ISSN:2958-0420 Contents lists available at JJOAS-N

Jordan Journal of Applied Science - Natural Science Series
Applied Science Private University

Review *Vol. 20*

Microbial Stewardship in Bioethics and Environmental Governance: A Minireview.

Luay Abu-Qatouseh[1]*, Phillip J Collier[2].

[1]Department of Medical Laboratories, Faculty of Pharmacy and Medical Sciences, University of Petra, Amman, Jordan.

[2]Department of Pharmaceutics, Faculty of Pharmacy and Medical Science, University of Petra, Amman, Jordan .

ARTICLE INFO

Article history:

Received 07 Sep 2026

Accepted 09 Nov 2026

Published 12 Nov 2026

DOI: https://doi.org/10.35192/jjoas-n.v20i1.814

***Corresponding author:**

Faculty of Pharmacy and Medical Sciences, University of Petra, Amman, Jordan.

Email: labuqatouseh@uop.edu.jo

ABSTRACT

Background: Microbial communities constitutes essential components of health and ecosystem processes across people, animals, plants, and environments. However, the main focus of public policy is on pathogens and antimicrobial resistance while beneficial functions and microbial habitats are minimally considered.

Objectives: This minireview offers a stewardship of how microorganisms can link bioethics, environmental governance, One Health, conservation, and emerging-biotechnology initiatives.

Methods: A targeted narrative investigation of PubMed and Crossref through 4 November 2026, supported by publicly available policy documents was conducted. Intentional selection of peer-reviewed research and policy sources in English language was based on thematic relevance; no new data was collected.

Results: Five ethical principles were identified as being interlinked within the synthesis. These included stewardship, intergenerational responsibility, justice, epistemic humility and respect for microbial communities. The study also explored the implications of the Nagoya Protocol, Kunming -Montreal Global Biodiversity Framework, digital sequence information, the 2024 United Nations declaration on antimicrobial resistance and the Quadripartite One Health framework. Practical considerations to incorporate into research include microbial biomarkers, sustained monitoring, interdisciplinary evaluation and meaningful engagement.

Conclusion: Microbes, when treated as context-dependent ecological partners and potential risks, instead of as threats or globally beneficial agents, would optimally provide more adaptive, transparent, and fair governance, with attention to ecology, unreliability, and the risks and benefits distribution.

Keywords: microbial stewardship; microbiome; One Health; bioethics; environmental governance;

Introduction

Microorganisms are one of the most abundant and functionally relevant life forms on Earth. Prokaryotes have been described as 'the invisible majority' (early global estimates), and more recent biomass calculations have demonstrated that bacteria and archaea account for a large proportion of the planet's biomass. This can be found in soils, sediments, oceans and the deep subsurface (1-2). Microbial activity underpins many chemical processes that support larger life forms. Carbon, nitrogen, sulphur and phosphorus cycles are highly driven by microbial activity. Many processes which seem to occur naturally in the environment are actually driven by microbes (3-4).

The importance of microbes has not been widely advocated in ethical and policy discussions. Typically, environmental legislation and conservation will focus on discussing forest, river, mammal, bird and endangered plant life. It is not typical to discuss soil microbial communities, marine plankton, gut microbiota and uncultivated microbial taxa (5-8). In health policy microbes are often discussed in terms of disease, cleanliness and antimicrobial resistance (AMR). Whilst these are important issues to consider, this does not allow for discussion of the many positive and neutral relationships microbes have with humans, plants, ecosystems and the environment. These include supporting our immune system, digestion, plant growth, resilient ecosystems and environmental restoration (9-14). Microbial stewardship is an ethical practice aiming to responsibly manage microbial communities to promote well-being for humans, animals, plants and the environment. Microbial systems can be considered as ecological partners, a source of innovation or as potential risks that need controlling. Institutions should therefore be cautious, equitable, transparent and have a long-term view to microbial systems (14-27).

This minireview explores ways in which microbial life can be represented appropriately within science, law and ethics. Why

Published by Jordan Journal of Applied Science - Natural Science Series — This is an open access article under the CC BY 4.0 license.

are microbes important to consider in policymaking? How is microbial community life made visible through microbiome science? How can microbes be incorporated into governance? And how can microbial stewardship, equity, engagement and intergenerational stewardship inform decision making? (12-32).

Methods

This narrative minireview was updated through 4 November 2026. Search strategies were implemented using PubMed (NCBI) AND Crossref, searching from the beginning of the databases. Policy documents were found in the Convention on Biological Diversity (CBD), United Nations AND Quadripartite. PubMed queries combined: "microbial stewardship" OR "microbiome stewardship" OR "microbial conservation"; (microbiome OR microbiota) AND (ethics OR governance OR policy OR One Health OR environmental justice); "microbial genetic resources" AND (Nagoya OR access and benefit-sharing OR digital sequence information OR bioprospecting); and (engineered microorganisms OR microbiome engineering) AND (ethics OR risk assessment OR public engagement). Similar search terms were used in Crossref. Papers AND policy documents were searched in English AND were peer reviewed. Foundational papers were included if they are conceptually relevant. Papers were screened on titles AND abstracts for direct relevance to microbial ecology OR genetic resources AND at least one of the governance OR ethics areas. If available, further targeted screening was performed on the full text. Papers were purposefully selected to include the areas of microbial functions AND indicators; One Health, antimicrobial resistance; conservation AND benefit sharing; regulation of biotechnology; justice; deliberation AND planetary protection. Findings were then grouped by themes. This is not a systematic review therefore there was no formal assessment of risk of bias OR meta-analysis.

Results

Across the reviewed literature four themes emerged. Microbial functions were not well represented within policy. Modern approaches enable quantification of changes to communities however there is no clear ethical meaning. Current governance frameworks can provide a helpful starting point however do not always provide clear microbial specific responsibilities. Lastly, stewardship should consider uncertainty, equity and who benefits.

Why Microbes Matter in Policy and Ethics

Microorganisms are not merely agents of disease. They are considered cofactors in animal development, plant nutrition, soil fertility, marine industry, and ecosystem structure and function. Research on animals in a bacterial world has shown that host biology cannot be fully understood without microbial symbiosis, while human microbiome studies have demonstrated that healthy bodies contain complex microbial communities with important metabolic and immunological roles (9-10). Similar relationships occur in plants, where microbiota affect nutrient acquisition, stress tolerance, and growth, making microbial ecology relevant to agriculture, food security, and environmental sustainability (11).

Microbial life plays a vital role in policy. Biodiversity below ground contributes to ecosystem health by contributing to decomposition, nutrient cycling, carbon sequestration and enhancing biodiversity above ground (8,33-36). Soil microbiomes are influenced by agricultural practices, land usage, compaction, organic matter and soil structure; therefore, the way land is farmed is essentially an environmental decision made for microbes (36-37). Therefore, the idea of soil as an inert growth medium does not consider the importance of soil as a living entity with microorganisms that have an impact on human and non-human wellbeing.

Marine and freshwater microbial communities play a vital role in the environment. Projects such as the Tara Oceans and Earth Microbiome Project have shown how using a co-ordinated approach to sequencing has increased our understanding of global microbial diversity and has made previously unseen life more accessible to science and policy (5-6,38). Comparing these projects to terrestrial and marine conservation initiatives, often protected areas will only protect the visible aspects of an area, however without including microbial indicators, the microbial aspects of the habitat may go unnoticed. These include microbial habitats, functions and interactions (8). These projects also draw attention to the fact that microbial diversity is complex and diverse, therefore it would be impossible to protect individual species. Often policies must protect the functions, habitats and relationships of microbes. By creating common data systems, microbial changes can be monitored over time (5-6,8,33,38).

Microbial ethics is difficult because microbial communities do not fit neatly into familiar moral categories. They are not individual sentient animals, and they are not always stable, bounded species in the way that legal and conservation systems often assume (37,39). The same organism may be beneficial in one ecological context and harmful in another. This context-dependence makes simple moral rules inadequate and suggests that microbial governance should be precautionary, evidence-based, and adaptive rather

Table 1. Policy areas in which microbial stewardship is relevant. The table highlights key microbial functions and governance concerns (8,14-16,22-29,36).

Policy area	Microbial contribution	Main governance concern
Public health	Human microbiomes, infectious-disease ecology, antimicrobial resistance, and commensal microbial protection.	Protecting people without unnecessarily damaging beneficial microbial diversity or weakening future antimicrobial effectiveness.
Agriculture	Soil fertility, plant-growth promotion, nutrient cycling, pest and stress tolerance.	Avoiding land-use practices that erode microbial ecosystem function and long-term food security.
Environmental restoration	Bioremediation, decomposition, carbon and nitrogen cycling, recovery of soil and water functions.	Assessing whether microbial functions recover, not only whether visible vegetation returns.
Biotechnology	Engineered microbes, microbial products, synthetic biology, microbiome engineering.	Ensuring safety, transparency, accountability, public trust, equitable access, and responsible innovation.
Biodiversity conservation	Microbial habitats, communities, genes, strains, interactions, and functions.	Developing conservation tools for invisible, dynamic, and often uncultured life forms.

Microbiological Methods for Understanding and Representing Microbial Life

Modern microbiology has made microbial communities more visible by moving beyond culture-dependent approaches. In this context, sequencing includes deoxyribonucleic acid (DNA)-based approaches such as shotgun metagenomics and marker-gene methods, including 16S ribosomal RNA (rRNA) amplicon sequencing for bacteria and archaea and internal transcribed spacer (ITS) amplicon sequencing for many fungi; ribonucleic acid (RNA)-based metatranscriptomics can show which genes are actively expressed, while proteomics and metabolomics can identify proteins and metabolites linked to microbial function (5-6,33,38-39). These tools allow researchers to describe community composition and infer function even when many organisms cannot be cultured in the laboratory. They have redefined the concept of the term "microbiome", which currently states for microorganisms and their genes, biological and environmental activities, and interaction with ecosystem (39).

Large-scale microbiome initiatives are especially important for governance because they create reference points. The Earth Microbiome Project was designed to build a broad catalogue of microbial diversity using coordinated protocols and open analytical resources, while later global surveys revealed patterns in terrestrial, marine, host-associated, and environmental microbiomes (5-6,33,38). Without such baselines, it is difficult to know whether a microbial community has been degraded, restored, displaced, or transformed by human action (5-8,33,38).

Microbial indicators have the potential to enhance environmental monitoring. A microbial indicator can be defined as a quantifiable characteristics of a microbial community that indicates something about the status of an ecosystem, potential health risks, restoration efforts or biogeochemical cycling. For example; microbial diversity, functional genes involved in nitrogen and carbon cycling, antimicrobial resistance genes, pathogens and microbial changes associated with pollution and land use change (8,14-15,28-29,33,36). Including microbial diversity and functionality when assessing soil, water and impact on ecosystems will help make more informed policy decisions. However, interpreting microbiome data can be challenging. Sequencing data can inform us about changes occurring, however it is subjective to determine if these are negative, reversible, acceptable or unfair (16-19,26). Risk assessment plays an important role in synthetic biology, engineered microorganisms and intentional environmental release. It can be challenging to fully predict the spread, evolution, gene transfer and interactions of microorganisms within local ecosystems (19, 22-23, 26, 39). As such, microbial technologies should have measures in place to ensure safe handling in the lab, risk assessment of environmental effects, monitoring after release, clear and open communication to the public and flexibility to change based on new information (17, 19, 23, 26).

International and Existing Frameworks for Microbial Inclusion

One Health is a natural starting point, but its scope should be stated precisely. The One Health High-Level Expert Panel (OHHLEP) defines it as an integrated, unifying approach that seeks to balance and optimize the health of people, animals, plants, and ecosystems, recognizing their interdependence (40). The Quadripartite One Health Joint Plan of Action (2022-2026) promotes this collaborative approach by providing a plan for coordinated action between FAO, UNEP, WHO and WOAH (42). Whilst this plan has a broad definition of ecosystem health, it does not necessarily ensure microbiomes and microbial genetic resources will be monitored or conserved. Microbiomes have been argued to be seen as dynamic links between hosts and the environment (12-14,36-37).

Antimicrobial resistance (AMR) highlights the multi-sectoral requirements for microbial governance. The World Health Organization's Global Action Plan emphasises the multi-sectoral nature of AMR, involving human healthcare, veterinary, agriculture, sanitation, monitoring, education and investment (28). The United Nations General Assembly adopted a political declaration in 2024, emphasising the importance of a multi-sectoral One Health approach to human, animal and plant health, agriculture, environment, research and other sectors. The declaration aims to reduce the number of deaths globally caused by bacterial AMR by 10% by 2030 compared to the 2019 baseline (43). Whilst this increases the political responsibility, national plans must still ensure clarity of responsibilities, with monitoring of the environment alongside clinical stewardship (15,29,43). One Health should not be focused solely on disease. Microbial stewardship should include beneficial microbes, environmental microbiomes, soil/water integrity and the impact of disrupting microbial networks (14,36-37). If microbes are viewed as a hazard only, it can cause an oversight of the benefits microbes provide to agriculture, climate regulation, ecosystem recovery and health (4,11,13-14,36).

A working definition of microbial conservation should be defined. For the purpose of this review, microbial conservation can be defined as the intentional conservation of diverse microbes, their function, habitat, genetic resources and interactions to ensure they continue to provide ecosystem services, host health and evolutionary potential (7-8). This does not mean every single microbe must be conserved, but rather focusing on conserving microbial function, habitats, strains and consortia and their interaction, to ensure soil fertility, ecosystem resilience, climate regulation and host health is not lost due to microbial loss (7-8). Access and benefit sharing is fundamental to microbial conservation. The Nagoya Protocol provides a framework for accessing genetic resources and ensuring fair and equitable sharing of benefits (44). However, this is a bilateral agreement and does not fully address issues surrounding Digital Sequence Information (DSI) which can be independent of the physical sample. The Kunming-Montreal Global Biodiversity Framework (KMGBF) includes genetic resources, DSI and associated traditional knowledge explicitly within Target 13. The CBD COP16 Decision 16/2 included modalities for a multilateral benefit sharing mechanism including the Cali Fund (45-46). This creates a conflict between open access to microbial sequence data, and ensuring fair benefits to those providing it. Bioprospecting agreements need to ensure provenance, capacity building, attribution and benefit sharing (27,44-46).

Rights of Nature frameworks (41) can challenge the idea of nature as a commodity. They can allow ecosystems to be recognised as legal persons (30-31). Often the Te Urewera Act 2014 in New Zealand is mentioned as it recognises Te Urewera as a legal person with rights, powers, responsibilities and liabilities (30). Whilst these laws do not specifically relate to microbes, they can broaden the

imagination of the legal system and recognize ecosystems as living entities and that part of their integrity is provided by microbes.

Public deliberation can be used to mediate bioethics issues. Public deliberation can be described as a structured process that encourages inclusive discussions between citizens, impacted communities, experts and decision makers. This allows them to consider evidence, values, uncertainty and policy decisions (16-18). Disagreement around antimicrobial use, genetically modified organisms, waste management, changes to land use and ecosystem restoration are often not purely technical issues but can involve trust, livelihood, uncertainty, institutional power and differing views on what risk is acceptable (16-18,26). This is not a gentle alternative to science, but can increase the legitimacy of scientific decisions. This is because there are often many factors to consider such as evidence, values and social impacts (16-18).

Synthetic-biology ethics concerns the design, construction, modification, or release of biological systems, including engineered microorganisms. It addresses biosafety, biosecurity, environmental impacts, dual-use risks, ownership, public trust, and distributive justice (19,22-23,26). Recent work on microbial products and research regulation underscores the need for long-term safety assessment, release prevention, dual-use review, regulatory transparency, and public accountability (22-23). Planetary protection is an early field in which microbial ethics became explicit. Cockell argues that if extraterrestrial life is microscopic, space-exploration ethics must consider whether microbial communities have value beyond their usefulness to humans (20–21). Earth-focused stewardship need not adopt every assumption of space ethics; this literature nevertheless clarifies debates about microbial value, respect for microbial communities, contamination, and intergenerational responsibility (20–21,25).Table 2 summarizes the selected frameworks and the governance roles they can play.

Table 2. Governance frameworks relevant to microbial stewardship. Examples span One Health, AMR, microbial conservation, access and benefit-sharing, biotechnology, legal pluralism, public deliberation, and planetary protection (8,14–32,40–46).

Framework	Main contribution	Relevance to microbial governance
One Health	Defines One Health as an integrated approach across people, animals, plants, and ecosystems.	Makes microbiomes visible as shared biological interfaces; the 2022 –2026 Joint Plan supports coordinated implementation.
AMR governance	Sets cross-sectoral AMR commitments and a 2030 mortality-reduction aim.	Links human, animal, plant, and environmental stewardship with equity and accountable One Health coordination.
Access and benefit-sharing / DSI	Connects genetic-resource use with fair and equitable benefit-sharing.	Nagoya, KMGBF Target 13, and the CBD DSI mechanism are directly relevant to microbial sampling and bioprospecting.
Microbial conservation	Protects microbial diversity, function, habitats, and community integrity.	Moves biodiversity policy beyond visible species alone and supports microbial ecosystem services.
Synthetic-biology ethics	Supports responsible innovation, biosafety, and risk assessment.	Guides engineered-microbe research, microbial products, microbiome engineering, and environmental release.
Rights of Nature	Recognizes ecological wholes as legally meaningful.	Creates space for protecting microbial integrity within ecosystems.
Public deliberation	Opens science policy to citizens and affected groups.	Builds trust around uncertain or contested microbial interventions.
Planetary protection	Frames ethical duties around avoiding harmful biological contamination during space exploration.	Shows how respect for microbial communities and stewardship can be debated beyond immediate human use.

Ethical Balancing Across Humans, Microbes, Ecosystems, and Future Generations

The first ethical principle is stewardship. Microbial stewardship does not mean preserving every microbial community exactly as it is, which would be neither possible nor desirable. Rather, it means managing human activity so that microbial systems retain the diversity and functional capacity needed for health, fertility, resilience, and ecological recovery (8,12,34). This principle is close to microbial conservation, which argues that microbial diversity and ecosystem services deserve direct attention rather than being protected only by accident (7-8).

The second principle is responsibility across time. The Brundtland definition of sustainable development remains useful because it asks present societies to meet their needs without compromising the ability of future generations to meet theirs (32). Applied to microbial life, this means avoiding short-term decisions that degrade soils, contaminate water, accelerate resistance, or narrow microbial diversity in ways that later communities may not easily repair (15,24,27-28,35).

The third principle is justice. The consequences of microbial technologies can have uneven impacts on different areas of the world. For example, areas with bad sanitation, contaminated land, unsafe waste disposal, high intensity animal farming and poor healthcare systems can show higher levels of infectious diseases, antimicrobial resistance and environmental damage (15,28-29). This relates to the debates about benefit sharing in microbial genetic resources and DSI. Value is created through sampling, sequencing and bioprospecting so it is important to consider how this will affect those providing resources. An ethical approach should ensure those impacted are involved in these decisions and value created in biotech, agricultural or medical fields should not come at a cost to ecosystems (17-18,22-23,26).

The fourth principle is epistemic humility. Microbial systems are complex and often not fully understood. A concept useful in understanding humility is 'technologies of humility' described by Jasanoff. This concept aims to make decision makers think about the way problems are framed, who is most vulnerable, who is most burdened and how institutions can learn (17). Humility in relation to microbial governance would mean acknowledging how powerful modern microbiology can be but also knowing we cannot predict all the consequences it will have on ecosystems (19,23,26,39). The fifth principle is respect for microbial communities. Concepts from

ethical considerations around space exploration are useful to consider here. Whilst it might not be possible to protect every individual microorganism, these concepts help us consider that we can have ethical concerns about protecting microbial communities, biospheres or lifeforms which have an inherent or relational value (20-21). On earth this helps us avoid having a bias against microbes due to them being tiny, or pushing to protect every organism in every scenario. Often we will look to protect the ecosystem community and conditions.

Discussion

This synthesis shows that the governance gap is not a lack of general policy guidance but a gap between what policies recommend and what should happen on the ground. While One Health and biodiversity policy frameworks highlight interdependence and benefit sharing, they do not provide clear guidance on microbial baseline, who is funding monitoring and how uncertainty needs to be managed. The DSI mechanism provides global benefit sharing but does not provide clarity on local issues such as provenance and stewardship. The recommendations provided below require agencies, oversight bodies, funders and impacted communities to act. These should be aligned to national legislation.

Policy Recommendations and Responsible Actors

First, national One Health coordinating mechanisms and the Quadripartite agencies—FAO, UNEP, WHO, and WOAH—are inquired to have complete microbiome indicators within relevant health and environmental surveillance plans. Ministries of health, agriculture, and environment, together with public laboratories and environmental agencies, should pair pathogen and AMR monitoring with measures of microbial function and habitat change. Research funders should support baseline data and long-term sampling so that surveillance can distinguish ecological change from short-term fluctuation (14,36–37,40,42–43).

Second, national biodiversity authorities, CBD focal points, protected-area agencies, and access-and-benefit-sharing competent authorities should incorporate microbial habitats and genetic resources into biodiversity strategies and conservation plans. They should align sampling, sequencing, and commercial use with applicable national access rules and benefit-sharing obligations, while building capacity for the CBD's DSI mechanism under KMGBF Target 13. This would make microbial bioprospecting more consistent with conservation and equitable benefit-sharing, rather than treating sequence access as detached from its biological and social provenance (8,27,34,39,44–46).

Third, environmental protection agencies, environmental-impact-assessment regulators, and project proponents should establish context-appropriate microbial baselines for land conversion, pesticide use, mining, wastewater discharge, and intensive agriculture. Assessment protocols should state which indicators are relevant, how uncertainty will be interpreted, how long sampling should continue, and who is responsible for follow-up. Where the scale of risk warrants it, regulators should make post-approval monitoring a permit condition and require project proponents or funders to resource it (33–37).

Fourth, institutional research ethics committees and institutional biosafety committees should jointly review projects involving engineered microorganisms, microbiome modification, environmental release, large-scale biological sampling, or industrial microbial products. Regulators should ensure access to microbial-ecology, clinical, environmental, legal, and biosafety expertise and include affected communities where risks or benefits may be locally concentrated. Grant agencies and commercial sponsors should budget for independent review, transparent reporting, and post-release monitoring (16,19,22–23,26).

Fifth, government agencies, local authorities, and research funders should resource public engagement early in decisions about contested microbial interventions. Community advisory groups and deliberative formats should be designed with affected communities, not introduced after decisions are settled. Sponsors and responsible agencies should report how public input changed a decision—or why it did not—and how distributional concerns were addressed (16–18,26).

Sixth, national space agencies and mission-specific planetary-protection boards should use planetary-protection ethics as a comparative resource when evaluating contamination risks, microbial communities, and future scientific options. Where space-ethics concepts are applied to Earth-focused policy, agencies should state the limits of that comparison. Mission funders, planetary scientists, and ethicists should jointly translate the relevant lessons into mission protocols (20–21,25).

Future Directions

There is a need to further develop the science and infrastructure around microbial governance. National research councils and other funding bodies should work towards creating long-term monitoring, shared data platforms, reference collections and interdisciplinary training in microbiology and law, ethics, public health, ecology, space governance and policy. Health and environmental agencies should work together to create standardised, interoperable metrics and data to inform national and international reporting from monitoring (3,5,8,14,25,34).

A realistic starting point would be using microbial metrics within environmental and health decision making. National AMR coordination bodies should monitor microbial reservoirs, residues, resistance genes and stewardship outcomes within the environment to support the multi-sectoral commitments within the 2024 declaration. Soil microbial function could be used as a land health metric by agricultural agencies. Restoration authorities could monitor microbial recovery alongside vegetation and macro-species recovery (8,11,15,24,27-29,36,43).

A priority would be developing adaptive governance for microbial technologies. Microbes evolve and ecosystems are dynamic, therefore regulatory processes should be able to adapt based on monitoring data (8,19,23,26). Adaptive governance would require clear accountability, transparent reporting and the opportunity to adjust or halt interventions if unexpected negative effects are seen (17,19,23,26).

Conclusion

Microbes deserve a clearer place in bioethical and environmental governance. They are central to human health, animal health, plant productivity, soil fertility, marine systems, climate-

relevant processes, antimicrobial effectiveness, ecosystem resilience, industrial biotechnology, and even debates about planetary protection, yet they remain underrepresented in many legal and policy frameworks (1,3,6,8,14,20-27,35). The task is not simply to add microbes to existing lists of protected life forms. It is to recognize that visible ecosystems are partly built and maintained by invisible microbial relationships (3,5-6,8,33,38-39).

A mature approach to microbial stewardship should combine microbiome science, One Health, antimicrobial-resistance governance, microbial conservation, public deliberation, synthetic-biology ethics, ecological legal thinking, and selected insights from planetary-protection ethics (14,19-28,31,34,37). Such an approach would move policy beyond a narrow focus on microbial threat and toward a fuller understanding of microbes as partners, risks, resources, communities, and ecological foundations. In doing so, governance can better protect the shared biological conditions that support present communities, non-human life, and future generations (12,14,32,36).

Conflict of Interests

The authors declare no competing interests.

Data Sharing Statement

No new data were generated or analyzed for this mini-review.

Funding

No specific funding was received.

Ethics Approval and Consent to Participate

Not applicable. This minireview did not involve human participants, animal subjects, or primary experimental data.

Consent for Publication

Not applicable.

Author Contributions

Luay Abu-Qatouseh conceived the review, synthesized the literature, drafted and revised the manuscript, and approved the final version. Phillip J. Collier revised the manuscript and approved the final version.

References

1. Bar-On YM, Phillips R, Milo R. The biomass distribution on Earth. Proc Natl Acad Sci U S A. 2018;115(25):6506-11. https://doi.org/10.1073/pnas.1711842115

2. Whitman WB, Coleman DC, Wiebe WJ. Prokaryotes: the unseen majority. Proc Natl Acad Sci U S A. 1998;95(12):6578-83. https://doi.org/10.1073/pnas.95.12.6578

3. Falkowski PG, Fenchel T, DeLong EF. The microbial engines that drive Earth's biogeochemical cycles. Science. 2008;320(5879):1034-9. https://doi.org/10.1126/science.1153213

4. Cavicchioli R, Ripple WJ, Timmis KN, Azam F, Bakken LR, Baylis M, et al. Scientists' warning to humanity: microorganisms and climate change. Nat Rev Microbiol. 2019;17(9):569-86. https://doi.org/10.1038/s41579-019-0222-5

5. Gilbert JA, Jansson JK, Knight R. The Earth Microbiome Project: successes and aspirations. BMC Biol. 2014;12:69. https://doi.org/10.1186/s12915-014-0069-1

6. Thompson LR, Sanders JG, McDonald D, Amir A, Ladau J, Locey KJ, et al. A communal catalogue reveals Earth's multiscale microbial diversity. Nature. 2017;551(7681):457-63. https://doi.org/10.1038/nature24621

7. Dominguez-Bello MG, Knight R, Gilbert JA, Blaser MJ. Preserving microbial diversity. Science. 2018;362(6410):33-4. https://doi.org/10.1126/science.aau8816

8. Junker RR, Farwig N. Microbial conservation is essential for sustaining ecosystem functions and services. Proc Natl Acad Sci U S A. 2025;122(38):e2503013122. https://doi.org/10.1073/pnas.2503013122

9. McFall-Ngai M, Hadfield MG, Bosch TCG, Carey HV, Domazet-Lošo T, Douglas AE, et al. Animals in a bacterial world, a new imperative for the life sciences. Proc Natl Acad Sci U S A. 2013;110(9):3229-36. https://doi.org/10.1073/pnas.1218525110

10. Human Microbiome Project Consortium. Structure, function and diversity of the healthy human microbiome. Nature. 2012;486(7402):207-14. https://doi.org/10.1038/nature11234

11. Hacquard S, Garrido-Oter R, González A, Spaepen S, Ackermann G, Lebeis S, et al. Microbiota and host nutrition across plant and animal kingdoms. Cell Host Microbe. 2015;17(5):603-16. https://doi.org/10.1016/j.chom.2015.04.009

12. Trinh P, Zaneveld JR, Safranek S, Rabinowitz PM. One Health relationships between human, animal, and environmental microbiomes: a mini-review. Front Public Health. 2018;6:235. https://doi.org/10.3389/fpubh.2018.00235

13. van Bruggen AHC, Goss EM, Havelaar A, van Diepeningen AD, Finckh MR, Morris JG. One Health—cycling of diverse microbial communities as a connecting force for soil, plant, animal, human, and ecosystem health. Sci Total Environ. 2019;664:927-37. https://doi.org/10.1016/j.scitotenv.2019.02.091

14. Couradeau E, Martiny JBH, Fontaine F, Brechot C, Bonneville M, Callens K, et al. Incorporating microbiomes into the One Health Joint Plan of Action. mBio. 2025;16(10):e01456-25. https://doi.org/10.1128/mbio.01456-25

15. Altevogt BM, Taylor P, Akwar HT, Graham DW, Ogilvie LA, Duffy E, et al. A One Health framework for global and local stewardship across the antimicrobial lifecycle. Commun Med (Lond). 2025;5(1):414. https://doi.org/10.1038/s43856-025-01090-4

16. Lioupi O, Kostoulas P, Monti G, Griva K, Billinis C, Tsiamis C. Harnessing medical bioethics mediation to advance One Health governance. Vet Sci. 2025;13(1):8. https://doi.org/10.3390/vetsci13010008

17. Jasanoff S. Technologies of humility: citizen participation in governing science. Minerva. 2003;41(3):223-44. https://doi.org/10.1023/A:1025557512320

18. Stirling A. Opening up and closing down: power, participation,

and pluralism in the social appraisal of technology. Sci Technol Human Values. 2008;33(2):262-94. https://doi.org/10.1177/0162243907311265

19. Presidential Commission for the Study of Bioethical Issues. New directions: the ethics of synthetic biology and emerging technologies [Internet]. Washington (DC): Presidential Commission for the Study of Bioethical Issues; 2010. Available from: https://www.govinfo.gov/app/details/GOVPUB-PR-PURL-gpo9019

20. Cockell CS. Planetary protection—a microbial ethics approach. Space Policy. 2005;21(4):287-92. https://doi.org/10.1016/j.spacepol.2005.08.003

21. Cockell CS. The ethical status of microbial life on Earth and elsewhere: in defence of intrinsic value. In: Schwartz JSJ, Milligan T, editors. The ethics of space exploration. Cham: Springer; 2016. p. 167-79. https://doi.org/10.1007/978-3-319-39827-3_12

22. Ahmed IA. Ethical issues of microbial products for industrialization. In: Sarkar A, Ahmed IA, editors. Microbial products for future industrialization. Singapore: Springer Nature Singapore; 2023. p. 393-411. https://doi.org/10.1007/978-981-99-1737-2_20

23. Nwakoby IP, Iheukwumere IH, Iheukwumere CM, Nwakoby NE, Idigo MA, Ike VE. Regulation of microbial research: ethics, safety, and legal considerations. IPS Journal of Law and Humanities. 2025;1(1):13-8. https://doi.org/10.54117/exm7zj68

24. Rieder TN, Modlin C. How should we think about clinicians' individual antibiotic stewardship duties? AMA J Ethics. 2024;26(6):E479-85. https://doi.org/10.1001/amajethics.2024.479

25. Sivula O, Puumala M, Palmroth M. Space research ethics. Sci Eng Ethics. 2026;32(1):9. https://doi.org/10.1007/s11948-025-00576-7

26. Hardwick A, Cummings C, Graves JL Jr, Kuzma J. Can societal and ethical implications of precision microbiome engineering be applied to the built environment? A systematic review of the literature. Environ Syst Decis. 2024;44(2):215-38. https://doi.org/10.1007/s10669-024-09965-y

27. Cartledge K, Short FL, Hall A, Lambert K, McDonald MJ, Lithgow T. Ethical bioprospecting and microbial assessments for sustainable solutions to the AMR crisis. IUBMB Life. 2025;77(1):e2931. https://doi.org/10.1002/iub.2931

28. World Health Organization. Global action plan on antimicrobial resistance [Internet]. Geneva: World Health Organization; 2015. Available from: https://www.who.int/publications/i/item/9789241509763

29. Anderson M, Schulze K, Cassini A, Plachouras D, Mossialos E. A governance framework for development and assessment of national action plans on antimicrobial resistance. Lancet Infect Dis. 2019;19(11):e371-84. https://doi.org/10.1016/S1473-3099(19)30415-3

30. Te Urewera Act 2014. Public Act 2014 No. 51 [Internet]. New Zealand Legislation; 2014 [cited 2026 May 27]. Available from: https://www.legislation.govt.nz/act/public/2014/0051/latest/DLM6183601.html

31. O'Donnell E, Talbot-Jones J. Creating legal rights for rivers: lessons from Australia, New Zealand, and India. Ecol Soc. 2018;23(1):7. https://doi.org/10.5751/ES-09854-230107

32. World Commission on Environment and Development. Our common future [Internet]. Oxford: Oxford University Press; 1987. Available from: https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf

33. Bahram M, Hildebrand F, Forslund SK, Anderson JL, Soudzilovskaia NA, van Bodegom PM, et al. Structure and function of the global topsoil microbiome. Nature. 2018;560(7717):233-7. https://doi.org/10.1038/s41586-018-0386-6

34. Bardgett RD, van der Putten WH. Belowground biodiversity and ecosystem functioning. Nature. 2014;515(7528):505-11. https://doi.org/10.1038/nature13855

35. van der Heijden MGA, Bardgett RD, van Straalen NM. The unseen majority: soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. Ecol Lett. 2008;11(3):296-310. https://doi.org/10.1111/j.1461-0248.2007.01139.x

36. Hartmann M, Six J. Soil structure and microbiome functions in agroecosystems. Nat Rev Earth Environ. 2023;4(1):4-18. https://doi.org/10.1038/s43017-022-00366-w

37. Fierer N. Embracing the unknown: disentangling the complexities of the soil microbiome. Nat Rev Microbiol. 2017;15(10):579-90. https://doi.org/10.1038/nrmicro.2017.87

38. Sunagawa S, Coelho LP, Chaffron S, Kultima JR, Labadie K, Salazar G, et al. Structure and function of the global ocean microbiome. Science. 2015;348(6237):1261359. https://doi.org/10.1126/science.1261359

39. Berg G, Rybakova D, Fischer D, Cernava T, Vergès MC, Charles T, et al. Microbiome definition re-visited: old concepts and new challenges. Microbiome. 2020;8(1):103. https://doi.org/10.1186/s40168-020-00875-0

40. One Health High-Level Expert Panel (OHHLEP), Adisasmito WB, Almuhairi S, Behravesh CB, Bilivogui P, Bukachi SA, et al. One Health: a new definition for a sustainable and healthy future. PLoS Pathog. 2022;18(6):e1010537. https://doi.org/10.1371/journal.ppat.1010537

41. Global Alliance for the Rights of Nature. World's biodiversity concentration [Internet]. Available from: https://www.garn.org/articles-and-reports/

42. Food and Agriculture Organization of the United Nations, United Nations Environment Programme, World Health Organization, World Organisation for Animal Health. One Health Joint Plan of Action (2022–2026): working together for the health of humans, animals, plants and the environment [Internet]. Geneva: World Health Organization; 2022 [cited 2026 Nov 4]. Available from: https://www.who.int/publications/i/item/9789240059139

43. United Nations General Assembly. Political declaration of the high-level meeting on antimicrobial resistance. Resolution A/RES/79/2 [Internet]. New York: United Nations; 2024 [cited 2026 Nov 4]. Available from: https://digitallibrary.un.org/record/4064023?ln=en

44. Convention on Biological Diversity. Nagoya Protocol on Access

to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization to the Convention on Biological Diversity [Internet]. 2010 [cited 2026 Nov 4]. Available from: https://www.cbd.int/abs/doc/protocol/nagoya-protocol-en.pdf

45. Convention on Biological Diversity. Kunming–Montreal Global Biodiversity Framework: Target 13 [Internet]. Montreal: Convention on Biological Diversity; 2022 [cited 2026 Nov 4]. Available from: https://www.cbd.int/gbf/targets/13/

46. Convention on Biological Diversity. Digital sequence information on genetic resources. Decision 16/2 [Internet]. Montreal: Convention on Biological Diversity; 2024 [cited 2026 Nov 4]. Available from: https://www.cbd.int/doc/decisions/cop-16/cop-16-dec-02-en.pdf