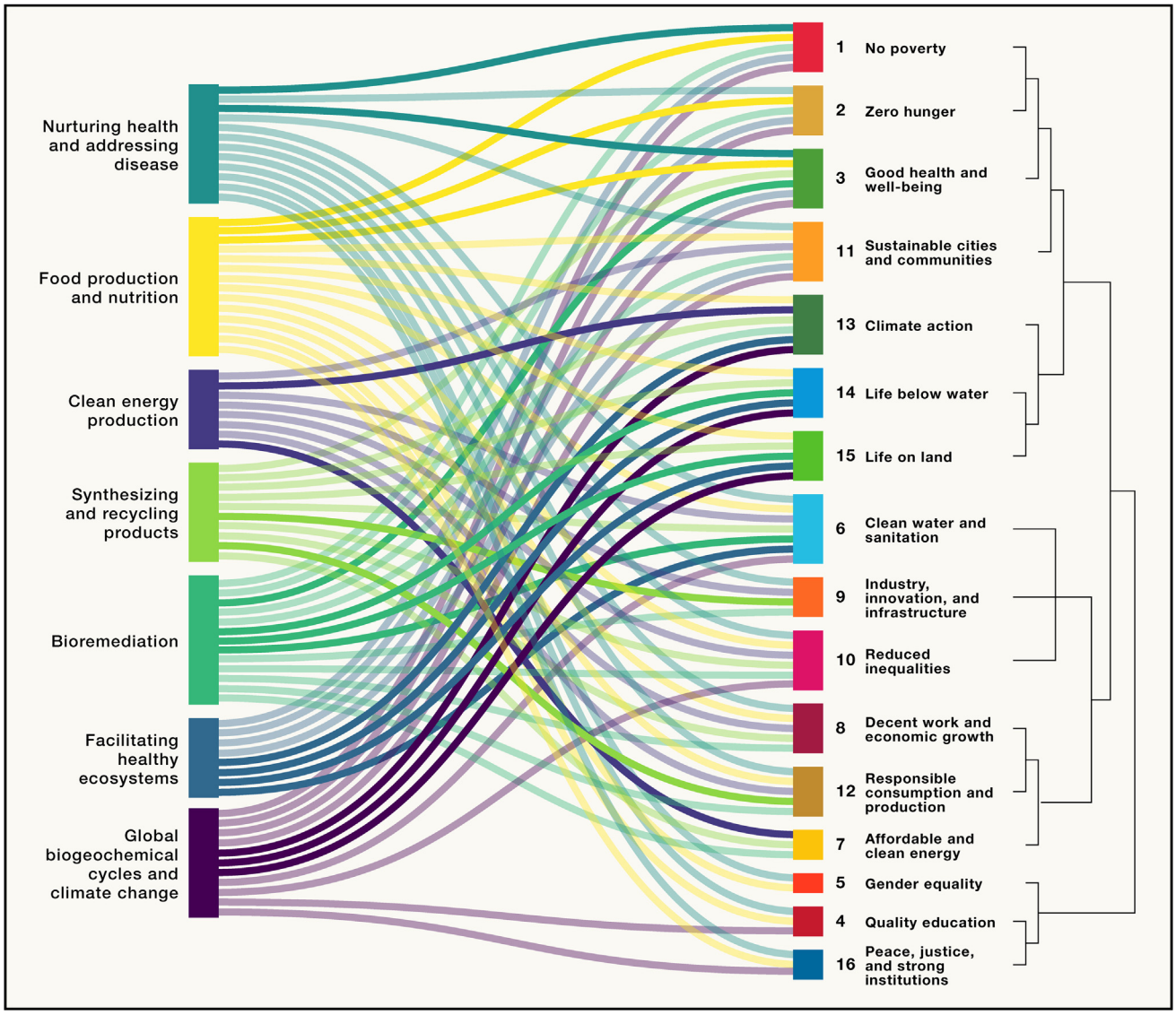

Figure 2. Seven key pathways that microbial research and technology can be used to reach the SDGs

Links show which SDGs (right) are most likely to be positively influenced by targeting each category (left), with the most direct links highlighted in bold. The dendrogram clusters the SDGs based on Euclidean dissimilarity of the connecting links, showing which SDGs are likely to be influenced by microbes in similar ways. Goal 17 (partnerships for the goals) is not included because this is an overarching SDG relevant to all goals but not specifically influenced by microbial research and technology. Goal 17 is discussed in section "partnerships for the goals."

introduction of highly promising microbiota-based interventions into standard practice is fecal microbiota transplant (FMT). While a Dutch randomized controlled trial in 2010 found that FMT was superior to standard treatment (vancomycin) for treating recurrent *Clostridium difficile* infection (rCDI)[57] and other trials have confirmed these findings,[58] the US Food and Drug Administration (FDA) did not grant regulatory approval for FMT treatment of rCDI until 2023. While there are good reasons for the delay of the decision to 2023, chiefly based on safety and quality concerns relating *inter alia* to donor screening, proper handling of fecal matter, and risks of undetected infectious agents or food allergens,[59,60] this case shows how long it can take for convincing evidence to be gathered and accepted. Also, more recent trial modes, such as N-of-1 studies in individuals (see Davidson et al.[61]), deserve more attention to find optimally personalized microbiota-based health and disease management strategies (Goals 3, 9, and 10). A better understanding of microbiota behaviors, metabolism of xenobiotics (chemicals present in organisms that are not naturally produced), and both adverse events and synergies with other interventions such as antimicrobials and phages is needed. Achieving this across complex microbiomes will require development of scalable capture and characterization approaches like viral tag and grow.[62]

Disease susceptibility and responses to prophylaxis and therapy vary significantly among individuals, due in part to human genetic and physiological variations, age, nutrition and lifestyle,

and environmental and socio-economical settings, but also in part to variations in microbiomes. As a result, many one-size-fits-all healthcare approaches have unacceptably high failure rates. Rapid transition to precision (personalized) medicine is essential. The complexity of integrating all of the contributing parameters in precision medicine, especially the complex variables of microbiome composition and function, will require serious involvement of artificial intelligence.[63,64]

Despite the enormous potential of microbial technologies to address many current challenges, it seems likely that challenges will continue to increase, in particular the problem of decreasing access to healthcare, especially in low-resource settings, given rising costs of healthcare, the increasing human population, the aging population, global warming, increasing economic and social inequalities, and increasing displacement of peoples into informal settlements and refugee camps. Some of the longer-term policies to confront these challenges are, by necessity, likely to be disruptive. To secure the success of such policies, it will be important that they are evidence-based, accountable, and supported by the general public. This requires raising the level of understanding of relevant issues in society, especially where societal participation in implementation of policies is required (e.g., in greater engagement of individuals in their own healthcare[64]). Global education—especially of children in school but also of adults in the context of lifelong learning, tertiary education, and other settings—in relevant aspects of healthcare will be crucial for confronting global healthcare challenges in the long term. Global education benefits Goal 3 for certain, but also Goals 4, 5, and 10. A concept for education in societally relevant microbiology was recently developed that could serve as a model for global education in healthcare and other societally important issues.[65]

FOOD PRODUCTION AND NUTRITION

SDGs: 1, 2, 3, 4, 5, 6, 8, 10, 11, 12, 13, 14, 15, 16

Inadequate food availability and access is a major contributor to global poverty (Goal 1), hunger (Goal 2), poor health and nutrition (Goal 3), and inequality (Goals 5 and 10). Soil, plant, and animal microorganisms are vital for regulating sustainable food production, decreasing waste, and improving food distribution and access, and so have the potential to significantly alleviate these pressures.[13,66] Making better use of microbial biotechnology in food systems will also help to reach key SDG targets of reducing food waste (Goal 12), greenhouse gas emissions (Goal 13), and pollution of soil, water, and air (Goals 6, 11, 14, and 15).

Microbial-based methods are already providing promising alternatives to the use of synthetic chemicals in food systems (e.g., as pesticides and fertilizers) that are harmful to the environment and human health.[13,67] For example, microbial inocula such as arbuscular mycorrhizal fungi or SynComs (synthetic microbial communities co-cultured to mimic the native microbiome[68]) can help to restore soil functions and increase plant yields and disease resistance, reducing reliance on artificial pesticides and fertilizers.[69,70] These solutions are becoming increasingly important as climate change and land use change continue to drive the degradation of soils across the globe. Promoting the functioning of soil microorganisms is increasingly critical for plant resilience and nutrient access as soil conditions become increasingly harsh.[71] While microbial inoculants are a promising strategy to improve plant health, approval of such products in Europe currently requires field tests that confirm increases in crop yields.[72] Nonetheless, failure may occur due to soil characteristics and competition by Indigenous microbiota. To overcome potential failures, biostimulant products derived from microbes are being developed. In a recent study, root irrigation with solid fermentation products of *Streptomyces* strain 769 significantly reduced watermelon *Fusarium* wilt disease incidence by 30% and increased plant biomass by 150% in a continuous cropping field.[73] Pre- and probiotics can also improve livestock growth and health and reduce harmful byproducts such as methane,[74,75] as well as strengthen fish immune responses and food digestion in aquaculture.[76] Biological control, whereby microbial antagonists are used to inhibit pathogen growth directly or indirectly through immune priming,[77] also offers an eco-friendly and cost-effective approach for managing diseases in plant and animal food systems. However, current methods are constrained by inconsistent efficacy in field conditions and limited product diversity.[67] More research is needed to ensure products are viable and can provide the desired outcomes in field conditions. New breeding strategies that focus on evolving symbioses[78] or breeding for traits that attract and maintain beneficial microbes via quantitative trait loci (QTLs) could also be harnessed to improve plant and animal health.[79] Integrating ecological theory (e.g., metacommunity theory, priority effects) to identify and develop microbes that can compete against pathogens and successfully colonize plants, or to alter microbiomes to be resistant to environmental disruption, could be used to help achieve this.[79]

In addition to the use of microbial amendments and products to increase efficiencies in plant and animal food systems, microbial protein can provide an important food source for humans and animals with reduced environmental impact.[80] Emerging technologies like precision fermentation can produce the proteins, fats, and carbohydrates traditionally sourced from plants and animals.[81,82] Mycoprotein is already a well-established food source, with the potential to reduce up to 583 $MtCO_2$ equivalents per year[83] and limit the use of freshwater, antibiotics, pesticides, and fertilizers.[80] Additionally, precision foods and complements based on pre-, pro, sym-, or postbiotics are being increasingly explored to promote healthy gut microbiota or treat dysbiosis. For example, a recent review[84] highlighted future developments based on genetic engineering of microbes to improve the nutritional quality of foods across a range of applications, such as ingredient production for live therapeutics, single-cell proteins for improving nutritional profiles, or cell-produced animal flavorings to allow meat and dairy alternatives to more closely resemble the products that they substitute.[84] However, while many of these applications are considered promising, research remains limited regarding their safety profiles and effectiveness in achieving concrete and reproducible health outcomes. As a consequence, important regulators (e.g., the European Medicines Agency and the US Food and Drug Administration) are hesitant to grant health claims, i.e., approving live biotherapeutic product status, which is a necessary prerequisite for reimbursement.[85] Therefore, a large proportion of

microbiota-based health intervention developers remain somewhat focused on markets in which health claims historically have also been granted for alternative forms of medicine, such as China, where interventions based on Chinese traditional medicine receive regulatory approval and can be reimbursed.[56] It remains to be seen when the evidence base matures and for microbiota-based food interventions to become mainstream in Western markets.

Efforts to improve poverty, hunger, health, and inequality must extend beyond increasing food production and include improvements in food distribution and accessibility. Over 30% of food is wasted during or post production,[86] with microbes both contributing to and mitigating this issue. Microbes cause disease and post-harvest spoilage, but they can also reduce waste through pre- and post-harvest biocontrol methods. Although various microbial treatments have been tested, their widespread application remains limited due to inconsistent effects and a lack of industry adoption.[86,87] Effective food preservation methods involve the implementation of the cold chain, airtight packaging, pH control, and moisture reduction to inhibit growth of spoilage microbes. Additionally, targeted fermentation by specific microorganisms (e.g., lactic bacteria and yeast) has been used by humans for millennia to preserve food and enhance flavor. Fermentation is affordable, scalable, adaptable, and safe when proper controls are in place,[88] and it can extend the shelf life of food products. However, a deeper understanding of the post-harvest microbiome is needed to develop more robust and scalable biocontrol and food storage methods.[86]

Making better use of microbial technology to enhance food production and nutrition will indirectly benefit numerous SDGs in addition to directly addressing the SDGs discussed above. Reducing hunger, poverty, disease, and inequality (Goals 1, 2, 3, and 10) will improve the ability of people to pursue education (Goal 4), likely open up new development opportunities for women (Goal 5), and have long-term positive effects on community well-being and peace (Goals 11 and 16). Improved health and nutrition will also improve the ability of people to contribute to the local and national economy (Goal 8). Additionally, the global food production system is a driver of climate change (Goal 13) and ecosystem destruction, and bioengineering of the soil microbiota can indeed reduce the climate impact.[89,90] Improving the efficiency and sustainability of food systems, as well as making better use of microbes as food products, will also reduce negative impacts on natural terrestrial and aquatic ecosystems (Goals 14 and 15).

CLEAN ENERGY PRODUCTION

SDGs: 6, 7, 8, 9, 10, 11, 12, 13

International reliance on fossil fuels for energy extraction, transportation, and consumption contributes to numerous social and environmental injustices, including energy inaccessibility, pollution at sites of extraction and during transportation, and the disproportionate burden of climate change on developing countries.[91] Development and deployment of microbial resources toward clean energy production will directly assist in achieving affordable and clean energy (Goal 7), and systems that simultaneously reduce and remove greenhouse gas emissions will support efforts toward climate action (Goal 13). Realizing this ambitious vision would set society on a path to develop a resilient supply of energy that can respond to events, natural or otherwise, that disrupt supply chains, achieve the NetZero emissions predictions of the International Energy Agency and the IPCC climate pathway reductions, and allow numerous new communities to reap the economic and other benefits of producing some or all of their own energy.[92] Achieving this vision in a responsible manner dictates that microbial bioenergy be only one of multiple solutions that take into account responsible management of natural resources, science-based and transparent accounting for carbon, initiatives to protect ecosystem biodiversity, and systems to support and include as many communities as possible.[93]

If done right, moving toward microbial bioenergy will transform the world's industry and infrastructure (Goal 9) and lead toward responsible consumption and production (Goal 12) by re-modeling energy grids and storage systems that must be built to accommodate bioenergy sources. Microbe-based clean energy systems that use abundant renewable agricultural, municipal, and industrial residues will also support efforts toward improving clean water and sanitation (Goal 6) by reducing overall energy consumption and expanding the availability of sustainable wastewater treatment solutions. Additionally, recent models predict that changes in agricultural practices for food, energy, and chemical production will lead to many positive environmental impacts for greenhouse gas reduction and climate mitigation.[94,95] Altogether, harnessing microbial biotechnology and resources for clean energy will ultimately contribute to more sustainable cities and communities (Goal 11).

In many industrialized nations, transportation fuels, including aviation, marine, shipping, and automotive sectors, account for over 30% of petroleum consumption (see https://www.eia.gov/energyexplained/us-energy-facts/). Microbes offer the potential to produce cost-effective biofuels from billions of tons of organic materials, including non-food animal and crop material, as well as agricultural, municipal, and industrial byproducts.[12] Recent studies have demonstrated that the greenhouse gas emissions associated with biological production of ethanol, butanol, and ethylene are 32%–55% less than use of petroleum.[96,97] The potential environmental and socio-economic benefits are substantial, offering regions the opportunity to shift from fuel importers to producers, utilizing locally abundant raw materials, and curtailing environmental hazards of transportation.[98,99] However, integrating microbe-generated biofuels into a circular economy requires innovative scientific approaches and changes in agricultural and industrial practices.

Autotrophic microorganisms, encompassing algae, bacteria, and archaea, possess the unique ability to capture carbon directly from the atmosphere or industrial waste gases, converting them into fuels. This represents the potential for producing net zero carbon emission biofuels.[100] However, the number of biofuels naturally produced by autotrophic bacteria is limited to methane and acetic acid. Through genetic and metabolic engineering, autotrophs have been the potential to produce a wider array of fuels, including methane, ethylene and butanol,

biological oil, and hydrogen,[101,102] but the cost of biofuel production remains high.[103] Challenges involved in scaling growth in industrial settings and enhancing fuel production efficiency (particularly in photosynthetic bacteria) must be overcome to reduce the gap in productions costs between biofuels and petroleum so that this technology can be more widely adopted.[103]

Methane is a potent greenhouse gas, but it is also an abundant carbon feedstock for microbes. It can be converted into valuable products such as bioplastics, biofuels, nutraceuticals, and single-cell proteins.[104] Furthermore, the transition into a hydrogen-based fuel economy is rapidly increasing the production of low-cost methanol, a versatile feedstock for bioconversion. Methylotrophic microorganisms utilize methane or methanol as sole carbon and energy sources, driving their bioconversion into value-added products.[105] Global-scale implementation of these methods requires advancement of genetic tools, adaptation to industrial conditions, and optimized bioreactor and bioprocess design.[106] Potential environmental benefits, including significant reductions in methane emissions and potential removal of atmospheric methane, underscore the importance of this microbial approach to mitigating climate change. An estimated 50,000–300,000 methanotrophic bioreactors are predicted to absorb 240 megatons of methane over 20 years.[107] The reduction of atmospheric methane will become more critical with upscaling of hydrogen production due to the depletion of the hydroxyl radical sink by hydrogen release to the atmosphere that will extend the residence time of methane, thus increasing its global warming potential.[108]

In summary, microorganisms can provide important contributions to the transformation of energy production and reduce greenhouse gas emissions (Goals 7, 9, 12, and 13). Because microbes can be cultivated across the globe by all nations and can grow using diverse local feedstocks, they have the potential to facilitate a transition toward affordable and clean energy by 2030. As such, they also have the potential to support efforts to reduce inequalities (Goal 10) and to promote decent work and economic growth (Goal 8). However, concerted efforts in scientific innovation, agricultural and industrial practices, and global collaboration are essential to realizing the full potential of microbial solutions in shaping a sustainable energy future.

SYNTHESIZING AND RECYCLING PRODUCTS

SDGs: 3, 6, 7, 8, 9, 10, 12, 13, 14, 15

20th century society converted billions of liters of petroleum yearly into a variety of chemicals and materials. Most of this multi-trillion dollar per year industry is located in a few well-developed countries and uses processes that have a negative environmental impact. For these and other reasons, there have been recent calls to create a circular bioeconomy to reduce greenhouse gas emissions and generate products from renewable raw materials[109–111] (Figure 3). The contribution of a circular bioeconomy to a 21st century industrial revolution is large since estimates are that up to 60% of the inputs to the global economy could, in principle, be produced biologically.[111] Below, we make the case that microbes can generate low greenhouse gas chemicals and materials while providing economic and environmental benefits to citizens and communities around the world (Goals 7, 9, 12, and 13).

Available renewable raw materials to feed this circular bioeconomy include billions of tons of organic residues that involve non-food animal and plant material, crops grown specifically for conversion into chemicals and materials, manure, waste from municipal and industrial activities, as well as carbon dioxide sequestered from the atmosphere or generated by industry.[12,112–114] The majority of these organic residues are either combusted (releasing carbon dioxide) as a source of heat and power or released to the environment, which can contribute to phosphorous or nitrogen accumulation and have other negative ecosystem impacts. While developing a circular bioeconomy to generate valuable products from these abundant raw materials will require changes in agricultural and industrial practices (Goal 9), its environmental, economic, and societal benefits (Goals 3, 6, 10, 13, 14, and 15) are enormous given the availability of raw materials in well- and less-developed regions across the globe.[98,99]

Microbes can serve as catalysts to power a new circular bioeconomy. Microbes have performed chemical transformations longer than humans and operate as circular economies themselves. These ubiquitous organisms have driven the evolution of and supported life on the planet, and processes based on their activity can be environmentally and economically sustainable (Goals 7, 9, 12, and 13). Examples include microbial production of hydrocarbons and hydrogen, the >100-year-old industrial use of acetone and butanol fermentations,[115] and using microbial nitrogen fixation to reduce dependence on fertilizer generated by the energy-intensive Haber-Bosch process.[101,102,116] While still in its infancy, there are both emerging and existing examples of the potential for industry to harness the metabolic power of microbes to convert an abundant supply of industrial carbon monoxide and dioxide into cost-competitive bio-based fuels, chemicals, and textiles.[117] In addition, studies and initiatives have both identified bottlenecks or demonstrated the ability to generate cost-competitive microbial products from abundant non-food lignocellulosic biomass[118] and dairy coproduct residues.[119] These examples provide a roadmap for how to develop microbial factories that convert other abundant raw materials into a suite of valuable chemicals and materials with local, regional, and global markets.[120,121]

The time is ripe to develop microbial cell factories. Recent advances in genomics have uncovered a plethora of previously unknown microbial activities with potential societal utility.[109,122] Genomic datasets also provide an ever-growing set of existing and modified genes to deploy for low-cost synthesis of hydrocarbon fuels, methane, substitutes for petrochemicals, or even other compounds that cannot be generated in a cost- or environmentally effective manner by today's industries (Goal 9). Tapping the chemical potential locked in the genomes of native or engineered microbes, or the combined activity of microbial communities, can help design new biological catalysts for a circular bioeconomy.[122] The potential exists for either use of the resulting microbial products directly or after they are chemically modified to increase their societal value and utility.

Life cycle analysis predicts that the benefits of a circular bioeconomy will be maximized by locating biorefineries near the raw materials and infrastructure needed to move materials from producers to consumers.[123] Success will ultimately require models that accurately predict raw material supply, costs of

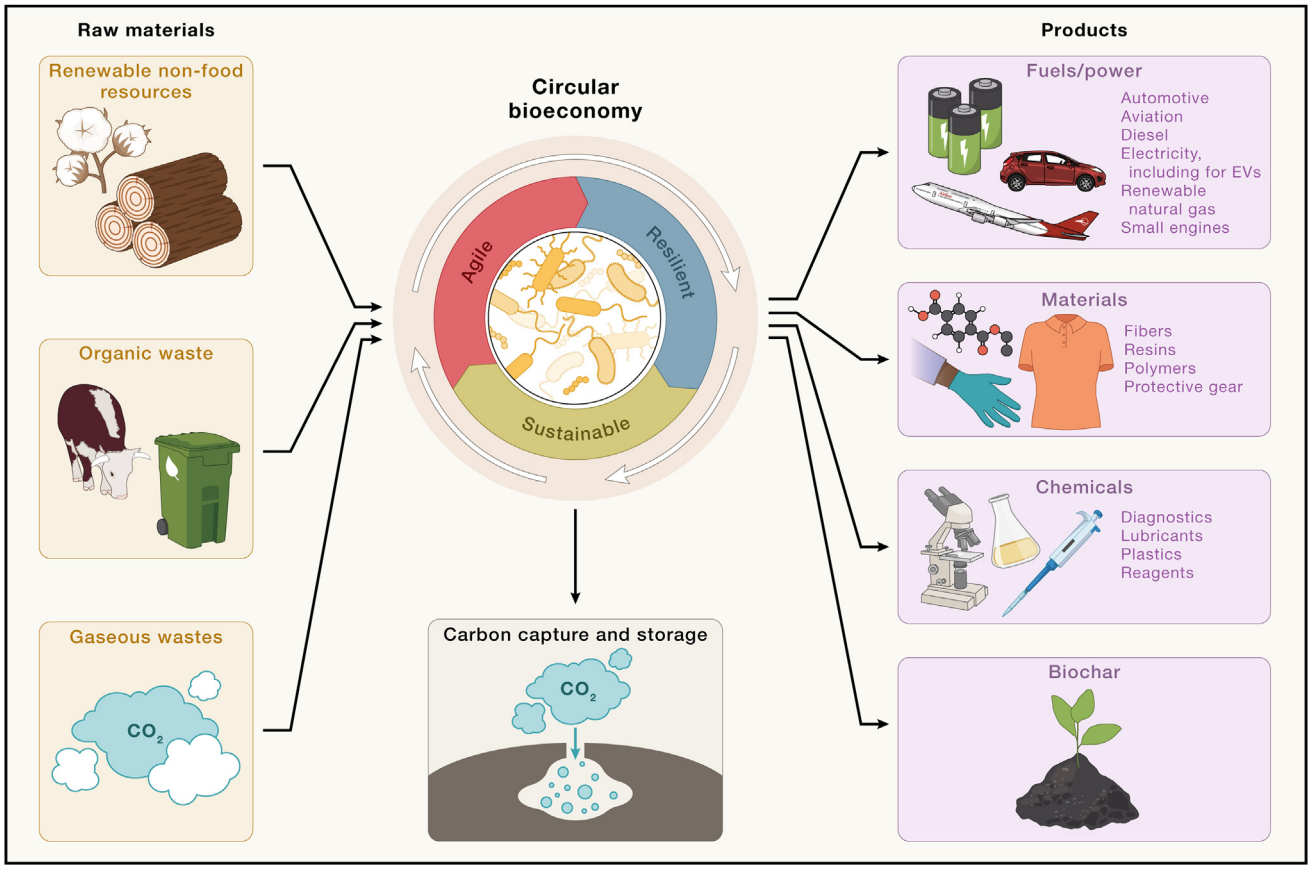

Figure 3. Components of a microbe-powered circular bioeconomy

Left: examples of abundant renewable raw materials (non-food organic residues, CO_2, and other gaseous wastes) to feed a microbially powered circular bioeconomy. Right: examples of potential products generated from these raw materials in a microbe-powered biorefinery (fuels, power, materials, chemicals, and biochar).

purchase and transport to refineries, and expenses to produce, purify, and distribute products.[99,123] Supply chain models predict that a microbe-powered circular bioeconomy can provide new high-technology and other jobs to both industrialized nations and less-developed regions, especially if one considers producing materials locally and moving raw materials from depots to centralized facilities of different scales.[20,110,124,125] It would also be an integral part of an agile supply chain that can respond to changes in raw material supply or consumer demand (Goals 8 and 11). While the cost of building and operating these biorefineries will require public and private sector support, the return on this investment can be substantial, especially in low-income regions of the world that need industrial development (Goals 9 and 11). For example, a microbe-powered circular bioeconomy can provide new high-value economic opportunities to raw materials producers, attract considerable investment, increase highly skilled domestic workforces, and, in turn, improve education and personal financial stability, especially in less-developed and low-income regions of the globe[110,111] (Goals 10, 11, and 12). Moving to a microbe-powered circular bioeconomy can create a new industrial ecosystem that is sustainable, resilient to natural or geopolitical disruptions in supply chains, generates decarbonized products from local renewable raw materials, and provides socio-economic opportunities to more regions of the globe. Over time, movement to a microbe-powered circular bioeconomy will pay considerable dividends to the planet and its inhabitants.

BIOREMEDIATION

SDGs: 1, 2, 3, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15

Current and past industrial and agricultural activities have left us with a legacy of polluted habitats around the world that threaten human health (Goal 3), the functioning of natural ecosystems (Goals 14 and 15), and their ecosystem services such as safe food (Goal 2) and clean water[126] (Goal 6). Bioremediation is a nature-based process that employs living organisms (e.g., bacteria, archaea, fungi, and microalgae and/or their metabolic products) to remove, detoxify, immobilize, and extract contaminants (e.g., hydrocarbons, polychlorobiphenyls, pesticides, herbicides, and/or heavy metals) in a variety of environmental matrices (e.g., soils, sediments, and water).[127]

Bioremediation interventions can use different approaches, including the enhancement of the capability of natural microbial assemblages to degrade/stabilize contaminants (e.g., biostimulation through the addition of nutrients or bioventing

through the insufflation of oxygen) and the addition of microorganisms with desired remediation capabilities to the host or environment (i.e., bioaugmentation[128]). Bioremediation allows an efficient, safe, and cost-effective decontamination of environmental matrices to levels that cannot be achieved by conventional treatments (e.g., pyrolysis, landfilling, and soil washing).[129,130] In addition, it reduces the risks of secondary contamination and ensures a lower carbon footprint[131,132] (Goal 13). A biostimulation experiment based on the addition of inorganic nutrients (nitrogen and phosphorous) to sediments highly contaminated by polycyclic aromatic hydrocarbons (PAHs) revealed a >90% reduction in PAH and greater environmental benefits (estimated in terms of CO_2 equivalents) compared with traditional approaches (i.e., disposal of sediments in landfill areas).[132] Microbial bioremediation has been proven to be effective for wastewater treatment to degrade recalcitrant contaminants (e.g., landfill leachates, textiles, and pharmaceutical wastes), which are generally left untreated by conventional wastewater processes. Bacterial and fungal enzymes such as azoreductase, lignin peroxidase, and laccase, as well as microalgae (e.g., *Chlorella vulgaris* UMACC 001), can accelerate the degradation of persistent organic dyes in textile wastewater.[133,134] Microbial bioremediation can also degrade toxic compounds while transforming organic waste into biofertilizers and biofuels, thus being highly cost-effective[135] (Goal 8).

Microbial bioremediation can also contribute to plastic pollution abatement, especially of micro- and nano-plastics that are extremely difficult to remove using traditional approaches. Most global plastic production ends up in the ocean,[136] with plastic pollution found from the surface down to the deep seafloor.[137–139] The microbial communities colonizing plastic surfaces[140] include bacteria and fungi and "pit-forming" microbes that modify the surface of plastics,[141] contributing to the degradation of several polymers.[142,143] For example, the plastic-degrading bacterium *Ideonella sakaiensis* is able to slowly degrade polyethylene terephthalate, commonly known as PET.[144] A crucial first step is the enzymatic breakdown of the plastic polymer into its monomers terephthalate and ethylene glycol, which are used by the bacterium as a carbon source for growth. The monomers can also be recycled to produce new plastics in an environmentally friendly way.[145,146] Companies are beginning to scale up this process, with the company CarBios announcing a new plant opening in 2025 that aims to recycle 50,000 tons of PET plastic per year.[147] PET is just one kind of plastic, and other plastics will have their own challenges.[148,149] Yet, further research investment has the potential to lead to new technologies that can contribute to the clean-up of plastic pollution (Goals 6 and 14).

Among bioremediation approaches, rhizoremediation, exploiting the high potential of root-associated microorganisms to degrade organic pollutants, appears to be particularly effective in improving the success of phytoremediation of contaminated soils.[150] For example, the rhizoremediation of agricultural soils in Italy heavily polluted by polychlorinated biphenyls (PCBs) reduced the concentration of such contaminants by approximately 20% in 18 months.[151] Other investigations at a German site historically contaminated by diesel fuel hydrocarbons revealed that rhizoremediation can enhance biodegradation by up to 96% in 60 days.[152] With the advent of -omics approaches, it has been possible to identify key rhizome microbiomes and their metabolites with unprecedented resolution, thus implementing microbiome-assisted restoration actions not only of terrestrial plants but also of mangroves and seagrasses.[153] However, rhizoremediation is still not widely adopted by accredited soil remediation experts, partly due to the inconsistencies in results (depending on the soil type and plants used), the slow time frame required to achieve outcomes, and a lack of communication between scientists and practitioners.[154] More research is needed to develop more consistent methods that could be adopted at larger scales.[154]

Microbial fuel cells are an innovative bioremediation practice in which metabolic activities of electroactive bacteria (such as such as *Geobacter*, *Shewanella*, *Pseudomonas*, and *Rhodoferax*)[155] transform organic and inorganic matter into bioelectricity.[156] This allows electricity to be generated from wastewater treatment plants, reducing operating costs and energy consumption.[157] Microbial fuel cells can generate around 30 W m^{-2} of electricity, ~1 m^3 day^{-1} of biohydrogen, and incomes of as much as \$2,498.77 × 10^{-2}/(W m^{-2}) annually through wastewater treatment and energy generation alone.[157]

Bioleaching is a remediation process used to naturally extract metals (e.g., copper, zinc, lead, lithium, and nickel) from different matrices (e.g., electronic waste, mobile phones, spent batteries, and other mineral waste) by exploiting the microbial ability to oxidize minerals. This approach is an eco-sustainable alternative to (highly impacting) traditional metallurgical processes (e.g., conventional fusion).[158,159] Among fungi, the *Aspergillus* and *Penicillium* genera appear to be the most effective in biological leaching. These genera have been employed for metal extraction from oxidic ores of different metals (e.g., nickel, iron, chromium, titanium and quartz sands, refractory gold, silver, copper manganese, cobalt, and zinc).[160] Among bacteria, *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans* can efficiently mobilize the main metals of electronic waste (i.e., copper in printed wire boards) together with other metals, such as zinc and lead.[161] Based on existing information, bioleaching is a valuable approach for the management of mine waste, reducing the environmental impact of mining activities and the release of toxic elements, thus facilitating the safe and efficient recovery of metals.[129]

The implementation of eco-compatible bioremediation can contribute to the renewable energy sector and to sustainable economic growth (Goals 7 and 8). At the same time, the implementation of microbial bioremediation can provide a relevant contribution to the sustainable management of waste (Goal 12) and the health of polluted terrestrial (and 15) and marine (Goals 14) habitats. As a result, these impacts are directly relevant for improving human health and well-being (Goal 3), ensuring better access to natural resources (Goal 6), basic services (Goals 1, 2, and 11), and fairer living conditions around the world (Goal 10). Yet, although bioremediation has great potential, many polluted sites contain complex mixtures of contaminants that present microbes with significant metabolic and ecophysiological challenges. Moreover, the implementation of bioremediation solutions at large spatial scales remains challenging, particularly under changing environmental conditions[132] (Goal 9). To carry

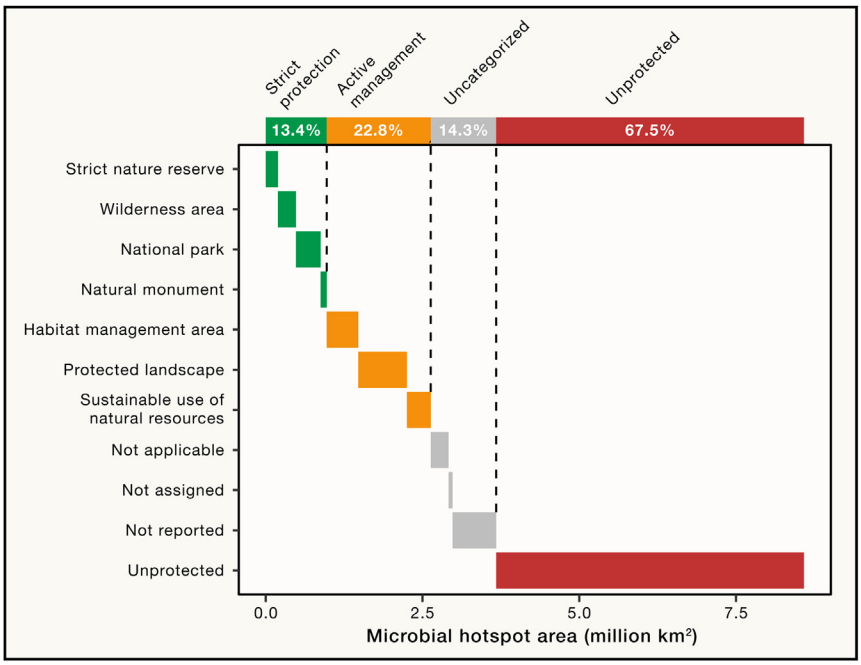

Figure 4. Microbial richness hotspots (the most diverse areas across the globe) are poorly protected

Microbial richness data from Guerra et al.[163] was extrapolated to the global scale using Random Forest machine learning following van den Hoogen et al.,[165] and area with richness values in the top 95th percentile ("hotspots") was overlaid with polygons from the World Database on Protected Areas.[166] Only 13.4% of the global hotspot areas of microbial richness fall within strict conservation areas. A further 22.8% are located in less strictly protected areas.

However, in general, there is little spatial overlap between the regions of high microbial diversity and existing protected areas across the globe, with a possible 67.5% of microbial biodiversity hotspot regions existing outside of protected areas (Figure 4). This highlights the need for conservation priorities to be readjusted if they intend to protect microbial diversity and its associated ecosystem services.

out such interventions, it will be necessary to develop an integrated approach including the best bioremediation techniques and the advanced engineering technologies (including remote sensing and GIS-based mapping) to assess the extent of contamination/damage and to understand the spatial and temporal variations of the impacted sites.[162]

FACILITATING HEALTHY ECOSYSTEMS

SDGs: 1, 2, 3, 6, 11, 13, 14, 15

Microorganisms overwhelmingly dominate the diversity of life on Earth, with an estimated 1 trillion species existing across the globe.[3] In addition, microbes shape the biochemical landscape by performing important metabolic functions,[8] including photosynthetic oxygen production, the degradation of organic molecules, nitrogen fixation, detoxification, nutrient release, and transformation of greenhouse gases. All of these processes are fundamental to supporting life in terrestrial, freshwater, and marine ecosystems and are vital to the health and well-being of humanity. As such, by maintaining the functionality of both natural and managed ecosystems, microbes play a key role in generating clean water (Goal 6), the regulation of our climate (Goal 13), life below water (Goal 14), and life on land (Goal 15).

When anthropogenic factors such as ecological degradation and climate change lead to the breakdown of microbial communities, they fundamentally undermine the capacity of ecosystems to support other life.[16,71] As such, there is growing awareness of the need to include microbial diversity into conservation planning, both to protect the high diversity that microbes represent and to preserve ecological functioning.[16,163] To facilitate more targeted conservation of microbial diversity, a growing body of research has begun to explore and characterize hotspots of microbial diversity across the globe.[163,164]

Along with improving efforts to conserve existing microbial biodiversity, there is a growing awareness of the need to restore microbial communities that have been degraded. Indeed, the soil microbiome often represents a key limiting factor for ecosystem recovery in both natural and managed ecosystems.[16] Across the globe, inoculants of diverse soil communities (e.g., via soil transplants, spore extracts, and cultured strains) have been shown to increase ecosystem recovery by an average of 64%.[16] It is likely that these impacts are driven by increases in soil metabolism and stability that enhance plant growth, survival, and biodiversity,[167] and the effects tend to have the greatest beneficial impacts in more degraded soils.[168] Direct manipulation of the microbiome will be enabled through much-needed work identifying when and where different types of inoculation are successful. Microbiome-based approaches (including the use of probiotics) are also being used to control diseases in wild animal populations.[169] However, because land use practices and climate change impact different ecosystems in different ways,[14] microbiome-based approaches need to be tailored to the target system. In order to avoid the damaging impacts of invasive species and maximize the beneficial impacts on ecological recovery, microbial inoculations or transplants are most effective when using native species from nearby local environments.[168] Metagenomic sequencing and other "omics" approaches[170] can provide valuable information regarding microbial diversity and functional capacity and can be used as biomonitoring tools to assess microbial communities in restoration interventions.[171,172]

Despite the potential of microbes to improve ecosystem health, substantial research is still needed to make full and informed use of microbial biotechnology in land conservation and restoration practices across agricultural, urban, and natural ecosystems. Microbial inoculation methods are not yet widely implemented in the field, and scaling-up methods to be applied

at the landscape level requires further development and full evaluation of risks.[16,79,173] However, a growing body of evidence supports the potential for native, diverse microbial communities to improve yields in both natural and managed environments.[174,175] Similarly, methods to control disease in animal populations need to be optimized, as they often need to be applied repeatedly or at specific stages of the life cycle.[169] Because the majority of microbial species remain undiscovered,[3] significant investment is needed to improve our understanding of the potential for using microorganisms to restore life on land (Goal 15).

As well as enhancing ecological recovery, microbes can also represent an important biological control tool for limiting the spread of invasive or harmful species. For example, across the globe, harmful algal and cyanobacterial blooms and waterborne pathogens (e.g., *Vibrio cholerae* and *Salmonella typhi*) represent key threats to the water quality of lakes, rivers, and coastal waters[176] (Goals 6 and 14). Microbial-mediated reduction of nutrient loads can be managed to help suppress damaging algal blooms[177] and can yield pathogen reduction co-benefits,[178] even though benefits may take years to accrue if high amounts of nutrients have already accumulated in the sediments. Recent research on microbial control of harmful algal blooms has identified several viruses, bacteria, and fungi that show algicidal activity,[179–181] as well as microorganisms that can degrade algal toxins[182] (Goal 6).

Over 30% of people in tropical countries are directly dependent on nature for their basic needs,[183] and the rest of the global economy is indirectly underpinned by the existence of natural ecosystems. As such, microbial solutions to improve the health and diversity of natural ecosystems will ensure that these systems continue to provide a sustainable source of food and clean water (Goals 1, 2, 6, and 11) and that disease outbreaks are reduced in frequency and severity (Goal 3).

GLOBAL BIOGEOCHEMICAL CYCLES AND CLIMATE CHANGE

SDGs: 1, 2, 3, 4, 6, 10, 11, 13, 14, 15, 16

Microbes have been central drivers of the evolution of Earth's atmosphere over the last 3 billion years, including the oxygenation of the Earth's early atmosphere that allowed life to flourish and higher forms of life to evolve (Goals 14 and 15). They remain primary drivers of modern-day carbon and nutrient cycling across the globe.[164] As such, they play a crucial role in regulating the atmospheric composition and climate. Currently, there are growing concerns that the climate-induced acceleration of microbial-mediated biogeochemical processes has the potential to accelerate CO_2 emissions into the atmosphere.[15,184] However, the scale of these biochemical impacts means that they also have the potential to act as a powerful ally in achieving Goal 13 of "climate action" if we can capitalize on solutions that enhance the microbially mediated mitigation of CO_2 (carbon dioxide), CH_4 (methane), and N_2O (nitrous oxide) emissions.[185]

Land use change and agriculture provide considerable opportunities for deliberate mitigation of global warming using microbes. As mentioned above, microbial inoculations that enhance productivity and soil carbon sequestration have the potential to enhance carbon storage in both managed ecological health[168] and natural[167] ecosystems. Moreover, any mechanisms that enhance photosynthesis and/or reduce the rate of organic carbon mineralization will also increase terrestrial carbon sequestration. In particular, the restoration of degraded peatlands, for instance, could yield a microbially mediated reduction in emissions of around 0.8 Gt of CO_2 equivalents per year by 2030[186] (Goals 13 and 15). Soil amendments such as biochar and compost can also enhance carbon sequestration by increasing its recalcitrance to microbial decomposition, while microbial uptake and deposition of root-exuded carbon compounds in the rhizosphere of deep-rooted perennial grasses could also be leveraged to enhance soil carbon stocks.[185] The use of microbes to reduce CO_2 emissions is already well established in the form of biofuel production, either via conversion of lignocellulosic feedstocks or as the feedstock itself (e.g., microalgae).

Microbially mediated CH_4 fluxes dominate anthropogenic emissions, with ruminant livestock, waste management, and rice agriculture all being significant global sources.[187] Improved feed quality and feed additives are proven methods to reduce CH_4 emissions from enteric fermentation during the digestion process in ruminants. There is also potential for systematic selection of the gut microbiome in ruminant livestock through genomic selection of low-emission traits.[188] Additionally, microbially derived meat substitutes can reduce reliance on ruminants, thereby cutting associated emissions.[81] In the waste management sector, options range from enhancing aeration of wastes (to limit methanogenesis) through encouragement of methanotrophy (e.g., landfill cover soils) to deliberately optimizing methanogenesis to generate CH_4 for substitution of fossil fuels (e.g., anaerobic digestion). In rice agriculture, established microbially mediated approaches to mitigation of CH_4 emissions, such as drainage and harvest residue management, could be complemented by development of new rice cultivars aimed at modifying root carbon allocation.[101]

N_2O emissions from soils and sediments, produced by microbes, are increasing due to human-induced nitrogen enrichment.[189] Nitrogen fertilization of farmlands is the main contributor, with spill-over effects on natural ecosystems (Goal 15). Significant mitigation relies on modifying microbial nitrogen transformations in farmed soils. N_2O is a by-product of ammonia oxidation, and inhibiting ammonia-oxidizing bacteria that produce more N_2O than their archaeal counterparts is a promising approach. Denitrifying bacteria are also attractive targets because reducing their overall N_2O/N_2 product ratio (R) determines farmland emissions of N_2O. Lime application lowers R by promoting synthesis of functional N_2O-reductase.[190] Another promising approach is bioaugmentation of denitrifying bacteria that reduce, but do not produce, N_2O.[191] Such bacteria can be effectively vectored by organic waste, with a relatively long-lasting effect on N_2O emissions, if selected for the ability to grow in organic waste and soil.[192] Field experiments demonstrated a 50%–95% reduction of N_2O-emission by fertilization with organic waste in which such bacteria had been grown to high cell densities.[90] The technology has the potential to reduce European-wide anthropogenic N_2O emissions by 5%–20%.[90]

Marine and freshwater systems contribute ~50% of global primary production, largely driven by the photosynthetic activity of cyanobacteria and unicellular eukaryotic algae. Hence, aquatic microorganisms play a key role in global carbon sequestration and provide the energy to drive aquatic food webs (Goal 14). Aquatic microorganisms also play an important role in climate regulation through the production and release of organic compounds to the atmosphere that subsequently influence aerosol loads, aerosol properties, and cloud formation.[193–195] However, aquatic microbiomes are also highly sensitive to climate-driven stressors, including increased water column (density) stratification and nutrient stress from climate warming, ocean acidification from rising atmospheric carbon dioxide, oxygen depletion, and extreme climatic events (e.g., marine heatwaves).[15,196] Impacts of these cumulative stressors include shifts in microbial diversity and species composition, changes in primary productivity, disease outbreaks, altered nutrient or gas cycling (including the enhanced release of potent greenhouse gases such as methane), and disruption of symbiotic and virus-microbe interactions.[197,198]

Microbial solutions to climate-driven stressors in water include natural processes and those that humans might manipulate and harness. It is essential that we understand the ramifications of both. Natural processes include metabolic feedbacks that buttress shifts in substrate availability. For example, some phytoplankton upregulate nitrogen fixation under ocean acidification,[199] thereby partially compensating for decreasing upwelling of nutrients.[200] Other phenomena influenced by climate change, such as the gradual loss of oxygen from the subsurface ocean and coastal waters[201,202] are associated with microbial communities producing and consuming potent greenhouse gases (e.g., methane and nitrous oxide).[203] Warming hastens respiratory return of carbon dioxide to the atmosphere, thereby decreasing carbon deposition to marine sediments (positive climate feedback).[204] Warming may also elevate plankton nitrogen-to-phosphorus ratios, thereby increasing carbon sequestration (negative climate feedback) because carbon-to-nitrogen ratios are relatively invariable.[205] Encouragingly, this natural complexity suggests potentially overlooked microbial constraints on climate-driven phenomena.

Some emerging lines of research highlight the potential to harness microbial processes for large-scale geoengineering to enhance carbon sequestration (e.g., iron fertilization of the oceans).[206] Although such large-scale mechanisms may not yet be advisable without considerable advances in our understanding of the downstream consequences,[206,207] many microbial solutions at local scales present more manageable options. For example, biofuel production involving freshwater and coastal microbes may provide an alternative for fossil fuels, with the potential to reduce arable land demands from traditional biofuel production.[208] Furthermore, microbial conversion of methane to high-value bioproducts (e.g., methanol and biodegradable plastics) may offer a sustainable solution to reduce greenhouse gas emission.[209] In all these cases, accelerating bioengineering research is needed, including expanded libraries of genetically manipulatable strains and upscaling of culturing techniques to improve potential economic benefits of biofuel production and other forms of microbial carbon sequestration.

Microbes therefore underpin global fluxes and the potential for mitigation of all 3 major anthropogenic greenhouse gases. Improved understanding and greater application of microbial ecology—such as through manipulation of plant-soil-microbial interactions or marine primary producers to enhance net carbon gain—has the potential to make a very significant contribution toward improving climate action (Goal 13) and subsequently life in aquatic and terrestrial ecosystems (Goals 14 and 15). Given the multifaceted implications of climate change for poverty, hunger, healthcare, clean water, and education,[210] microbial-based climate mitigation solutions have the capacity to contribute to numerous other SDGs (Goals 1, 2, 3, 4, 6, 10, 11, and 16).

PARTNERSHIPS FOR THE GOALS (GOAL 17)

SDG 17, "partnerships for the goals," aims to strengthen ways of implementing the SDGs and revitalize global partnerships for achieving sustainable development.[9] Our review highlights that the consideration of microbes and microbial-based technologies may be critical for achieving each of the SDGs. More importantly, this review reveals how microbial technologies have the potential to provide synergistic opportunities for achieving multiple SDGs simultaneously, facilitating collaboration and alignment in achieving those goals (Figures 2 and 5). For example, the central role of soil microbial diversity in promoting carbon storage on land[164] suggests that efforts to promote healthy microbial communities can contribute synergistically to both climate (Goal 13) and biodiversity (Goals 14 and 15) goals.[16] As such, explicitly recognizing this role of microbial diversity in the official documentation for the United Nations Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity (CBD) can help provide a common lexicon to develop partnerships for organizations and governments to achieve both sustainability targets simultaneously. In Figure 5, we highlight diverse microbial roles that are conceptually linked to achieving the SDGs, presenting different pathways for potential partnerships in achieving multiple sustainability targets.

Some SDGs are more directly influenced by microbes than others (Figure 5). Specifically, microbes may not initially appear directly relevant for achieving quality education (Goal 4), gender equality (Goal 5), or peace, justice, and strong institutions (Goal 16). However, the highly interdependent nature of the SDGs means that microbial advances in other areas (e.g., food production, healthcare, and bioremediation) will have immediate knock-on consequences for all aspects of equity, peace, and justice. This becomes especially relevant for Indigenous communities that steward ~80% of global biodiversity but are often overlooked in strategic global planning and excluded from the direct benefits provided by natural product development.[211,212] Microbes are already being deployed in bioremediation efforts to decontaminate ecosystems disrupted by extractive mining projects that disproportionately impact marginalized communities,[213] thereby contributing to equity SDGs. The plethora of microbially relevant interactions between SDGs that we have identified (Figure 5) illustrates that microbes can indeed accelerate progress toward all goals.

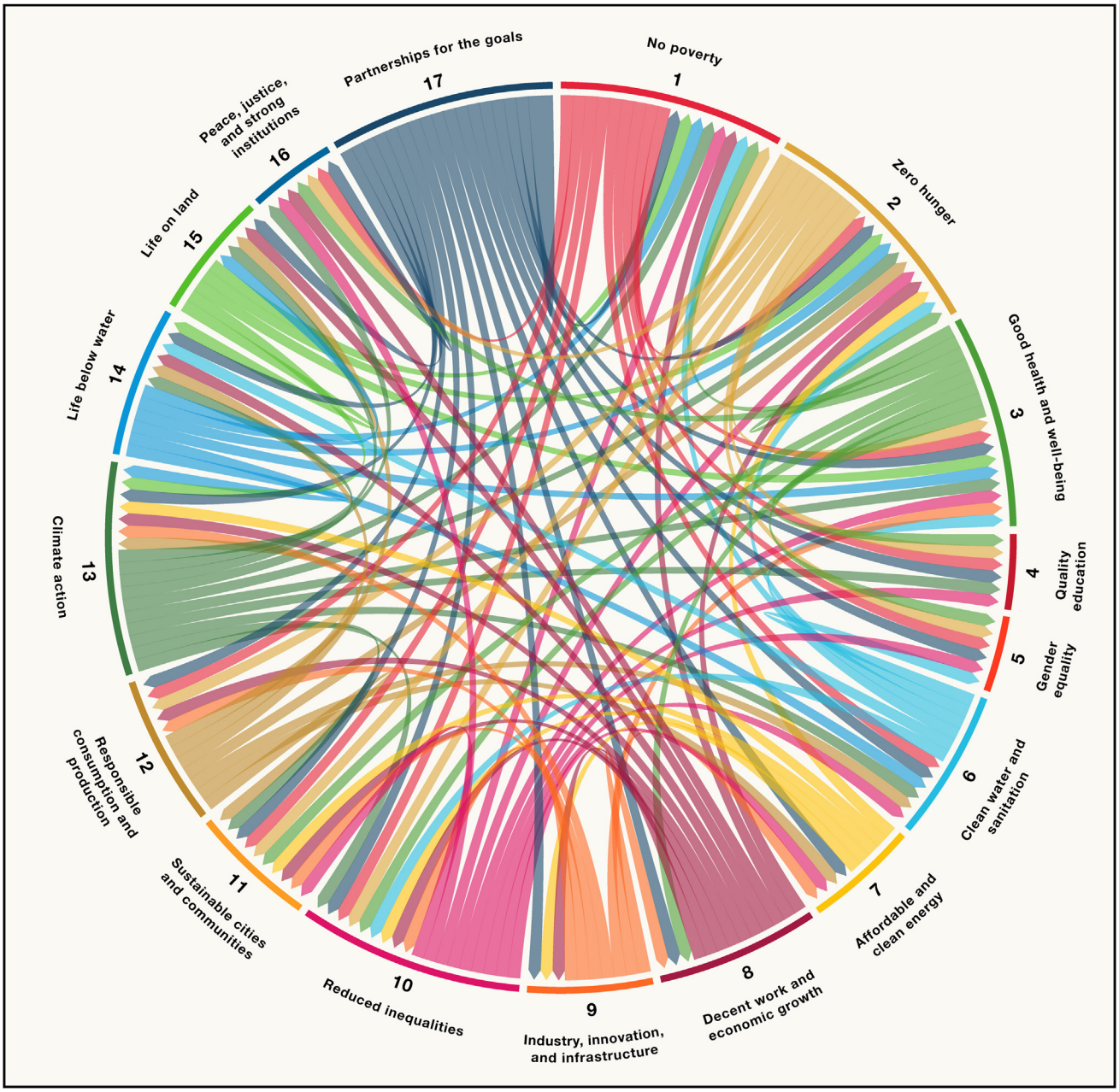

Figure 5. Microbe-relevant positive interactions between the SDGs

Using microbes to directly advance each SDG will likely indirectly advance other SDGs (outgoing arrows). For example, microbial biotechnology used to reduce hunger (Goal 2) will also indirectly reduce poverty and inequality (Goals 1, 5, and 10), improve health (Goal 3), educational experience (Goal 4), community and commercial sustainability (Goals 11 and 12), and peace (Goal 16). Detailed descriptions of all arrows are provided in Table S1. Although Goal 17 cannot be directly advanced by microbial technology, outgoing links are shown to all other SDGs because including microbes in international and organizational policy agreements will likely benefit all goals (see section "partnerships for the goals").

Ultimately, the universal roles of microbes in driving biochemical processing of elements make them relevant to every aspect of sustainability. The clustering of microbial functions into 7 overarching areas (Figure 2) reveals the significant amount of overlap between the sustainability implications of different microbial solutions. While it is impossible to characterize the full dimensionality of these partnerships across all natural and human systems, our synthesis highlights clear clustering of microbial processes that are relevant for different groupings of SDGs (Figure 2). Increased familiarity of public and private sector decision-makers with these general microbial processes may be key to improving efforts to address the combined global sustainability challenges facing humanity in the coming century.

CONCLUSIONS

Accelerating the transition toward a sustainable future requires that we capitalize on all tools in our arsenal, including those provided by the most ecologically diverse organisms with the most powerful catalytic capacity in the natural world. Our review highlights a range of microbial innovations that have the potential to facilitate a rapid transition toward a sustainable economy (Table 1). Our overarching conclusion—that microbial processes are fundamental to achieving the SDGs—may seem trivial, given that they underpin all life on Earth. However, the real insight is the extent of overlap in the importance of microbial innovations that can simultaneously help us accelerating progress toward achieving multiple sustainability agendas (see Figures 2 and 5). With increasing regulatory pressure for governments and organizations to achieve a range of sustainability targets, identifying common frameworks to address multiple goals is an urgent priority. The broad importance of microbial innovations means it is possible to identify synergies that can reveal pathways to achieving multiple sustainability targets. For example, if improving soil microbial diversity can contribute to our biodiversity (Goals 14 and 15), climate (Goal 13), and food security (Goal 2) goals, then it may present an efficient and cost-effective avenue for accelerating impact. Similarly, if microbial-based bioreactors can drive transitions toward sustainable energy production (Goal 7), materials transformations/production (Goal 12), and infrastructure (Goal 9), then they represent powerful opportunities for accelerating sustainable development. Such synergistic roles of microbial processes in facilitating sustainable transitions across different sectors highlight that they can provide decision-makers with a common lexicon for collective action toward simultaneously addressing multiple sustainability goals.

Given the ubiquitous roles of microbial research and technology across all SDGs, it is surprising that microorganisms remain largely absent from the intergovernmental policy agreements and multilateral treaties of the United Nations. At the highest level, the biggest challenge is public and political awareness of the central role of microorganisms and changing behavioral norms so that the necessary microbial solutions can be adopted.[214] Funding for downstream development is another critical hurdle limiting the widespread adoption of microbial technologies. As such, the scaling of microbial innovations will require the establishment of proactive financial and regulatory policies that recognize their unique potential. Following recent calls for decision-makers to recognize the importance of microbes in guiding action on climate change,[15] our review highlights the need for similar consideration across the full range of our international sustainability agendas. To build a sustainable future on this planet, we must work with our oldest ancestors.

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AUTHOR CONTRIBUTIONS

Conceptualization, T.W.C., L.G.v.G., R.R., and R.C.; writing – original draft, T.W.C., L.G.v.G., R.R., C.C., R.D., T.J.D., J.H., L.Y.S., J.K.T., K.T., M.Z.A., L.R.B., M.B., M.J.B., P.W.B., I.B., C.S.D., C.M.F., J.K.J., B.K., K.M.-M., J.A.N., D.P., M.P., J.L.R., D.R., J.V.R., V.R., W.J.R., B.K.S., G.R.S., F.J.S., M.S., M.J.H.v.O., and N.S.W.; writing – review and editing, all authors who wrote the original draft plus C.M.Z.; figures, L.G.v.G., J.v.d.H., and T.J.D.

DECLARATION OF INTERESTS

M.Z.A. is on the board of the Native BioData Consortium (NBDC; https://nativebio.org/); D.R. is co-chair of Just Transition Commission (https://www.justtransition.scot/); J.K.J. is chair of the Scientific Advisory Board for Oath Inc. (https://www.oathinc.com/); J.A.N. has a patent holding: North JA, Tabita FR, Young SJ, and Murali S. 2021. Nitrogenase-like enzyme system that catalyzes methionine, ethylene, and methane biogenesis. P2021-099-6249; WIPO 20240060037.

SUPPLEMENTAL INFORMATION

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REFERENCES

1. Rasmussen, B. (2000). Filamentous microfossils in a 3,235-million-year-old volcanogenic massive sulphide deposit. Nature *405*, 676–679.
2. Larsen, B.B., Miller, E.C., Rhodes, M.K., and Wiens, J.J. (2017). Inordinate fondness multiplied and redistributed: the number of species on earth and the new pie of life. Q. Rev. Biol. *92*, 229–265.
3. Locey, K.J., and Lennon, J.T. (2016). Scaling laws predict global microbial diversity. Proc. Natl. Acad. Sci. USA *113*, 5970–5975.
4. Hug, L.A., Baker, B.J., Anantharaman, K., Brown, C.T., Probst, A.J., Castelle, C.J., Butterfield, C.N., Hernsdorf, A.W., Amano, Y., Ise, K., et al. (2016). A new view of the tree of life. Nat. Microbiol. *1*, 16048. https://doi.org/10.1038/nmicrobiol.2016.48.
5. Bar-On, Y.M., Phillips, R., and Milo, R. (2018). The biomass distribution on Earth. Proc. Natl. Acad. Sci. USA *115*, 6506–6511.
6. Bar-On, Y.M., and Milo, R. (2019). Towards a quantitative view of the global ubiquity of biofilms. Nat. Rev. Microbiol. *17*, 199–200. https://doi.org/10.1038/s41579-019-0162-0.
7. Yan, M., Pratama, A.A., Somasundaram, S., Li, Z., Jiang, Y., Sullivan, M.B., and Yu, Z. (2023). Interrogating the viral dark matter of the rumen ecosystem with a global virome database. Nat. Commun. *14*, 5254. https://doi.org/10.1038/s41467-023-41075-2.
8. Falkowski, P.G., Fenchel, T., and Delong, E.F. (2008). The microbial engines that drive Earth's biogeochemical cycles. Science *320*, 1034–1039.
9. Desa UN (2023). The Sustainable Development Goals Report July 2023 (New York). https://unstats.un.org/sdgs/report/2023/.
10. United Nations Treaty Collection (2024). https://treaties.un.org/.
11. Bullman, S. (2023). The intratumoral microbiota: from microniches to single cells. Cell *186*, 1532–1534.
12. Lizundia, E., Luzi, F., and Puglia, D. (2022). Organic waste valorisation towards circular and sustainable biocomposites. Green Chem. *24*, 5429–5459.
13. Ramos, J.L., Bernal, P., and Salvachúa, D. (2023). Microbial biotechnology in the effort to end hunger. Microb. Biotechnol. *16*, 1581–1583. https://doi.org/10.1111/1751-7915.14295.
14. Jansson, J.K., and Hofmockel, K.S. (2020). Soil microbiomes and climate change. Nat. Rev. Microbiol. *18*, 35–46.
15. Cavicchioli, R., Ripple, W.J., Timmis, K.N., Azam, F., Bakken, L.R., Baylis, M., Behrenfeld, M.J., Boetius, A., Boyd, P.W., Classen, A.T., et al. (2019). Scientists' warning to humanity: microorganisms and climate

Table 1. Recommended actions to facilitate achieving the SDGs that can be directly influenced by microorganisms

SDG	Recommendations
1, no poverty	implement in appropriate countries cost-effective, scalable bioremediation procedures to produce local jobs and advance local expertise in microbiology
	increase availability of microbes that improve food production and preservation practices
	require benefit-sharing models in microbial development projects that target under-resourced communities to alleviate poverty
2, zero hunger	invest in microbiome research and development for agriculture and aquaculture
	implement solutions that enhance *in situ* production of cost-effective, scalable methods for microbiome-based products
	establish robust education and training programs to inform food producers about microbial solutions
	invest in research to characterize and monitor the diversity of the microbiome
3, good health and well-being	establish biobanking to store the microbial diversity and implement actions to restore the loss of diversity
	implement equitable distribution of vaccines and medical interventions
	invest in research for sustainable solutions alternative to broad-spectrum antibiotics and disinfectants
	establish dedicated research institutes to identify, monitor, register, and prevent waterborne diseases and harmful algal blooms
6, clean water and sanitation	improve water recycling and wastewater process engineering innovations to meet the needs of the cultural, economic, political, and environmental contexts in which they are to be placed
	develop multi-omics approaches to advance the theories, methods, and applications of biological water recycling and wastewater treatment processes
	invest in research for metabolic engineering of methylotrophic microorganisms for bioconversion of methane into value-added products
7, affordable and clean energy	invest in research for metabolic engineering of microbes that can capture carbon directly from the atmosphere and convert it into fuels
	invest in engineering, bioreactors, and bioprocess design to scale up and industrialize the bioconversion of carbon- and methane-derived products
	invest in workforce development and infrastructures to move raw materials from producers to refiners and products to consumers, especially in low-income countries
	implement policies to recognize the economic value of goods produced by sustainable solutions
8, decent work and economic growth	invest in metabolic engineering and industrialization of microbial processes for the production of proteins, carbohydrates, and fats
	invest in metabolic engineering and industrialization of microorganisms that can depolymerize plastics
	invest in metabolic engineering and industrialization of microbes that degrade organic sewage waste, converting them into biofertilizers and biofuels
	develop policies and financial incentives programs to reskill and ensure a just transition for those whose incomes are disrupted by emerging microbial-based technologies
	prohibit planned obsolescence and impose requirements on manufacturers and producers to recycle their waste
	develop policies to favor investments in a circular economy harnessing the potential of natural and engineered microbes to perform biocompatible chemical transformations

(*Continued on next page*)

Table 1. *Continued*

SDG	Recommendations
9, industry, innovation, and infrastructure	replace heavily polluting chemical plants producing plastics and fuels with environmentally sustainable microbe-powered industrial plants
	census of the types and quantity of renewable raw materials and the chemical products that are needed in regions of the globe
	develop the workforce needed to ensure that raw materials producers and citizens in lower-income regions of the world benefit from the transition to producing chemicals in a circular bioeconomy
	establish biocompatible plants close to the source of raw materials and develop the principles of circular economy locally
10, reduced inequalities	develop individual microbial technology solutions to satisfy setting-specific needs in conjunction with local communities
	create microbial technology hubs close to the local industries to complement, synergize, and innovate
	implement equitable distribution of vaccines and medical interventions (as in Goal 3)
	advance biocontrol technologies at large scale to reduce pre-harvest and post-harvest food waste
12, responsible consumption and production	continue to develop microbially mediated methods for sustainable management and efficient use of natural resources, such as biofuels and other products from renewable raw materials
	expand microbial technology available for managing chemicals and other wastes though bioremediation pathways in wastewater, plastic pollution, and contaminated soil
	further develop bioremediation methods such as microbial fuel cells to convert organic and inorganic matter from wastewater treatment plants into bioelectricity
	develop microbial biofilters for capture of CO_2 and CH_4 to reduce atmospheric loads and deploy biofuels to reduce CO_2 emissions from fossil fuels (as in Goal 7)
13, climate action	explore fertilization technologies to capture CO_2 by primary producers in marine systems
	reduce reliance on ruminant production through adoption of plant-based food alternatives
	develop better landscape management strategies to reduce methane production from rice cultivation, peatlands, and thawing permafrost
	invest in research on microbial communities living in marine ecosystems through metagenomic sequencing and by expanding the library of genetically manipulatable and culturable aquatic microbes
14, life below water	address the issue of scale, clarifying whether solutions at small scales (e.g., probiotics in defined communities) are feasible and effective across larger regions and time
	invest in research on coral reef microbiology to progress the development of effective microbial probiotics that boost coral climate resilience
	invest in research to understand the responses of microbial communities to anthropogenic impacts (e.g., aquaculture, agriculture, and chemical pollution) and climate change (e.g., global warming, oxygen depletion, and ocean acidification) and their health implications for human and resource exploitation
	invest in advance satellite remote sensing technologies that improve assessment of plankton and other microeukaryote stocks within the full sunlit surface layer and enable improved detection of change in response to climate and other stressors
	deploy metagenomic sequencing and other omics approaches for biomonitoring of microbial communities in healthy and degraded terrestrial ecosystems
15, life on land	develop and assess the effectiveness of microbial inoculants and microbial consortia to increase soil fertility and stability and improve plant growth and survival in specific terrestrial ecosystems
	enhance growth of native beneficial soil microbial populations via improved land management strategies such as regenerative agriculture and prairie restoration and degradation of environmental pollutants
	develop landscape management practices to reduce CO_2 and methane emissions (e.g., from wetlands and thawing permafrost) and increase soil carbon sequestration

change. Nat. Rev. Microbiol. *17*, 569–586. https://doi.org/10.1038/s41579-019-0222-5.

16. Averill, C., Anthony, M.A., Baldrian, P., Finkbeiner, F., Van den Hoogen, J., Kiers, T., Kohout, P., Hirt, E., Smith, G.R., and Crowther, T.W. (2022). Defending Earth's terrestrial microbiome. Nat. Microbiol. *7*, 1717–1725.
17. Wu, R., Trubl, G., Taş, N., and Jansson, J.K. (2022). Permafrost as a potential pathogen reservoir. One Earth *5*, 351–360. https://doi.org/10.1016/j.oneear.2022.03.010.
18. Rappuoli, R., Young, P., Ron, E., Pecetta, S., and Pizza, M. (2023). Save the microbes to save the planet. A call to action of the International Union of the Microbiological Societies (IUMS). One Health Outlook *5*, 5. https://doi.org/10.1186/s42522-023-00077-2.
19. Anand, S., Hallsworth, J.E., Timmis, J., Verstraete, W., Casadevall, A., Ramos, J.L., Sood, U., Kumar, R., Hira, P., Dogra Rawat, C., et al. (2023). Weaponising microbes for peace. Microb. Biotechnol. *16*, 1091–1111.
20. Timmis, K., de Vos, W.M., Ramos, J.L., Vlaeminck, S.E., Prieto, A., Danchin, A., Verstraete, W., de Lorenzo, V., Lee, S.Y., Brüssow, H., et al. (2017). The contribution of microbial biotechnology to sustainable development goals. Microb. Biotechnol. *10*, 984–987.
21. Akinsemolu, A.A. (2018). The role of microorganisms in achieving the sustainable development goals. J. Cleaner Prod. *182*, 139–155.
22. WHO (2024). One Health (World Health Organisation). https://www.who.int/health-topics/one-health#tab=tab_1.
23. Singh, B.K., Yan, Z.-Z., Whittaker, M., Vargas, R., and Abdelfattah, A. (2023). Soil microbiomes must be explicitly included in One Health policy. Nat. Microbiol. *8*, 1367–1372. https://doi.org/10.1038/s41564-023-01386-y.
24. Yan, Z., Xiong, C., Liu, H., and Singh, B.K. (2022). Sustainable agricultural practices contribute significantly to One Health. J. Sustain. Agric. Environ. *1*, 165–176.
25. Fowler, S.J., and Smets, B.F. (2017). Microbial biotechnologies for potable water production. Microb. Biotechnol. *10*, 1094–1097.
26. Wu, L., Ning, D., Zhang, B., Li, Y., Zhang, P., Shan, X., Zhang, Q., Brown, M.R., Li, Z., Van Nostrand, J.D., et al. (2019). Global diversity and biogeography of bacterial communities in wastewater treatment plants. Nat. Microbiol. *4*, 1183–1195. https://doi.org/10.1038/s41564-019-0426-5.
27. Diamond, M.B., Keshaviah, A., Bento, A.I., Conroy-Ben, O., Driver, E.M., Ensor, K.B., Halden, R.U., Hopkins, L.P., Kuhn, K.G., Moe, C.L., et al. (2022). Wastewater surveillance of pathogens can inform public health responses. Nat. Med. *28*, 1992–1995. https://doi.org/10.1038/s41591-022-01940-x.
28. Tuan Tran, H., Lin, C., Bui, X.-T., Ky Nguyen, M., Dan Thanh Cao, N., Mukhtar, H., Giang Hoang, H., Varjani, S., Hao Ngo, H., and Nghiem, L.D. (2022). Phthalates in the environment: characteristics, fate and transport, and advanced wastewater treatment technologies. Bioresour. Technol. *344*, 126249.
29. Hiller, C.X., Hübner, U., Fajnorova, S., Schwartz, T., and Drewes, J.E. (2019). Antibiotic microbial resistance (AMR) removal efficiencies by conventional and advanced wastewater treatment processes: a review. Sci. Total Environ. *685*, 596–608.
30. Hoang, A.T., Nižetić, S., Ng, K.H., Papadopoulos, A.M., Le, A.T., Kumar, S., Hadiyanto, H., and Pham, V.V. (2022). Microbial fuel cells for bioelectricity production from waste as sustainable prospect of future energy sector. Chemosphere *287*, 132285.
31. Indriani, C., Tantowijoyo, W., Rancès, E., Andari, B., Prabowo, E., Yusdi, D., Ansari, M.R., Wardana, D.S., Supriyati, E., Nurhayati, I., et al. (2020). Reduced dengue incidence following deployments of *Wolbachia*-infected *Aedes aegypti* in Yogyakarta, Indonesia: a quasi-experimental trial using controlled interrupted time series analysis. Gates Open Res. *4*, 50. https://doi.org/10.12688/gatesopenres.13122.1.
32. O'Neill, S.L., Ryan, P.A., Turley, A.P., Wilson, G., Retzki, K., Iturbe-Ormaetxe, I., Dong, Y., Kenny, N., Paton, C.J., Ritchie, S.A., et al. (2019). Scaled deployment of *Wolbachia* to protect the community from dengue and other *Aedes* transmitted arboviruses. Gates Open Res. *13*, 2–36. https://doi.org/10.12688/gatesopenres.12844.3.
33. Kalia, V.C., Patel, S.K.S., Cho, B.-K., Wood, T.K., and Lee, J.-K. (2022). Emerging applications of bacteria as antitumor agents. Semin. Cancer Biol. *86*, 1014–1025.
34. MacDiarmid, J.A., Mugridge, N.B., Weiss, J.C., Phillips, L., Burn, A.L., Paulin, R.P., Haasdyk, J.E., Dickson, K.A., Brahmbhatt, V.N., Pattison, S.T., et al. (2007). Bacterially derived 400 nm particles for encapsulation and cancer cell targeting of chemotherapeutics. Cancer Cell *11*, 431–445. https://doi.org/10.1016/j.ccr.2007.03.012.
35. Kim, O.Y., Park, H.T., Dinh, N.T.H., Choi, S.J., Lee, J., Kim, J.H., Lee, S.-W., and Gho, Y.S. (2017). Bacterial outer membrane vesicles suppress tumor by interferon-γ-mediated antitumor response. Nat. Commun. *8*, 626. https://doi.org/10.1038/s41467-017-00729-8.
36. Law, N., and Aslam, S. (2020). Phage therapy: primer and role in the treatment of MDROs. Curr. Infect. Dis. Rep. *22*, 31. https://doi.org/10.1007/s11908-020-00742-x.
37. De Oliveira, D.M.P., Forde, B.M., Kidd, T.J., Harris, P.N.A., Schembri, M.A., Beatson, S.A., Paterson, D.L., and Walker, M.J. (2020). Antimicrobial resistance in ESKAPE pathogens. Clin. Microbiol. Rev. *33*. e00181–19. https://doi.org/10.1128/cmr.00181-19.
38. Fernández-García, L., Muthami, J.M., Tomas, M., and Wood, T.K. (2022). What are the options for treating infections by persister-forming pathogens? Environ. Microbiol. *24*, 4500–4504.
39. Filutowicz, M., Burgess, R., Gamelli, R.L., Heinemann, J.A., Kurenbach, B., Rakowski, S.A., and Shankar, R. (2008). Bacterial conjugation-based antimicrobial agents. Plasmid *60*, 38–44.
40. Reuter, A., Hilpert, C., Dedieu-Berne, A., Lematre, S., Gueguen, E., Launay, G., Bigot, S., and Lesterlin, C. (2021). Targeted-antibacterial-plasmids (TAPs) combining conjugation and CRISPR/Cas systems achieve strain-specific antibacterial activity. Nucleic Acids Res. *49*, 3584–3598. https://doi.org/10.1093/nar/gkab126.
41. Rodrigues, M., McBride, S.W., Hullahalli, K., Palmer, K.L., and Duerkop, B.A. (2019). Conjugative delivery of CRISPR-Cas9 for the selective depletion of antibiotic-resistant enterococci. Antimicrob. Agents Chemother. *63*. e01454–19. https://doi.org/10.1128/aac.01454-19.
42. Murray, E.J., Dubern, J.-F., Chan, W.C., Chhabra, S.R., and Williams, P. (2022). A Pseudomonas aeruginosa PQS quorum-sensing system inhibitor with anti-staphylococcal activity sensitizes polymicrobial biofilms to tobramycin. Cell Chem. Biol. *29*, 1187–1199.e6.
43. Ottonello, A., Wyllie, J.A., Yahiaoui, O., Sun, S., Koelln, R.A., Homer, J.A., Johnson, R.M., Murray, E., Williams, P., Bolla, J.R., et al. (2023). Shape-shifting bullvalene-linked vancomycin dimers as effective antibiotics against multidrug-resistant gram-positive bacteria. Proc. Natl. Acad. Sci. USA *120*, e2208737120. https://doi.org/10.1073/pnas.2208737120.
44. McCallin, S., Sarker, S.A., Sultana, S., Oechslin, F., and Brüssow, H. (2018). Metagenome analysis of Russian and Georgian Pyophage cocktails and a placebo-controlled safety trial of single phage versus phage cocktail in healthy *Staphylococcus aureus* carriers. Environ. Microbiol. *20*, 3278–3293.
45. Hitchcock, N.M., Devequi Gomes Nunes, D., Shiach, J., Valeria Saraiva Hodel, K., Dantas Viana Barbosa, J., Alencar Pereira Rodrigues, L., Coler, B.S., Botelho Pereira Soares, M., and Badaró, R. (2023). Current clinical landscape and global potential of bacteriophage therapy. Viruses *15*, 1020.
46. Budd, J., Miller, B.S., Weckman, N.E., Cherkaoui, D., Huang, D., Decruz, A.T., Fongwen, N., Han, G.-R., Broto, M., Estcourt, C.S., et al. (2023). Lateral flow test engineering and lessons learned from COVID-19. Nat. Rev. Bioeng. *1*, 13–31. https://doi.org/10.1038/s44222-022-00007-3.

47. Galeano Niño, J.L., Wu, H., LaCourse, K.D., Kempchinsky, A.G., Baryiames, A., Barber, B., Futran, N., Houlton, J., Sather, C., Sicinska, E., et al. (2022). Effect of the intratumoral microbiota on spatial and cellular heterogeneity in cancer. Nature *611*, 810–817. https://doi.org/10.1038/s41586-022-05435-0.

48. Gilbert, J.A., Blaser, M.J., Caporaso, J.G., Jansson, J.K., Lynch, S.V., and Knight, R. (2018). Current understanding of the human microbiome. Nat. Med. *24*, 392–400. https://doi.org/10.1038/nm.4517.

49. Xiao, L., and Zhao, F. (2023). Microbial transmission, colonisation and succession: from pregnancy to infancy. Gut *72*, 772–786. https://doi.org/10.1136/gutjnl-2022-328970.

50. Moore, R.E., and Townsend, S.D. (2019). Temporal development of the infant gut microbiome. Open Biol. *9*, 190128. https://doi.org/10.1098/rsob.190128.

51. Cryan, J.F., O'Riordan, K.J., Cowan, C.S.M., Sandhu, K.V., Bastiaanssen, T.F.S., Boehme, M., Codagnone, M.G., Cussotto, S., Fulling, C., Golubeva, A.V., et al. (2019). The microbiota-gut-brain axis. Physiol. Rev. *99*, 1877–2013.

52. Ehlers, L., Bannert, K., Rohde, S., Berlin, P., Reiner, J., Wiese, M., Doller, J., Lerch, M.M., Aghdassi, A.A., Meyer, F., et al. (2020). Preclinical insights into the gut-skeletal muscle axis in chronic gastrointestinal diseases. J. Cell. Mol. Med. *24*, 8304–8314.

53. Puebla-Barragan, S., and Reid, G. (2019). Forty-five-year evolution of probiotic therapy. Microb. Cell *6*, 184–196. https://doi.org/10.15698/mic2019.04.673.

54. Sharma, A., Das, P., Buschmann, M., and Gilbert, J.A. (2020). The future of microbiome-based therapeutics in clinical applications. Clin. Pharmacol. Ther. *107*, 123–128.

55. Cullin, N., Azevedo Antunes, C.A., Straussman, R., Stein-Thoeringer, C.K., and Elinav, E. (2021). Microbiome and cancer. Cancer Cell *39*, 1317–1341.

56. Timmis, J.K., Roussilhon, D.F., and van de Burgwal, L.H.M. (2022). Innovations for microbiome targeting interventions–a patent landscape analysis indicating overall patenting activity decline and promising target disease areas. Benef. Microbes *13*, 265–282.

57. van Nood, E., Vrieze, A., Nieuwdorp, M., Fuentes, S., Zoetendal, E.G., de Vos, W.M.d., Visser, C.E., Kuijper, E.J., Bartelsman, J.F.W.M., Tijssen, J.G.P., et al. (2013). Duodenal infusion of donor feces for recurrent *Clostridium difficile*. N. Engl. J. Med. *368*, 407–415. https://doi.org/10.1056/NEJMoa1205037.

58. Hanssen, N.M.J., de Vos, W.M., and Nieuwdorp, M. (2021). Fecal microbiota transplantation in human metabolic diseases: from a murky past to a bright future? Cell Metab. *33*, 1098–1110.

59. Drekonja, D., Reich, J., Gezahegn, S., Greer, N., Shaukat, A., MacDonald, R., Rutks, I., and Wilt, T.J. (2015). Fecal microbiota transplantation for *Clostridium difficile* infection: A systematic review. Ann. Intern. Med. *162*, 630–638. https://doi.org/10.7326/m14-2693.

60. Carlson, P.E. (2020). Regulatory considerations for fecal microbiota transplantation products. Cell Host Microbe *27*, 173–175.

61. Davidson, K.W., Silverstein, M., Cheung, K., Paluch, R.A., and Epstein, L.H. (2021). Experimental designs to optimize treatments for individuals: personalized N-of-1 trials. JAMA Pediatr. *175*, 404–409. https://doi.org/10.1001/jamapediatrics.2020.5801.

62. Jang, H.B., Chittick, L., Li, Y.-F., Zablocki, O., Sanderson, C.M., Carrillo, A., van den Engh, G., and Sullivan, M.B. (2022). Viral tag and grow: a scalable approach to capture and characterize infectious virus–host pairs. ISME Commun. *2*, 12. https://doi.org/10.1038/s43705-022-00093-9.

63. Cammarota, G., Ianiro, G., Ahern, A., Carbone, C., Temko, A., Claesson, M.J., Gasbarrini, A., and Tortora, G. (2020). Gut microbiome, big data and machine learning to promote precision medicine for cancer. Nat. Rev. Gastroenterol. Hepatol. *17*, 635–648. https://doi.org/10.1038/s41575-020-0327-3.

64. Timmis, J.K., and Timmis, K. (2017). The DIY digital medical centre. Microb. Biotechnol. *10*, 1084–1093.

65. Timmis, K., Hallsworth, J.E., McGenity, T.J., Armstrong, R., Colom, M.F., Karahan, Z.C., Chavarría, M., Bernal, P., Boyd, E.S., Ramos, J.L., et al. (2024). A concept for international societally relevant microbiology education and microbiology knowledge promulgation in society. Microb. Biotechnol. *17*, e14456.

66. Suman, J., Rakshit, A., Ogireddy, S.D., Singh, S., Gupta, C., and Chandrakala, J. (2022). Microbiome as a key player in sustainable agriculture and human health. Front. Soil Sci. *2*, 821589. https://doi.org/10.3389/fsoil.2022.821589.

67. Panda, S., and Zhou, K. (2023). Engineering microbes to overproduce natural products as agrochemicals. Synth. Syst. Biotechnol. *8*, 79–85.

68. Shayanthan, A., Ordoñez, P.A.C., and Oresnik, I.J. (2022). The role of synthetic microbial communities (SynCom) in sustainable agriculture. Front. Agron. *4*, 896307.

69. Patil, H.J., and Solanki, M.K. (2016). Microbial inoculant: modern era of fertilizers and pesticides. In Microbial Inoculants in Sustainable Agricultural Productivity: vol. 1: Research Perspectives, D. Singh, H. Singh, and R. Prabha, eds. (Springer), pp. 319–343.

70. Lutz, S., Bodenhausen, N., Hess, J., Valzano-Held, A., Waelchli, J., Deslandes-Hérold, G., Schlaeppi, K., and van der Heijden, M.G.A. (2023). Soil microbiome indicators can predict crop growth response to large-scale inoculation with arbuscular mycorrhizal fungi. Nat. Microbiol. *8*, 2277–2289. https://doi.org/10.1038/s41564-023-01520-w.

71. Timmis, K., and Ramos, J.L. (2021). The soil crisis: the need to treat as a global health problem and the pivotal role of microbes in prophylaxis and therapy. Microb. Biotechnol. *14*, 769–797.

72. Regulation (EU) 2019/1009 of the European Parliment and of the Council (2019). Laying down Rules on the Making Available on the Market of EU Fertilising Products and Amending Regulations (EC) 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC). http://data.europa.eu/eli/reg/2019/1009/oj.

73. Ge, A.-H., Li, Q.-Y., Liu, H.-W., Zhang, Z.-K., Lu, Y., Liang, Z.-H., Singh, B.K., Han, L.-L., Xiang, J.-F., Xiao, J.-L., et al. (2024). *Streptomyces*-triggered coordination between rhizosphere microbiomes and plant transcriptome enables watermelon *Fusarium* wilt resistance. Microb. Biotechnol. *17*, e14435.

74. Mansilla, F.I., Ficoseco, C.A., Miranda, M.H., Puglisi, E., Nader-Macías, M.E.F., Vignolo, G.M., and Fontana, C.A. (2022). Administration of probiotic lactic acid bacteria to modulate fecal microbiome in feedlot cattle. Sci. Rep. *12*, 12957.

75. Arowolo, M.A., and He, J. (2018). Use of probiotics and botanical extracts to improve ruminant production in the tropics: a review. Anim. Nutr. *4*, 241–249.

76. El-Saadony, M.T., Alagawany, M., Patra, A.K., Kar, I., Tiwari, R., Dawood, M.A.O., Dhama, K., and Abdel-Latif, H.M.R. (2021). The functionality of probiotics in aquaculture: an overview. Fish Shellfish Immunol. *117*, 36–52.

77. Singh, B.K., Delgado-Baquerizo, M., Egidi, E., Guirado, E., Leach, J.E., Liu, H., and Trivedi, P. (2023). Climate change impacts on plant pathogens, food security and paths forward. Nat. Rev. Microbiol. *21*, 640–656.

78. Obeng, N., Czerwinski, A., Schütz, D., Michels, J., Leipert, J., Bansept, F., García García, M.J., Schultheiß, T., Kemlein, M., Fuß, J., et al. (2023). Bacterial c-di-GMP has a key role in establishing host–microbe symbiosis. Nat. Microbiol. *8*, 1809–1819. https://doi.org/10.1038/s41564-023-01468-x.

79. Morales Moreira, Z.P., Chen, M.Y., Yanez Ortuno, D.L., and Haney, C.H. (2023). Engineering plant microbiomes by integrating eco-evolutionary principles into current strategies. Curr. Opin. Plant Biol. *71*, 102316.

80. Ciani, M., Lippolis, A., Fava, F., Rodolfi, L., Niccolai, A., and Tredici, M.R. (2021). Microbes: food for the future. Foods *10*, 971.

81. Augustin, M.A., Hartley, C.J., Maloney, G., and Tyndall, S. (2023). Innovation in precision fermentation for food ingredients. Crit. Rev. Food Sci. Nutr. *64*, 6218–6238.

82. Humpenöder, F., Bodirsky, B.L., Weindl, I., Lotze-Campen, H., Linder, T., and Popp, A. (2022). Projected environmental benefits of replacing beef with microbial protein. Nature *605*, 90–96.

83. Ritchie, H., Reay, D.S., and Higgins, P. (2018). Potential of meat substitutes for climate change mitigation and improved human health in high-income markets. Front. Sustain. Food Syst. *2*. https://doi.org/10.3389/fsufs.2018.00016.

84. Graham, A.E., and Ledesma-Amaro, R. (2023). The microbial food revolution. Nat. Commun. *14*, 2231. https://doi.org/10.1038/s41467-023-37891-1.

85. Cordaillat-Simmons, M., Rouanet, A., and Pot, B. (2020). Live biotherapeutic products: the importance of a defined regulatory framework. Exp. Mol. Med. *52*, 1397–1406. https://doi.org/10.1038/s12276-020-0437-6.

86. Kusstatscher, P., Cernava, T., Abdelfattah, A., Gokul, J., Korsten, L., and Berg, G. (2020). Microbiome approaches provide the key to biologically control postharvest pathogens and storability of fruits and vegetables. FEMS Microbiol. Ecol. *96*, fiaa119.

87. Wassermann, B., Abdelfattah, A., Cernava, T., Wicaksono, W., and Berg, G. (2022). Microbiome-based biotechnology for reducing food loss post harvest. Curr. Opin. Biotechnol. *78*, 102808.

88. Motarjemi, Y. (2002). Impact of small scale fermentation technology on food safety in developing countries. Int. J. Food Microbiol. *75*, 213–229.

89. Poore, J., and Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. Science *360*, 987–992.

90. Hiis, E.G., Vick, S.H.W., Molstad, L., Røsdal, K., Jonassen, K.R., Winiwarter, W., and Bakken, L.R. (2024). Unlocking bacterial potential to reduce farmland N_2O emissions. Nature *630*, 421–428. https://doi.org/10.1038/s41586-024-07464-3.

91. Healy, N., Stephens, J.C., and Malin, S.A. (2019). Embodied energy injustices: unveiling and politicizing the transboundary harms of fossil fuel extractivism and fossil fuel supply chains. Energy Res. Soc. Sci. *48*, 219–234.

92. Azapagic, A., and Perdan, S. (2010). Sustainable Development in Practice: Case Studies for Engineers and Scientists (John Wiley & Sons).

93. Jeswani, H.K., Chilvers, A., and Azapagic, A. (2020). Environmental sustainability of biofuels: a review. Proc. Math. Phys. Eng. Sci. *476*, 20200351. https://doi.org/10.1098/rspa.2020.0351.

94. Lei, C., Chen, J., and Robertson, G.P. (2023). Climate cooling benefits of cellulosic bioenergy crops from elevated albedo. GCB Bioenergy *15*, 1373–1386.

95. Robertson, G.P., Hamilton, S.K., Barham, B.L., Dale, B.E., Izaurralde, R.C., Jackson, R.D., Landis, D.A., Swinton, S.M., Thelen, K.D., and Tiedje, J.M. (2017). Cellulosic biofuel contributions to a sustainable energy future: choices and outcomes. Science *356*, eaal2324. https://doi.org/10.1126/science.aal2324.

96. Lee, U., Kwon, H., Wu, M., and Wang, M. (2021). Retrospective analysis of the U.S. corn ethanol industry for 2005–2019: implications for greenhouse gas emission reductions. Biofuels Bioprod. Biorefin. *15*, 1318–1331.

97. Wu, M., Wang, M., Liu, J., and Huo, H. (2008). Assessment of potential life-cycle energy and greenhouse gas emission effects from using corn-based butanol as a transportation fuel. Biotechnol. Prog. *24*, 1204–1214.

98. Northrup, D.L., Basso, B., Wang, M.Q., Morgan, C.L.S., and Benfey, P.N. (2021). Novel technologies for emission reduction complement conservation agriculture to achieve negative emissions from row-crop production. Proc. Natl. Acad. Sci. USA *118*, e2022666118.

99. Robertson, G.P., Hamilton, S.K., Paustian, K., and Smith, P. (2022). Land-based climate solutions for the United States. Glob. Change Biol. *28*, 4912–4919.

100. Markham, J.N., Tao, L., Davis, R., Voulis, N., Angenent, L.T., Ungerer, J., and Yu, J. (2016). Techno-economic analysis of a conceptual biofuel production process from bioethylene produced by photosynthetic recombinant cyanobacteria. Green Chem. *18*, 6266–6281. https://doi.org/10.1039/C6GC01083K.

101. Chen, C.-T., and Liao, J.C. (2016). Frontiers in microbial 1-butanol and isobutanol production. FEMS Microbiol. Lett. *363*, fnw020.

102. Xu, X., Zhou, Q., and Yu, D. (2022). The future of hydrogen energy: bio-hydrogen production technology. Int. J. Hydrog. Energy *47*, 33677–33698.

103. Rafa, N., Ahmed, S.F., Badruddin, I.A., Mofijur, M., and Kamangar, S. (2021). Strategies to produce cost-effective third-generation biofuel from microalgae. Front. Energy Res. *9*. https://doi.org/10.3389/fenrg.2021.749968.

104. Gęsicka, A., Oleskowicz-Popiel, P., and Łężyk, M. (2021). Recent trends in methane to bioproduct conversion by methanotrophs. Biotechnol. Adv. *53*, 107861.

105. Singh, H.B., Kang, M.-K., Kwon, M., and Kim, S.-W. (2022). Developing methylotrophic microbial platforms for a methanol-based bioindustry. Front. Bioeng. Biotechnol. *10*, 1050740.

106. Jeong, J., Kim, T.H., Jang, N., Ko, M., Kim, S.K., Baek, J.I., Emelianov, G., Rha, E., Kwon, K.K., Kim, H., et al. (2023). A highly efficient and versatile genetic engineering toolkit for a methanotroph-based biorefinery. Chem. Eng. J. *453*, 139911.

107. He, L., Groom, J.D., Wilson, E.H., Fernandez, J., Konopka, M.C., Beck, D.A.C., and Lidstrom, M.E. (2023). A methanotrophic bacterium to enable methane removal for climate mitigation. Proc. Natl. Acad. Sci. USA *120*, e2310046120. https://doi.org/10.1073/pnas.2310046120.

108. Bertagni, M.B., Pacala, S.W., Paulot, F., and Porporato, A. (2022). Risk of the hydrogen economy for atmospheric methane. Nat. Commun. *13*, 7706. https://doi.org/10.1038/s41467-022-35419-7.

109. Antranikian, G., and Streit, W.R. (2022). Microorganisms harbor keys to a circular bioeconomy making them useful tools in fighting plastic pollution and rising CO2 levels. Extremophiles *26*, 10. https://doi.org/10.1007/s00792-022-01261-4.

110. Lange, L. (2021). Strategies for a rapid transition to a circular, biobased society. In Bio#Futures: Foreseeing and Exploring the Bioeconomy, E. Koukios and A. Sacio-Szymańska, eds. (Springer International Publishing), pp. 55–71. https://doi.org/10.1007/978-3-030-64969-2_4.

111. Chui, M., Evers, M., Manyika, J., Zheng, A., and Nisbet, T. (2023). The bio revolution: innovations transforming economies, societies, and our lives. In Augmented Education in the Global Age, D. Araya and P. Marber, eds. (Routledge), pp. 48–74.

112. Burger, L., and Van Nimwegen, E. (2008). Accurate prediction of protein–protein interactions from sequence alignments using a Bayesian method. Mol. Syst. Biol. *4*, 165.

113. Elhacham, E., Ben-Uri, L., Grozovski, J., Bar-On, Y.M., and Milo, R. (2020). Global human-made mass exceeds all living biomass. Nature *588*, 442–444. https://doi.org/10.1038/s41586-020-3010-5.

114. Gallo, M. (2022). The Bioeconomy: A Primer. Congressional Research Service Report r46881. https://crsreports.congress.gov/.

115. Jones, D.T., Schulz, F., Roux, S., and Brown, S.D. (2023). Solvent-producing Clostridia Revisited. Microorganisms *11*, 2253.

116. Chen, J.G., Crooks, R.M., Seefeldt, L.C., Bren, K.L., Bullock, R.M., Darensbourg, M.Y., Holland, P.L., Hoffman, B., Janik, M.J., Jones, A.K., et al. (2018). Beyond fossil fuel–driven nitrogen transformations. Science *360*, eaar6611. https://doi.org/10.1126/science.aar6611.

117. Khan, Y. (2024). A yeast-like bacteria can cut carbon emissions while creating sustainable aviation fuel and sneakers. https://www.wsj.com/

articles/a-yeast-like-bacteria-can-cut-carbon-emissions-while-creating-sustainable-aviation-fuel-and-sneakers-a98fb98b.

118. Kim, B., Misra, S., and Maravelias, C.T. (2023). Lignocellulosic fuel and chemical co-production. Joule *7*, 2403–2407.

119. Tirlán (2020). Sustainable dairy processing and the circular bio-economy. https://www.tirlan.com/our-story/news/sustainable-dairy-processing-and-the-circular-bio-economy-0.

120. Wu, W., and Maravelias, C.T. (2019). Identifying the characteristics of promising renewable replacement chemicals. iScience *15*, 136–146.

121. Wu, W., Long, M.R., Zhang, X., Reed, J.L., and Maravelias, C.T. (2018). A framework for the identification of promising bio-based chemicals. Biotechnol. Bioeng. *115*, 2328–2340.

122. Sheldon, R.A. (2020). Biocatalysis and biomass conversion: enabling a circular economy. Philos. Trans. A Math. Phys. Eng. Sci. *378*, 20190274. https://doi.org/10.1098/rsta.2019.0274.

123. Gelfand, I., Sahajpal, R., Zhang, X., Izaurralde, R.C., Gross, K.L., and Robertson, G.P. (2013). Sustainable bioenergy production from marginal lands in the US Midwest. Nature *493*, 514–517. https://doi.org/10.1038/nature11811.

124. Kim, S., Dale, B.E., Basso, B., Thelen, K., and Maravelias, C.T. (2023). Supply chain system for a centralized biorefinery system based on switchgrass grown on marginal land in Michigan. Biofuels Bioprod. Biorefin. *17*, 1502–1514.

125. Rogers, J.N., Stokes, B., Dunn, J., Cai, H., Wu, M., Haq, Z., and Baumes, H. (2017). An assessment of the potential products and economic and environmental impacts resulting from a billion ton bioeconomy. Biofuels Bioprod. Biorefin. *11*, 110–128.

126. Fuller, R., Landrigan, P.J., Balakrishnan, K., Bathan, G., Bose-O'Reilly, S., Brauer, M., Caravanos, J., Chiles, T., Cohen, A., Corra, L., et al. (2022). Pollution and health: a progress update. Lancet Planet. Health *6*, e535–e547. https://doi.org/10.1016/S2542-5196(22)00090-0.

127. Arora, N.K. (2018). Bioremediation: a green approach for restoration of polluted ecosystems. Environ. Sustain. *1*, 305–307. https://doi.org/10.1007/s42398-018-00036-y.

128. Mohanty, I., and Rath, A. (2020). Bioremediation: current research trends and applications. In Waste to Energy: Prospects and Applications, B.K. Kashyap, M.K. Solanki, D.V. Kamboj, and A.K. Pandey, eds. (Springer), pp. 99–120. https://doi.org/10.1007/978-981-33-4347-4_5.

129. Hou, D., O'Connor, D., Igalavithana, A.D., Alessi, D.S., Luo, J., Tsang, D.C.W., Sparks, D.L., Yamauchi, Y., Rinklebe, J., and Ok, Y.S. (2020). Metal contamination and bioremediation of agricultural soils for food safety and sustainability. Nat. Rev. Earth Environ. *1*, 366–381. https://doi.org/10.1038/s43017-020-0061-y.

130. Pande, V., Pandey, S.C., Sati, D., Pande, V., and Samant, M. (2020). Bioremediation: an emerging effective approach towards environment restoration. Environ. Sustain. *3*, 91–103. https://doi.org/10.1007/s42398-020-00099-w.

131. Hou, D., Al-Tabbaa, A., O'Connor, D., Hu, Q., Zhu, Y.-G., Wang, L., Kirkwood, N., Ok, Y.S., Tsang, D.C.W., Bolan, N.S., et al. (2023). Sustainable remediation and redevelopment of brownfield sites. Nat. Rev. Earth Environ. *4*, 271–286. https://doi.org/10.1038/s43017-023-00404-1.

132. Dell'Anno, A., Beolchini, F., Corinaldesi, C., Amato, A., Becci, A., Rastelli, E., Hekeu, M., Regoli, F., Astarita, E., Greco, S., et al. (2020). Assessing the efficiency and eco-sustainability of bioremediation strategies for the reclamation of highly contaminated marine sediments. Mar. Environ. Res. *162*, 105101.

133. Jain, M., Khan, S.A., Sharma, K., Jadhao, P.R., Pant, K.K., Ziora, Z.M., and Blaskovich, M.A.T. (2022). Current perspective of innovative strategies for bioremediation of organic pollutants from wastewater. Bioresour. Technol. *344*, 126305.

134. Lim, S.-L., Chu, W.-L., and Phang, S.-M. (2010). Use of *Chlorella vulgaris* for bioremediation of textile wastewater. Bioresour. Technol. *101*, 7314–7322.

135. Singh, D., Goswami, R.K., Agrawal, K., Chaturvedi, V., and Verma, P. (2022). Bio-inspired remediation of wastewater: A contemporary approach for environmental clean-up. Curr. Res. Green Sustain. Chem. *5*, 100261.

136. Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., and Law, K.L. (2015). Marine pollution. Plastic waste inputs from land into the ocean. Science *347*, 768–771. https://doi.org/10.1126/science.1260352.

137. Chiba, S., Saito, H., Fletcher, R., Yogi, T., Kayo, M., Miyagi, S., Ogido, M., and Fujikura, K. (2018). Human footprint in the abyss: 30 year records of deep-sea plastic debris. Mar. Policy *96*, 204–212.

138. Materić, D., Kjær, H.A., Vallelonga, P., Tison, J.-L., Röckmann, T., and Holzinger, R. (2022). Nanoplastics measurements in Northern and Southern polar ice. Environ. Res. *208*, 112741.

139. Zhao, S., Zettler, E.R., Bos, R.P., Lin, P., Amaral-Zettler, L.A., and Mincer, T.J. (2022). Large quantities of small microplastics permeate the surface ocean to abyssal depths in the South Atlantic gyre. Glob. Change Biol. *28*, 2991–3006.

140. Amaral-Zettler, L.A., Zettler, E.R., and Mincer, T.J. (2020). Ecology of the plastisphere. Nat. Rev. Microbiol. *18*, 139–151. https://doi.org/10.1038/s41579-019-0308-0.

141. Zettler, E.R., Mincer, T.J., and Amaral-Zettler, L.A. (2013). Life in the "plastisphere": microbial communities on plastic marine debris. Environ. Sci. Technol. *47*, 7137–7146. https://doi.org/10.1021/es401288x.

142. Krueger, M.C., Harms, H., and Schlosser, D. (2015). Prospects for microbiological solutions to environmental pollution with plastics. Appl. Microbiol. Biotechnol. *99*, 8857–8874. https://doi.org/10.1007/s00253-015-6879-4.

143. Pathak, V.M., and Navneet. (2017). Review on the current status of polymer degradation: a microbial approach. Bioresour. Bioprocess. *4*, 15. https://doi.org/10.1186/s40643-017-0145-9.

144. Yoshida, S., Hiraga, K., Takehana, T., Taniguchi, I., Yamaji, H., Maeda, Y., Toyohara, K., Miyamoto, K., Kimura, Y., and Oda, K. (2016). A bacterium that degrades and assimilates poly(ethylene terephthalate). Science *351*, 1196–1199. https://doi.org/10.1126/science.aad6359.

145. Bornscheuer, U.T. (2016). MICROBIOLOGY. Feeding on plastic. Science *351*, 1154–1155. https://doi.org/10.1126/science.aaf2853.

146. Tournier, V., Topham, C.M., Gilles, A., David, B., Folgoas, C., Moya-Leclair, E., Kamionka, E., Desrousseaux, M.L., Texier, H., Gavalda, S., et al. (2020). An engineered PET depolymerase to break down and recycle plastic bottles. Nature *580*, 216–219. https://doi.org/10.1038/s41586-020-2149-4.

147. CarBios (2023). Carbios Obtains Building and Operating Permits, in Line with Announced Schedule, for World's First PET Biorecycling Plant in Longlaville. https://www.carbios.com/newsroom/en/carbios-obtains-building-and-operating-permits-in-line-with-announced-schedule-for-worlds-first-pet-biorecycling-plant-in-longlaville/.

148. Wei, R., Tiso, T., Bertling, J., O'Connor, K., Blank, L.M., and Bornscheuer, U.T. (2020). Possibilities and limitations of biotechnological plastic degradation and recycling. Nat. Cat. *3*, 867–871. https://doi.org/10.1038/s41929-020-00521-w.

149. Choi, S.Y., Lee, Y., Yu, H.E., Cho, I.J., Kang, M., and Lee, S.Y. (2023). Sustainable production and degradation of plastics using microbes. Nat. Microbiol. *8*, 2253–2276. https://doi.org/10.1038/s41564-023-01529-1.

150. Gerhardt, K.E., Huang, X.-D., Glick, B.R., and Greenberg, B.M. (2009). Phytoremediation and rhizoremediation of organic soil contaminants: potential and challenges. Plant Sci. *176*, 20–30.

151. Terzaghi, E., Vergani, L., Mapelli, F., Borin, S., Raspa, G., Zanardini, E., Morosini, C., Anelli, S., Nastasio, P., Sale, V.M., et al. (2019). Rhizoremediation of weathered PCBs in a heavily contaminated agricultural soil: results of a biostimulation trial in semi field conditions. Sci. Total Environ. *686*, 484–496.

152. Eze, M.O., Thiel, V., Hose, G.C., George, S.C., and Daniel, R. (2022). Bacteria-plant interactions synergistically enhance biodegradation of diesel fuel hydrocarbons. Commun. Earth Environ. *3*, 192. https://doi.org/10.1038/s43247-022-00526-2.

153. Corinaldesi, C., Bianchelli, S., Candela, M., Dell'Anno, A., Gambi, C., Rastelli, E., Varrella, S., and Danovaro, R. (2023). Microbiome-assisted restoration of degraded marine habitats: a new nature-based solution? Front. Mar. Sci. *10*. https://doi.org/10.3389/fmars.2023.1227560.

154. Correa-García, S., Pande, P., Séguin, A., St-Arnaud, M., and Yergeau, E. (2018). Rhizoremediation of petroleum hydrocarbons: a model system for plant microbiome manipulation. Microb. Biotechnol. *11*, 819–832. https://doi.org/10.1111/1751-7915.13303.

155. Lovley, D.R. (2006). Microbial fuel cells: novel microbial physiologies and engineering approaches. Curr. Opin. Biotechnol. *17*, 327–332.

156. Yang, Y., Wang, Z., Gan, C., Klausen, L.H., Bonné, R., Kong, G., Luo, D., Meert, M., Zhu, C., Sun, G., et al. (2021). Long-distance electron transfer in a filamentous Gram-positive bacterium. Nat. Commun. *12*, 1709. https://doi.org/10.1038/s41467-021-21709-z.

157. Ahmed, S.F., Mofijur, M., Islam, N., Parisa, T.A., Rafa, N., Bokhari, A., Klemeš, J.J., and Indra Mahlia, T.M. (2022). Insights into the development of microbial fuel cells for generating biohydrogen, bioelectricity, and treating wastewater. Energy *254*, 124163.

158. Baniasadi, M., Vakilchap, F., Bahaloo-Horeh, N., Mousavi, S.M., and Farnaud, S. (2019). Advances in bioleaching as a sustainable method for metal recovery from e-waste: a review. J. Ind. Eng. Chem. *76*, 75–90.

159. Tezyapar Kara, I., Kremser, K., Wagland, S.T., and Coulon, F. (2023). Bioleaching metal-bearing wastes and by-products for resource recovery: a review. Environ. Chem. Lett. *21*, 3329–3350. https://doi.org/10.1007/s10311-023-01611-4.

160. Dusengemungu, L., Kasali, G., Gwanama, C., and Mubemba, B. (2021). Overview of fungal bioleaching of metals. Environ. Adv. *5*, 100083.

161. Wang, J., Bai, J., Xu, J., and Liang, B. (2009). Bioleaching of metals from printed wire boards by *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans* and their mixture. J. Hazard. Mater. *172*, 1100–1105.

162. Nandy, S., Andraskar, J., Lanjewar, K., and Kapley, A. (2021). Chapter 23. Challenges in bioremediation: from lab to land. In Bioremediation for Environmental Sustainability, G. Saxena, V. Kumar, and M.P. Shah, eds. (Elsevier), pp. 561–583.

163. Guerra, C.A., Berdugo, M., Eldridge, D.J., Eisenhauer, N., Singh, B.K., Cui, H., Abades, S., Alfaro, F.D., Bamigboye, A.R., Bastida, F., et al. (2022). Global hotspots for soil nature conservation. Nature *610*, 693–698. https://doi.org/10.1038/s41586-022-05292-x.

164. Crowther, T.W., van den Hoogen, J., Wan, J., Mayes, M.A., Keiser, A.D., Mo, L., Averill, C., and Maynard, D.S. (2019). The global soil community and its influence on biogeochemistry. Science *365*, eaav0550. https://doi.org/10.1126/science.aav0550.

165. van den Hoogen, J., Geisen, S., Routh, D., Ferris, H., Traunspurger, W., Wardle, D.A., de Goede, R.G.M., Adams, B.J., Ahmad, W., Andriuzzi, W.S., et al. (2019). Soil nematode abundance and functional group composition at a global scale. Nature *572*, 194–198. https://doi.org/10.1038/s41586-019-1418-6.

166. Bingham, H.C., Juffe Bignoli, D., Lewis, E., MacSharry, B., Burgess, N.D., Visconti, P., Deguignet, M., Misrachi, M., Walpole, M., Stewart, J.L., et al. (2019). Sixty years of tracking conservation progress using the World Database on Protected Areas. Nat. Ecol. Evol. *3*, 737–743. https://doi.org/10.1038/s41559-019-0869-3.

167. Anthony, M.A., Crowther, T.W., van der Linde, S., Suz, L.M., Bidartondo, M.I., Cox, F., Schaub, M., Rautio, P., Ferretti, M., Vesterdal, L., et al. (2022). Forest tree growth is linked to mycorrhizal fungal composition and function across Europe. ISME J. *16*, 1327–1336. https://doi.org/10.1038/s41396-021-01159-7.

168. Jiang, M., Delgado-Baquerizo, M., Yuan, M.M., Ding, J., Yergeau, E., Zhou, J., Crowther, T.W., and Liang, Y. (2023). Home-based microbial solution to boost crop growth in low-fertility soil. New Phytol. *239*, 752–765.

169. Jin Song, S., Woodhams, D.C., Martino, C., Allaband, C., Mu, A., Javorschi-Miller-Montgomery, S., Suchodolski, J.S., and Knight, R. (2019). Engineering the microbiome for animal health and conservation. Exp. Biol. Med. (Maywood) *244*, 494–504. https://doi.org/10.1177/1535370219830075.

170. Shaffer, J.P., Nothias, L.-F., Thompson, L.R., Sanders, J.G., Salido, R.A., Couvillion, S.P., Brejnrod, A.D., Lejzerowicz, F., Haiminen, N., Huang, S., et al. (2022). Standardized multi-omics of Earth's microbiomes reveals microbial and metabolite diversity. Nat. Microbiol. *7*, 2128–2150. https://doi.org/10.1038/s41564-022-01266-x.

171. Guerra, C.A., Bardgett, R.D., Caon, L., Crowther, T.W., Delgado-Baquerizo, M., Montanarella, L., Navarro, L.M., Orgiazzi, A., Singh, B.K., Tedersoo, L., et al. (2021). Tracking, targeting, and conserving soil biodiversity. Science *371*, 239–241. https://doi.org/10.1126/science.abd7926.

172. Hart, M.M., Cross, A.T., D'Agui, H.M., Dixon, K.W., Van der Heyde, M., Mickan, B., Horst, C., Grez, B.M., Valliere, J.M., Rossel, R.V., et al. (2020). Examining assumptions of soil microbial ecology in the monitoring of ecological restoration. Ecol. Solut. Evid. *1*, e12031.

173. Kaminsky, L.M., Trexler, R.V., Malik, R.J., Hockett, K.L., and Bell, T.H. (2019). The inherent conflicts in developing soil microbial inoculants. Trends Biotechnol. *37*, 140–151.

174. Bender, S.F., Schlaeppi, K., Held, A., and Van der Heijden, M.G.A. (2019). Establishment success and crop growth effects of an arbuscular mycorrhizal fungus inoculated into Swiss corn fields. Agric. Ecosyst. Environ. *273*, 13–24.

175. Koziol, L., and Bever, J.D. (2017). The missing link in grassland restoration: arbuscular mycorrhizal fungi inoculation increases plant diversity and accelerates succession. J. Appl. Ecol. *54*, 1301–1309.

176. Huisman, J., Codd, G.A., Paerl, H.W., Ibelings, B.W., Verspagen, J.M.H., and Visser, P.M. (2018). Cyanobacterial blooms. Nat. Rev. Microbiol. *16*, 471–483.

177. Fastner, J., Abella, S., Litt, A., Morabito, G., Vörös, L., Pálffy, K., Straile, D., Kümmerlin, R., Matthews, D., Phillips, M.G., et al. (2016). Combating cyanobacterial proliferation by avoiding or treating inflows with high P load—experiences from eight case studies. Aquat. Ecol. *50*, 367–383.

178. Richkus, J., Wainger, L.A., and Barber, M.C. (2016). Pathogen reduction co-benefits of nutrient best management practices. PeerJ *4*, e2713.

179. Grasso, C.R., Pokrzywinski, K.L., Waechter, C., Rycroft, T., Zhang, Y., Aligata, A., Kramer, M., and Lamsal, A. (2022). A review of cyanophage–host relationships: highlighting cyanophages as a potential cyanobacteria control strategy. Toxins *14*, 385.

180. Mohamed, Z.A., Hashem, M., Alamri, S., Campos, A., and Vasconcelos, V. (2021). Fungal biodegradation and removal of cyanobacteria and microcystins: potential applications and research needs. Environ. Sci. Pollut. Res. Int. *28*, 37041–37050.

181. Van Wichelen, J., Vanormelingen, P., Codd, G.A., and Vyverman, W. (2016). The common bloom-forming cyanobacterium *Microcystis* is prone to a wide array of microbial antagonists. Harmful Algae *55*, 97–111.

182. Li, J., Li, R., and Li, J. (2017). Current research scenario for microcystins biodegradation–a review on fundamental knowledge, application prospects and challenges. Sci. Total Environ. *595*, 615–632.

183. Fedele, G., Donatti, C.I., Bornacelly, I., and Hole, D.G. (2021). Nature-dependent people: mapping human direct use of nature for basic needs across the tropics. Glob. Environ. Change *71*, 102368.

184. Crowther, T.W., Todd-Brown, K.E.O., Rowe, C.W., Wieder, W.R., Carey, J.C., Machmuller, M.B., Snoek, B.L., Fang, S., Zhou, G., Allison, S.D.,

et al. (2016). Quantifying global soil carbon losses in response to warming. Nature *540*, 104–108. https://doi.org/10.1038/nature20150.

185. Jansson, J.K. (2023). Microorganisms, climate change, and the Sustainable Development Goals: progress and challenges. Nat. Rev. Microbiol. *21*, 622–623.
186. Strack, M., Davidson, S.J., Hirano, T., and Dunn, C. (2022). The Potential of peatlands as nature-based climate solutions. Curr. Clim. Change Rep. *8*, 71–82.
187. Reay, D.S., Smith, P., Christensen, T.R., James, R.H., and Clark, H. (2018). Methane and global environmental change. Annu. Rev. Environ. Resour. *43*, 165–192. https://doi.org/10.1146/annurev-environ-102017-030154.
188. Lassen, J., and Difford, G.F. (2020). Review: genetic and genomic selection as a methane mitigation strategy in dairy cattle. Animal *14*, s473–s483.
189. Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., De Vries, W., De Wit, C.A., et al. (2015). Sustainability. Planetary boundaries: guiding human development on a changing planet. Science *347*, 1259855.
190. Bakken, L.R., and Frostegård, Å. (2020). Emerging options for mitigating N_2O emissions from food production by manipulating the soil microbiota. Curr. Opin. Environ. Sustain. *47*, 89–94.
191. Jonassen, K.R., Hagen, L.H., Vick, S.H.W., Arntzen, M.Ø., Eijsink, V.G.H., Frostegård, Å., Lycus, P., Molstad, L., Pope, P.B., and Bakken, L.R. (2022). Nitrous oxide respiring bacteria in biogas digestates for reduced agricultural emissions. ISME J. *16*, 580–590. https://doi.org/10.1038/s41396-021-01101-x.
192. Jonassen, K.R., Ormåsen, I., Duffner, C., Hvidsten, T.R., Bakken, L.R., and Vick, S.H.W. (2022). A dual enrichment strategy provides soil- and digestate-competent nitrous oxide-respiring bacteria for mitigating climate forcing in agriculture. mBio *13*, e0078822. https://doi.org/10.1128/mbio.00788-22.
193. Meskhidze, N., and Nenes, A. (2006). Phytoplankton and cloudiness in the Southern Ocean. Science *314*, 1419–1423. https://doi.org/10.1126/science.1131779.
194. O'Dowd, C.D., and de Leeuw, G. (2007). Marine aerosol production: a review of the current knowledge. Philos. Trans. A Math. Phys. Eng. Sci. *365*, 1753–1774. https://doi.org/10.1098/rsta.2007.2043.
195. Sanchez, K.J., Chen, C.-L., Russell, L.M., Betha, R., Liu, J., Price, D.J., Massoli, P., Ziemba, L.D., Crosbie, E.C., Moore, R.H., et al. (2018). Substantial seasonal contribution of observed biogenic sulfate particles to cloud condensation nuclei. Sci. Rep. *8*, 3235. https://doi.org/10.1038/s41598-018-21590-9.
196. Doney, S.C., Ruckelshaus, M., Duffy, J.E., Barry, J.P., Chan, F., English, C.A., Galindo, H.M., Grebmeier, J.M., Hollowed, A.B., Knowlton, N., et al. (2012). Climate change impacts on marine ecosystems. Annu. Rev. Mar. Sci. *4*, 11–37.
197. Intergovernmental Panel on Climate Change (2022). The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change (Cambridge University Press) https://doi.org/10.1017/9781009157964.
198. Gruber, N., Boyd, P.W., Frölicher, T.L., and Vogt, M. (2021). Biogeochemical extremes and compound events in the ocean. Nature *600*, 395–407. https://doi.org/10.1038/s41586-021-03981-7.
199. Walworth, N.G., Lee, M.D., Fu, F.-X., Hutchins, D.A., and Webb, E.A. (2016). Molecular and physiological evidence of genetic assimilation to high CO_2 in the marine nitrogen fixer *Trichodesmium*. Proc. Natl. Acad. Sci. USA *113*, E7367–E7374. https://doi.org/10.1073/pnas.1605202113.
200. Hutchins, D.A., and Capone, D.G. (2022). The marine nitrogen cycle: new developments and global change. Nat. Rev. Microbiol. *20*, 401–414.
201. Breitburg, D., Levin, L.A., Oschlies, A., Grégoire, M., Chavez, F.P., Conley, D.J., Garçon, V., Gilbert, D., Gutiérrez, D., Isensee, K., et al. (2018). Declining oxygen in the global ocean and coastal waters. Science *359*, eaam7240. https://doi.org/10.1126/science.aam7240.
202. Schmidtko, S., Stramma, L., and Visbeck, M. (2017). Decline in global oceanic oxygen content during the past five decades. Nature *542*, 335–339. https://doi.org/10.1038/nature21399.
203. Chronopoulou, P.-M., Shelley, F., Pritchard, W.J., Maanoja, S.T., and Trimmer, M. (2017). Origin and fate of methane in the Eastern Tropical North Pacific oxygen minimum zone. ISME J. *11*, 1386–1399.
204. Boscolo-Galazzo, F., Crichton, K.A., Barker, S., and Pearson, P.N. (2018). Temperature dependency of metabolic rates in the upper ocean: A positive feedback to global climate change? Glob. Planet. Change *170*, 201–212.
205. Toseland, A., Daines, S.J., Clark, J.R., Kirkham, A., Strauss, J., Uhlig, C., Lenton, T.M., Valentin, K., Pearson, G.A., Moulton, V., et al. (2013). The impact of temperature on marine phytoplankton resource allocation and metabolism. Nat. Clim. Change *3*, 979–984.
206. Chisholm, S.W., Falkowski, P.G., and Cullen, J.J. (2001). Oceans. Discrediting ocean fertilization. Science *294*, 309–310. https://doi.org/10.1126/science.1065349.
207. Boyd, P., and Vivian, C. (2019). High level review of a wide range of proposed marine geoengineering techniques (GESAMP No. 98, 144p). http://www.gesamp.org/site/assets/files/1723/rs98e.pdf.
208. Zaky, A.S. (2021). Introducing a marine biorefinery system for the integrated production of biofuels, high-value-chemicals, and co-products: A path forward to a sustainable future. Processes *9*, 1841.
209. Weng, C., Peng, X., and Han, Y. (2023). Chapter FOUR. From methane to value-added bioproducts: microbial metabolism, enzymes, and metabolic engineering. In Advances in Applied Microbiology, G.M. Gadd and S. Sariaslani, eds. (Academic Press), pp. 119–146.
210. Cattaneo, C., Beine, M., Fröhlich, C.J., Kniveton, D., Martinez-Zarzoso, I., Mastrorillo, M., Millock, K., Piguet, E., and Schraven, B. (2019). Human migration in the era of climate change. Rev. Environ. Econ. Policy *13*, 189–206. https://doi.org/10.1093/reep/rez008.
211. Garnett, S.T., Burgess, N.D., Fa, J.E., Fernández-Llamazares, Á., Molnár, Z., Robinson, C.J., Watson, J.E.M., Zander, K.K., Austin, B., Brondizio, E.S., et al. (2018). A spatial overview of the global importance of Indigenous lands for conservation. Nat. Sustain. *1*, 369–374. https://doi.org/10.1038/s41893-018-0100-6.
212. Mc Cartney, A.M., Anderson, J., Liggins, L., Hudson, M.L., Anderson, M.Z., TeAika, B., Geary, J., Cook-Deegan, R., Patel, H.R., and Phillippy, A.M. (2022). Balancing openness with Indigenous data sovereignty: an opportunity to leave no one behind in the journey to sequence all of life. Proc. Natl. Acad. Sci. USA *119*, e2115860119. https://doi.org/10.1073/pnas.2115860119.
213. Medfu Tarekegn, M., Zewdu Salilih, F., and Ishetu, A.I. (2020). Microbes used as a tool for bioremediation of heavy metal from the environment. Cogent Food Agric. *6*, 1783174. https://doi.org/10.1080/23311932.2020.1783174.
214. Merz, J.J., Barnard, P., Rees, W.E., Smith, D., Maroni, M., Rhodes, C.J., Dederer, J.H., Bajaj, N., Joy, M.K., Wiedmann, T., et al. (2023). World scientists' warning: the behavioural crisis driving ecological overshoot. Sci. Prog. *106*, 368504231201372. https://doi.org/10.1177/00368504231201372.