PERSPECTIVE

Advancing Equity and Inclusion in Microbiome Research and Training

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ABSTRACT This article proposes ways to improve inclusion and training in microbiome science and advocates for resource expansion to improve scientific capacity across institutions and countries. Specifically, we urge mentors, collaborators, and decision-makers to commit to inclusive and accessible research and training that improves the quality of microbiome science and begins to rectify long-standing inequities imposed by wealth disparities and racism that stall scientific progress.

KEYWORDS collaboration, equity, inclusion, international, mentoring, microbiome, training

MAKING THE CASE FOR EQUITY IN MICROBIOME SCIENCE

Microbiome research is being applied to important global challenges like pandemic preparedness, infectious disease prevention, climate change, and food security. This research is currently concentrated in a few resource-rich countries (1) which limits the field in several ways. The best solutions to these global challenges come from the work of scientists who understand the cultural and logistical needs of implementing solutions in their communities. The microbiomes of natural, host-associated, and built environments vary geographically, so undersampling large regions of the world limits our understanding of microbial communities (2, 3). This leaves a valuable subset of the microbial biosphere uncharacterized and a valuable subset of researchers excluded. Changes to microbiome science that increase scientific opportunities for persons historically excluded due to ethnicity and people from low- and middle-income countries will improve the quality of research in the field as well as being the right thing to do.

UNIQUE AND SHARED CHALLENGES FOR PEER AND LMIC MICROBIOME SCIENTISTS

Persons who identify as Black or African American, Latinx or Hispanic, and peoples indigenous to land comprising the United States and its territories (henceforth called PEERs for persons excluded due to ethnicity or race) (4, 5) have been excluded from, and therefore underrepresented in microbial science, and the sciences more broadly. Scientists from low- and middle-income countries (LMICs) are similarly underrepresented in contemporary science. To make microbiome science global, equitable, and inclusive, and thus serve everyone, we explicitly focus on support for PEER and LMIC scientists and trainees. These groups differ in the challenges they face for different socio-political reasons, but we identify common needs and advocate for changes and resources aimed at improving inclusion and access to microbiome research. This article

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FIG 1 Decision-makers, key areas of change within the microbiome sciences, and actions that will foster inclusion for PEER and LMIC scientists in microbiome sciences.

is intended to start a conversation within the microbiome community, and we provide resources for persons in decision-making positions (e.g., principal investigators, mentors, collaborators, funders, administrators, professional societies) to implement and invest in equity in science and health (Fig. 1).

PEER scientists. The systematic exclusion of PEERs from academic and scientific pursuits contributes to the persistent underrepresentation of PEER individuals in the microbial sciences (4, 6). Decades of efforts have failed to lead to major, sustained increases in representation of PEER scientists, especially in leadership roles and other positions of influence; this is especially acute in microbiology (7). Recent critiques have highlighted the need to shift narratives (and therefore solutions) away from a deficit framework and toward making changes to institutions themselves. A deficit framework focuses only on diversity and emphasizes a perceived lack of ability or "fit" of PEER individuals. However, improvements can be made by prioritizing the transformation of teaching, training, and research environments to better serve PEER individuals and an organization as a whole (8). This transformation requires a commitment to equity and inclusion that includes stakeholders at all levels and a willingness to identify and address structural and systemic barriers (9). Challenges exist at every step from recruitment into undergraduate and graduate training through promotion and tenure (10–12), mentoring (13, 14),

TABLE 1 Organizational resources and examples of equitable research and mentoring practices with LMIC and PEER scientists and trainees

Theme	Resources
Guidelines for equitable collaboration and mentoring practices with LMIC and PEER scientists	Montreal Statement on Research Integrity in Cross-Boundary Research Collaborations (33): guidance on agreements and responsibilities when engaging in cross-national, -institutional, and -disciplinary research The Swiss Commission for Research Partnership with Developing Countries (34) and The Research Fairness Initiative (35, 36): organization and program for equitable collaboration with LMIC scientists The Nagoya Protocol (37): equitable access and benefit-sharing of genetic resources National Academy of Sciences, Engineering, and Medicine mentoring report (38): guidance on inclusive mentoring practices IDEA Network of Biomedical Research Excellence (INBRE): support for research, mentoring, collaboration. and faculty training in Puerto Rico (http://inbre.hpcf.upr.edu/bioinformatics-resource-core/)
Microbiome-focused equitable partnerships	The Earth Microbiome Project (39): a global initiative focused on the development of standard operating procedures for the characterization of the earth microbiome The international Human Microbiome Standards (https://cordis.europa.eu/project/id/261376): a global initiative focused on the development of standard operating procedures for the characterization of the human microbiome The Benioff Center for Microbiome Medicine (https://microbiome.ucsf.edu/commitment-diversity-equity-and-inclusion): example of PEER support and in microbiome sciences
Team building and communication resources	Cold Spring Harbor Laboratory Leadership in Bioscience Workshop (https://meetings.cshl.edu/courses.aspx?course=c-leader&year=19): workshop on effective leadership and mentoring in science EMBO Laboratory Leadership course (https://lab-management.embo.org/): leadership courses with an emphasis on research and research dissemination Springer Nature Effective Collaboration course (https://masterclasses.nature.com/online-course-effective-collaboration-in-research/17078834): course on effective collaboration in science UCSF The Scientific Leadership and Management Skills course (https://postdocs.ucsf.edu/slms): example of a leadership program for postdoctoral researchers in sciences
Microbiome training and conference-based support for LMIC and PEER scientists	International Society for Microbial Ecology (https://www.isme-microbes.org/ambassadors): Ambassador program with global organizations for workshops and activities The Microbiota Vault (https://www.microbiotavault.org) and MV-Global Microbiome Network (GloMiNe) symposia: example of global symposium with the goal of education to promote preservation of microbial ecosystems in nature and in collections Codes of ethics at conferences to support underrepresented scientists (40) Guidelines for organizing an intentional bioinformatics training in LMIC (41)

appointment to leadership positions (7, 15), career development for nonacademic pursuits (16, 17), publishing (18–21), and acquisition of funding (22–25). However, PEERs in the microbial sciences are expected to persist despite cultures that devalue them and their talents. The institutions that have historically served PEER scientists like American community colleges, tribal colleges, and historically black colleges and universities often contend with reduced access to resources and infrastructure needed to train students in computing and communication skills (26–28). There is a need for bold, resourced, and strategic programs that support the careers and training of PEERs in microbiome sciences, their matriculation to leadership positions, and the transformation of programs, departments, and organizations to ensure inclusive cultures where everyone can thrive.

LMIC scientists. Like PEER scientists, LMIC scientists bring a wealth of talent, ideas, and perspectives that would enrich the scientific process and culture, and yet, researchers from both groups often lack opportunities to acquire the training, funds, and support to make significant contributions to their fields. Countries holding economic and technological wealth must cooperate synergistically with LMICs to promote their participation and leadership in research for a more globally inclusive microbiome training agenda (29–32). In Table 1, the "Guidelines for equitable collaboration and mentoring practices with LMIC and PEER scientists" detail resources that have been successfully used toward developing guidelines that promote equitable research collaborations between well-funded research institutions and LMIC scientists. When establishing global partnerships for microbiome research, consider following the guidelines and successful examples detailed in Table 1. Existing international programs in microbiome surveying (Table 1, "Microbiome-focused equitable partnerships") show that equitable partnerships in this field are not only possible but are successful through sharing of resources, project responsibilities, and funding. Their contributions to the field include significant microbiome curation efforts, including the design of standard protocols for sample collection and processing, data analysis, and data sharing (39). We propose that these and other international working groups, already at the forefront of microbiome research, serve as exemplars in the creation of guidelines for inclusive and equitable collaborations with LMIC scientists.

We also highlight more specific pathways toward training and research practices that enrich the experiences of both LMIC and PEER scientists that scientists from high-income countries (HIC) can take up. For mentoring and collaboration, HIC scientists can create mentoring communities with more than one mentor to provide various perspectives for PEER and LMIC mentees (38) and understand and dismantle power dynamics associated with privilege within PEER mentorship. Mentors and collaborators from positions of privilege should counteract factors that negatively affect mentees' experiences (e.g., combating institutional racism) and should employ culturally responsive mentoring and collaboration which embraces questions asked by PEER and LMIC scientists that are important to their cultural identities but may differ from norms set by Western or white scientists (38, 42–46). These scientists should engage in mentor and collaborator training such as team-building courses to communicate roles and responsibilities effectively and improve team productivity (Table 1, "Team building and communication resources") and should model expectations for an inclusive environment and practice transparent and impartial conflict resolution (38, 42–46). However, all team members, regardless of identity, should understand their own cultural identities and biases and how they impact the team.

Towards equitable research practices, scientists from HIC should actively apply for international grant funding opportunities which foster microbiome studies with LMIC scientists (e.g., the NIH Fogarty International Center) and while doing so, should discuss ownership of data and authorship of publications with trainees and collaborators, support the active participation of LMIC scientists in designing microbiome studies and avoid "helicopter research" in which HIC scientists travel to conduct research in an LMIC with little or no involvement of local scientists. This is a practice that has become worryingly common as global collaborations increase (47). Collaborating with, rather than extracting from, communities or regions under study helps to decolonize science (48). This means including LMIC and PEER scientists as coauthors and not just mentioning them in the acknowledgments and avoiding exploitation of their knowledge and labor, identifying research needs for these communities, or taking local specimens with limited engagement.

ADDRESSING LANGUAGE AND COMMUNICATION BARRIERS

Scientists from different fields, cultures, and languages must be able to clearly communicate with each other to discover connections between ideas and develop sustainable collaborations to advance the microbiome sciences. We urge support for virtual training programs that include efforts to create resources in multiple languages like translation of programming tutorials of The Carpentries training organization into Spanish. Current technology translates virtual resources and provides closed captioning in real time which accommodates scientists with disabilities and nonnative speakers. We also urge funding agencies and professional societies to allocate resources for translating conference materials and to host multilingual workshops, particularly to highlight research performed by LMIC scientists (Table 1, "Microbiome training and conference-based support for LMIC and PEER scientists"). Virtual conferences have increased access for scientists who cannot easily travel due to accessibility issues, family commitments (49), visa requirements, and funding limitations that disproportionately limit LMIC scientist's participation in training, symposia, and conferences. One notable success has been the National Summer Undergraduate Research Program (NSURP), a paid virtual research program that has successfully recruited microbiologists to mentor PEER students from the United States, providing a completely online microbial training experience and professional development opportunities (10). Since this program currently reaches a limited number of mentees, we call for funding to expand such initiatives and their scope to serve trainees across geographical boundaries; increased funding would increase the program's reach as well as allowing for international trainees to participate. For all trainees, including PEER microbiome scientists, science outreach at community venues like schools, science centers, and museums, helps build communication skills. Science outreach also positively impacts the communities by enhancing interest and engagement in science and offering role models representative of students' social identities (50, 51), which can lead to higher recruitment of PEER scientists in STEM (science, technology, education, and mathematics) (52). We also recommend that academic programs incentivize students with credits, certification, or awards to participate in outreach events and science communication classes as part of their training (for examples, see Table S1 in the supplemental material).

INCREASING ACCESS TO MICROBIOME TECHNOLOGY AND PUBLISHING

Microbiome data sets are large, and their analysis requires expertise in molecular biology, microbiology, and computational biology. The extraction of nucleic acids from samples can be done with standard molecular biology equipment, but the generation and interpretation of these data typically require access to expensive reagents, sequencing services, and computer clusters which is often a barrier for scientists from LMICs. We present resources that could reduce financial and technological barriers to sequencing and provide free resources to high-performance computing for microbiome research in Table S1. These resources are primarily published modifications to standard protocols for sample preservation, DNA extraction, library preparation, and multiplexing that reduce costs at each step in the process. Sequencing itself remains a financial barrier, but a few programs like the U.S. Department of Energy Joint Genome Institute's Community Science Program provides access to sequencing and advanced microbiome methods to scientists anywhere in the world through a grant-based, user facility model. Free, cluster-based metagenomics computing resources are available through Kbase, Xcede, Cyverse, MGnify, and MG-Rast (53–56). In the longer term, work should be publicly funded to develop and nonexclusively license a suite of low-cost, validated, open-source protocols for preservation, extraction, and library preparation. This could radically lower costs of sample preparation and thereby increase access and equity, create new products, and open new lines of microbiome research, especially if supported by public sector investment and technology transfer.

Microbiome data sets are large and multivariate, and analyzing these data effectively requires specialized training. Data analysis training should be made accessible to LMICs so that *in silico* experiments are supported alongside training of bioinformaticians who are comfortable using and developing projects with sequence data. We also recommend the creation of online "code clubs" (57) or cross-institutional working groups who learn to code and analyze data together. Such clubs enable peer learning, foster opportunities for research collaborations, and provide resource and skill-sharing between institutions with unequal economic access.

In addition to lack of access to technology, the high cost of publication in science can be a barrier to LMIC scientists in particular (58). Some microbiome research journals offer free publication, or fee waivers or cost reductions for scientists from LMICs (for a list of journals, see Table S2). Publishing in high-impact open-access journals constitutes approximately 6 months' salary of African scientists, and government and universities do not cover these fees (59). While fee waivers exist, the processes are veiled and need transparency, and other journals, including society journals, must consider providing free publishing mechanisms. Sharing research as preprints is now standard practice in fields like physics, and microbiome research would benefit from a similar adoption. Preprints offer the opportunity to make research rapid and more transparent, though they may require careful evaluation prior to being peer reviewed.

Open science will allow PEER and LMIC trainees to learn key data analysis skills, contribute new research, and further their careers through the meta-analysis of previously published microbiome data in the absence of funding to produce new data. However, this requires both freely available data sets and high-quality metadata. Some federal agencies are addressing issues associated with data accessibility by recommending data sharing upon request (60). Transparency can also be reinforced by making sure that accepted manuscripts provide accessible, high-quality, accessioned raw data and provide metadata spreadsheets compatible with microbiome data management software (e.g., for Qiita and European Bioinformatics Institute [EBI]). Funding agencies, journals, and repositories should require and provide incentives to enforce high-quality submission standards, allow data sets to be cited, and provide better tutorials and consistent submission expectations across databases to normalize open-science practices for microbiome data (61).

CALL TO ACTION

Shifting the research culture in microbiome science by making research and training more inclusive will improve retention of underserved scientists and contribute to the field's intellectual growth. Such endeavors are opportunities to broaden our perspectives of how the environment, social identity, biopsychosocial factors, and cultural practices affect microbiome science around the world but are also imperative to restore equity and social justice in the field. We urge collaborators, mentors, funders, and decision-makers in resource-rich countries to take concrete actions to improve the inclusiveness of microbiome science (Fig. 1). Changing cultural norms can take time, but implementing even small improvements can create a considerable difference for a trainee or collaborator. As microbiome scientists, we call on other members of the community to set an example of inclusivity and accessibility for the broader scientific community.

SUPPLEMENTAL MATERIAL

Supplemental material is available online only.
TEXT S1, DOCX file, 0.02 MB.
TABLE S1, DOCX file, 0.01 MB.
TABLE S2, DOCX file, 0.02 MB.
TABLE S3, DOCX file, 0.02 MB.

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