Integrating Ecological and Human Communities into the Governance of Genetically Modified Microbes for Environmental Release

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Executive Summary: Environmental synthetic biology promises to tackle complex environmental issues and critical ecological challenges. By harnessing genetically modified microbes, the field offers sustainable, biodegradable solutions for issues with few technological alternatives, such as contaminant degradation, critical metal recovery, and crop resilience to extreme weather. As such, the use of genetically modified microbes has great potential in the bioeconomy to tackle these issues. However, the safe and effective use of genetically modified microbes must prioritize ecological and social responsibility. This piece highlights two key areas for responsible development. First, we emphasize the need for interdisciplinary research and integration of ecological concepts when studying and deploying genetically modified microbes. Second, we call for the integration of academic and non-academic communities into environmental synthetic biology research and governance. By fostering interdisciplinary research and incorporating environmental justice principles, the field can ensure that its innovations are both safe and equitable.

I. Introduction

Climate change, pollution, and extreme weather are environmental problems that biotechnology and synthetic biology are especially well-positioned to address (Marken, Maxon, and Murray 2024; Aminian-Dehkordi et al. 2023; Del Valle et al. 2021; Chemla et al. 2025). Unlike conventional materials, synthetic biology promises solutions that are biodegradable and may decrease our reliance on highly polluting technologies. One proposed approach is to use genetically modified microbes. Genetically modified microbes can extract carbon dioxide from the atmosphere, help degrade environmental contaminants like oil spills, sustainably degrade plastic, and increase crop resilience (Zahed et al. 2021; Nguyen et al. 2023; Skariyachan et al. 2022; Yeom, Le, and Yun 2022; Kozaeva et al. 2024).

While these emerging technologies hold great promise for supporting a circular bioeconomy, consideration of the ecological and social context of emerging biotechnologies is necessary to mitigate risk (Parker and Kunjapur 2020). Failing to consider the effect of biotechnologies on ecological communities could pose a risk to the environment, for example, by altering local microbiomes or introducing “invasive genes” (Ricciardi et al. 2017). Similarly, failing to consider the implications of biotechnology on human communities may result in ineffective or harmful technologies that exacerbate inequality and break public trust.

An increasing percentage of genetically engineered biotechnology products are microbial (Nielsen, Tillegreen, and Petranovic 2022). To ensure that these genetically modified microbes support – instead of hinder – an environmentally sustainable future, we call for (1) increased environmental research on potential ecological effects of genetically modified microbes, and (2) an environmental justice approach that centers affected human communities in the production and evaluation of emerging biotechnologies (Figure 1). We also provide policy recommendations to ensure that genetically modified microbes are synergistic with local communities, both human and ecological.

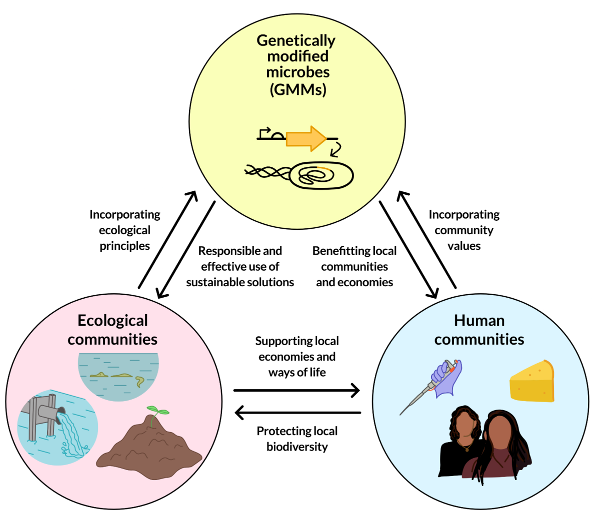

Figure 1: Integrating ecological and human communities is necessary to ensure the effective and ethical deployment of genetically modified microbes.

II. Integrating environmental, evolutionary, and ecological research into synthetic biology

To evaluate potential biosafety risks of genetically modified microbes, research is needed on their environmental effects (Reichman et al. 2022). However, the research community developing these emerging biotechnologies (bioengineers, synthetic biologists) is often detached from researchers who are best equipped to evaluate their impacts on the environment (ecologists, evolutionary biologists, conservationists). Research that spans these fields is necessary to develop informed policies that maximize societal and environmental benefits while minimizing risk (Power 2021).

Existing research on biological invasions provides a cautionary tale. Invasive alien species are species that, due to human activities, expand beyond their native range and have negative local impacts (Roy et al. 2024). Whether introduced intentionally or inadvertently, these species can have unexpected effects on their new environments (David et al. 2017). For example, cane toads (*Rhinella marina,* formerly known as *Bufo marinus*) were introduced to Australia in 1929 as a biocontrol agent to reduce the population of two native pest beetle species that preyed on sugarcane crops. This solution was rationalized by studies indicating that beetles were important components of the South American toads' native diet. However, cane toads were ineffective biocontrol agents, failing to control populations of these beetle species. Moreover, they became pests themselves by attaining a much higher population density than in their native habitats and threatening other native Australian species by eating non-pest insects and killing predators lacking defenses against the toad's poison (Lampo and De Leo 1998). Biotechnologists should avoid making similar mistakes with the introduction of genetically modified microbes to the environment. Without understanding their ecological context, microbial biotechnologies that are meant to positively benefit the planet may have unexpected negative outcomes (Ricciardi et al. 2017).

We have identified two interdisciplinary research directions that can assist policymakers and regulatory bodies in evaluating the environmental effects of genetically modified microbes:

i. Quantify the persistence of genetically modified microbes and their genes in the environment

The persistence – or lack thereof – of genetically modified microbes is crucial to assess their ecological impacts. For example, a genetically modified microbe engineered from an isolate in its target environment(s) may be more likely to persist than one that is not adapted to its target environment (Chemla et al. 2025). In contrast, a gene that provides a competitive advantage may also be more likely to persist in an environment (Bottery

2022). Ideally, genetically modified microbes would persist in the environment only as long as they are needed and no longer persist in the environment after that. One example of this "engineered persistence" comes from microbes engineered to remove contaminants. If decontamination by an engineered microbe is successful and contaminant concentration dips below a critical level, there may simply not be enough of that contaminant chemical to support the microbe consuming it. In this way, the organism and the trait should only persist when the contaminant is still present above a critical level, a remarkable advantage of using genetically modified microbes over chemical methods for bioremediation

Genes are not only passed down from parent to offspring — they can also be exchanged between unrelated species through horizontal gene transfer (HGT). HGT allows organisms to adapt to environmental stress by rapidly acquiring new traits from non-parent organisms, and is a main biocontainment concern when introducing new species into an environment. While most mechanisms of HGT are well understood, researchers are currently working to elucidate the movement of individual genes within communities, and the impact of that movement on complex microbial communities (Kalvapalle et al. 2025; Rubin et al. 2022; Munck et al. 2020). Although synthetic constructs are not inherently more likely to be transferred than natural ones, HGT is still a key consideration when assessing the potential impact of an introduced gene into the environment. Thus, research is needed on the environmental persistence and impact of genetically modified microbes and their genes, as well as the factors driving gene transfer in complex microbial communities, and methods for studying these phenomena (Corich et al. 2007; Szyjka et al. 2017, Saak, Dinh, and Dutton 2020).

ii. Identify and predict the environmental and ecological impacts of genetically modified microbes

Genetic engineering is often meant to affect the traits of the engineered microbe in a particular system (e.g. a bacterium that is engineered to improve the uptake of nutrients by crop plants) (van Dillewijn, Villadas, and Toro 2002). However, these engineered traits may also alter how genetically modified microbes interact with other organisms in the environment, such as native microbes, plants, and animals (Power 2021). Furthermore, the introduction of genes generated outside of the local evolutionary context could alter evolutionary processes through eco-evolutionary dynamics, where ecological processes such as resource competition can drive rapid evolutionary change (Ellner, Geber, and Hairston Jr 2011; Post and Palkovacs 2009). Studies that evaluate the effects of genetically modified microbes on ecological communities and ecosystems are necessary to ensure that emerging technologies avoid off-target effects such as outcompeting a native microbe in a similar niche.

In summary, we call for more research on the environmental implications of synthetic biology products, especially on horizontal gene transfer, the persistence of genetically modified microbes, and their interactions with other species within ecological communities. Expert convenings can identify specific research activities and best practices. These efforts could be convened through a National Academies study, scientific advisory panel by a government agency such as the EPA, or non-profit research entity such as the Engineering Biology Research Consortium (EBRC). In order to ensure that the diverse array of potential impacts are considered, these expert convenings should include different perspectives, especially rural farmers, Indigenous communities, climate activists, youth, and others who are historically excluded from the development and assessment of emerging technologies (Wolf 2021).

III. Considering human communities in the development of microbial biotechnologies

For emerging biotechnologies to be broadly safe and beneficial, we must consider their social context. The environmental justice movement highlights the intersectional nature of environmental sustainability and social justice, with emerging implications for genetic engineering (George et al. 2025). Genetically modified microbes have great promise for ameliorating harm. Engineered microbes can decrease the environmental impact of mining critical metals, detoxify soil from Superfund sites, and reduce reliance on chemical fertilizers that can cause groundwater contamination, which disproportionately harms marginalized communities (Pakostova, Falagan, and Zhang 2024; Yaashikaa, Devi, and Kumar 2022; Wen et al. 2021). However, these promising solutions are rarely developed by the communities that are affected by environmental injustices (Clark and Hurd 2020). This can result in ineffective, harmful, or misapplied technologies that may fail to achieve their intended purpose. Further, ways of knowing that have historically been excluded from academic research may offer more sustainable and synergistic solutions to environmental challenges (Parsons, Fisher, and Nalau 2016). To ensure that biotechnologies are truly sustainable, their development and assessment must center on voices and knowledge systems that have historically been excluded (Edwards 2011). These communities should be the leaders and power-holders to create a truly sustainable future with biotechnology.

To enable this vision, we propose recommendations that engage two communities: academic researchers at universities and scientists in local communities. These non-academic scientists and practitioners may include community scientists, nature enthusiasts, conservationists, gardeners, and hunters.

i. Educate academic biotechnology researchers on ecology, environmental justice, and equitable research practices

Current training for synthetic biologists and bioengineers should include consideration of the environment, as well as social and historical context for their work (Higgins, Wallace, and Bazzul 2018). Academic training and research in bioengineering must center the needs of local communities (Kofler et al. 2018).

Undergraduate and graduate training in the life sciences should incorporate courses that situate biotechnologies in their environmental, ecological, and social context (Sacchi, Lotti, and Branduardi 2021). This can include formal and informal learning experiences in the fields of ecology and evolution, science and technology studies, history of science, and environmental justice. Graduate programs should require seminars on microbial ecology, community-engaged research, and biosecurity (Lloyd 2022b). These can be supplemented with hands-on educational experiences such as internships with environmental justice groups, policymakers, and cultural centers (Mercer 2015). Departments should also offer biosafety training that emphasizes best practices to reduce the risk of accidental HGT and particularly the spread of antibiotic resistance genes. These practices include using non-clinically relevant antibiotic resistance genes whenever possible, not using antibiotic selection for microbes intended for environmental release, and taking steps to reduce the likelihood of HGT such as incorporating engineered functions into the microbe's genome instead of a plasmid.

ii. Encourage academics to participate in community-led science and partnerships

Academic research on biotechnology products should be co-led by communities and academics. Academic researchers can build equitable relationships with non-academic community members that guide collective research questions and collaborative technology development (Reynolds-Cuéllar and Delgado Ramos 2020). This approach stands in opposition to the status quo, where academic researchers are often "hammers-looking-for-a-nail"- innovators looking for an application of their technology without building relationships before development. Because equitable partnerships with communities are not yet standard in academic settings, universities and departments must incentivize researchers to take a community-centered approach. This could involve revising tenure requirements, offering funding for community-centered research, and rewarding collaborations with non-academic entities, such as policymakers, nonprofits, or cultural and arts groups.

iii. Enable broad and democratic participation in the life sciences

While the majority of research and development in emerging biotechnologies occurs in academic institutions and companies, the public also can contribute to innovation in emerging biotechnologies (Schoenberg 2022). However, many communities are distrustful of biotechnology (Liu et al. 2024). This distrust stems from a history of environmental harm, structural racism, and economic disempowerment that often originate from new technologies (Weinreb and Sun 2023). Simultaneously, many people have significant relationships with microbes and microbial biotechnology. These are often deeply rooted in culture and history, such as garden composting and fermented foods like sourdough bread, kimchi, and wine (Hendy et al. 2021). Building trust in biotechnology requires broadening what we conceive of as biotechnologies to include cultural and land-based knowledge. In addition, communities, especially those that have been historically marginalized, must have ownership and power over the technologies they originate and develop (Astolfi et al. 2025). Changing the flow of power in the development of emerging microbial biotechnologies may require new or different innovation spaces (Lloyd 2022a). These can include community gardens, cultural groups, and amateur biology spaces like community biology labs.

These spaces can be hubs for the public to explore and innovate with microbial biotechnologies (Chappell, Perez, and Takara 2023). For example, a group of amateur biologists, from children to elders, are working together in public biology labs in the Bay Area of California (USA) to create a new vegan cheese ("Real Vegan Cheese"). Spaces like these can reinvent the public perception of science, centering values like community, collaboration, and care in the production of biotechnologies (Chappell 2024). Expanding "what counts as science" can broaden participation and help ensure that emerging biotechnologies are broadly beneficial to local communities (Wong, Gishen, and Lokugamage 2021; Guibrunet et al. 2024).

We call for universities and research institutions to integrate ecological and social concepts in their curricula. These should be especially targeted to programs in biotechnology, synthetic biology, and bioengineering. Universities should also set aside funding for initiatives that promote community-led science. Grassroots spaces for bio-innovation can be supported by federal and state programs, philanthropic support, and local organizations (Kuldell and Aurand 2022). This can involve creating and supporting public community labs, local biotechnology cooperatives, land-based learning, and community gardens.

IV. Conclusion

Environmental synthetic biology has the potential to be a transformative force in addressing many environmental problems and contributing to a circular bioeconomy. But there is much work to be done to ensure that genetically modified microbes are safe for ecological and human communities and have broad, public benefits. Here, we argue that research and development of genetically modified microbes must be situated within their social-ecological context. Without considering effects on the environment and human communities, environmental synthetic biology projects have the propensity to cause significant harm. We call for interdisciplinary research that incorporates ecology and evolution to quantify potential risks of genetically modified microbes on the environment. Engaging both the scientific community of academic researchers and the public in considering the social and ethical implications of emerging biotechnologies is crucial to ensure broad benefits. In order to enable a bioeconomy that benefits all, consideration of both people and the planet is essential.

References

Aminian-Dehkordi, Javad, Shadi Rahimi, Mehdi Golzar-Ahmadi, Amritpal Singh, Javiera Lopez, Rodrigo Ledesma-Amaro, and Ivan Mijakovic. 2023. "Synthetic Biology Tools for Environmental Protection." Biotechnology Advances 68 (November):108239. https://doi.org/10.1016/j.biotechadv.2023.108239.

Astolfi, Maria C. T., WarīNkwī Flores, Rolando Perez, Ulises J. Espinoza, Teal B. Zimring, Jay D. Keasling, and Keolu Fox. 2025. "Partnerships with Indigenous Peoples for an Ethical Bioeconomy." Nature Communications 16 (1): 3010. https://doi.org/10.1038/s41467-025-57935-y.

Bacher, Sven, Tim M. Blackburn, Franz Essl, Piero Genovesi, Jaakko Heikkilä, Jonathan M. Jeschke, Glyn Jones, et al. 2018. "Socio-Economic Impact Classification of Alien Taxa (SEICAT)." Methods in Ecology and Evolution 9 (1): 159–68. https://doi.org/10.1111/2041-210X.12844.

Bottery, Michael J. 2022. "Ecological Dynamics of Plasmid Transfer and Persistence in Microbial Communities." Current Opinion in Microbiology 68 (August):102152. https://doi.org/10.1016/j.mib.2022.102152.

Brito, Ilana Lauren. 2021. "Examining Horizontal Gene Transfer in Microbial Communities." Nature Reviews Microbiology, April, 1–12. https://doi.org/10/gjs4s7.

Chappell, Callie. 2024. "LABraries & LABrarians: A Proposal for a National LABrary System." https://doi.org/10.25740/KS530DC5511.

Chappell, Callie R., Rolando Perez, and Corinne Okada Takara. 2023. "Growing Biodesign Ecosystems: Community Exchange Spaces Advance Biotechnology Innovation." Research Directions: Biotechnology Design 1 (January):e13. https://doi.org/10.1017/btd.2023.8.

Chemla, Yonatan, Connor J. Sweeney, Christopher A. Wozniak, and Christopher A. Voigt. 2025. "Design and Regulation of Engineered Bacteria for Environmental Release." Nature Microbiology 10 (2): 281–300. https://doi.org/10.1038/s41564-024-01918-0.

Clark, Uraina S., and Yasmin L. Hurd. 2020. "Addressing Racism and Disparities in the Biomedical Sciences." Nature Human Behaviour 4 (8): 774–77. https://doi.org/10.1038/s41562-020-0917-7.

Cooper, Robert M, Lev Tsimring, and Jeff Hasty. 2017. "Inter-Species Population Dynamics Enhance Microbial Horizontal Gene Transfer and Spread of Antibiotic Resistance." Edited by Ben Cooper. eLife 6 (November):e25950. https://doi.org/10/ggr4ds.

Corich, Viviana, Alessio Giacomini, Elena Vendramin, Patrizia Vian, Milena Carlot, Giuseppe Concheri, Elisa Polone, Sergio Casella, Marco P. Nuti, and Andrea Squartini. 2007. "Long Term Evaluation of Field-Released Genetically Modified Rhizobia." Environmental Biosafety Research 6 (3): 167–81. https://doi.org/10.1051/ebr:2007006.

David, P., E. Thébault, O. Anneville, P. -F. Duyck, E. Chapuis, and N. Loeuille. 2017. "Chapter One - Impacts of Invasive Species on Food Webs: A Review of Empirical Data." In Advances in Ecological Research, edited by David A. Bohan, Alex J. Dumbrell, and François Massol, 56:1–60. Networks of Invasion: A Synthesis of Concepts. Academic Press. https://doi.org/10.1016/bs.aecr.2016.10.001.

De Silva, Muthu, Zaheer Khan, Tim Vorley, and Jing Zeng. 2020. "Transcending the Pyramid: Opportunity Co-Creation for Social Innovation." Industrial Marketing Management 89 (August):471–86. https://doi.org/10.1016/j.indmarman.2019.12.001.

Del Valle, Ilenne, Emily M. Fulk, Prashant Kalvapalle, Jonathan J. Silberg, Caroline A. Masiello, and Lauren B. Stadler. 2021. "Translating New Synthetic Biology Advances for Biosensing Into the Earth and Environmental Sciences." Frontiers in Microbiology 11 (February). https://doi.org/10.3389/fmicb.2020.618373.

Di Chiro, Giovanna. 2007. "Indigenous Peoples and Biocolonialism: Defining the Science of Environmental Justice in the Century of the Gene," January. https://doi.org/10.7551/mitpress/2781.003.0015.

Dillewijn, Pieter van, Pablo J. Villadas, and Nicolás Toro. 2002. "Effect of a Sinorhizobium Meliloti Strain with a Modified putA Gene on the Rhizosphere Microbial Community of Alfalfa." Applied and Environmental Microbiology 68 (9): 4201–8. https://doi.org/10.1128/AEM.68.9.4201-4208.2002.

Edwards, Anne. 2011. "Building Common Knowledge at the Boundaries between Professional Practices: Relational Agency and Relational Expertise in Systems of Distributed Expertise." International Journal of Educational Research, Learning at the boundary, 50 (1): 33–39. https://doi.org/10.1016/j.ijer.2011.04.007.

Ellner, Stephen P., Monica A. Geber, and Nelson G. Hairston Jr. 2011. "Does Rapid Evolution Matter? Measuring the Rate of Contemporary Evolution and Its Impacts on Ecological Dynamics." Ecology Letters 14 (6): 603–14. https://doi.org/10.1111/j.1461-0248.2011.01616.x.

George, Dalton, Avery Brewer, Anna Dale, Mark Danciu, Casey Isabelle, and Emma Frow. 2025. "Opening up 'Containment': Technological and Social Dimensions of Biocontainment for Genetically Engineered Organisms Designed for Deliberate Release," April. https://doi.org/10.22541/au.174526562.21903148/v1.

Gonzalez, Carmen G. 2006. "Genetically Modified Organisms and Justice: The International Environmental Justice Implications of Biotechnology." Georgetown International Environmental Law Review 19:583. SSRN: https://ssrn.com/abstract=986864.

Guibrunet, Louise, David González-Jiménez, Gabriela Arroyo-Robles, Mariana Cantú-Fernández, Victoria Contreras, Daniela Flores Mendez, Arlen Valeria Ocampo Castrejón, et al. 2024. "Geographic and Epistemic Pluralism in the Sources of Evidence Informing International Environmental Science–Policy Platforms: Lessons Learnt from the IPBES Values Assessment." Global Sustainability 7 (January):e36. https://doi.org/10.1017/sus.2024.23.

Hendy, Jessica, Matthäus Rest, Mark Aldenderfer, and Christina Warinner. 2021. "Cultures of Fermentation: Living with Microbes: An Introduction to Supplement 24." Current Anthropology 62 (S24): S197–206. https://doi.org/10.1086/715476.

Higgins, Marc, Maria F. G. Wallace, and Jesse Bazzul. 2018. "Disrupting and Displacing Methodologies in STEM Education: From Engineering to Tinkering with Theory for Eco-Social Justice." Canadian Journal of Science, Mathematics and Technology Education 18 (3): 187–92. https://doi.org/10.1007/s42330-018-0020-5.

Kalvapalle, Prashant B., August Staubus, Matthew J. Dysart, Lauren Gambill, Kiara Reyes Gamas, Li Chieh Lu, Jonathan J. Silberg, Lauren B. Stadler, and James Chappell. 2025. "Information Storage across a Microbial Community Using Universal RNA Barcoding." Nature Biotechnology, March, 1–8. https://doi.org/10.1038/s41587-025-02593-0.

Kofler, Natalie, James P. Collins, Jennifer Kuzma, Emma Marris, Kevin Esvelt, Michael Paul Nelson, Andrew Newhouse, et al. 2018. "Editing Nature: Local Roots of Global Governance." Science 362 (6414): 527–29. https://doi.org/10.1126/science.aat4612.

Kozaeva, Ekaterina, Abdul Aziz Eida, Ella F Gunady, Jeffery L Dangl, Jonathan M Conway, and Jennifer AN Brophy. 2024. "Roots of Synthetic Ecology: Microbes That Foster Plant Resilience in the Changing Climate." Current Opinion in Biotechnology 88 (August):103172. https://doi.org/10.1016/j.copbio.2024.103172.

Kuldell, Natalie, and Emily R Aurand. 2022. "Revising Legacy Approaches to Biology Education."

Lam, Busayawan, Theodore Zamenopoulos, Mihaela Kelemen, and Jea Hoo Na. 2017. "Unearth Hidden Assets through Community Co-Design and Co-Production." The Design Journal 20 (sup1): S3601–10. https://doi.org/10.1080/14606925.2017.1352863.

Lampo, Margarita, and Giulio A. De Leo. 1998. "The Invasion Ecology of the Toad Bufo Marinus:From South America to Australia." Ecological Applications 8 (2): 388–96. https://doi.org/10.1890/1051-0761(1998)008[0388:TIEOTT]2.0.CO;2.

Liu, Xinsheng, Carol L. Goldsmith, Ki Eun Kang, Arnold Vedlitz, Zach N. Adelman, Leah W. Buchman, Elizabeth Heitman, and Raul F. Medina. 2024. "General Science-Technology Orientation, Specific Benefit–Risk Assessment Frame, and Public Acceptance of Gene Drive Biotechnology." Risk Analysis 44 (6): 1381–95. https://doi.org/10.1111/risa.14242.

Lloyd, Jay. 2022a. "Building a Bottom-Up Bioeconomy." Issues in Science and Technology (blog). May 16, 2022. https://issues.org/building-bioeconomy-engineering-biology-shapira/.

Lloyd, Jay. 2022b. "When All Research Is Dual Use." Issues in Science and Technology (blog). May 23, 2022. https://issues.org/dual-use-research-biosecurity-social-context-science-evans/.

Marken, John P., Mary E. Maxon, and Richard M. Murray. 2024. "Policy Recommendations for the Regulation of Engineered Microbes for Environmental Release." The Linde Center for Science, Society, and Policy, Caltech. https://doi.org/10.57959/BGNY-V542.

Mercer, David. 2015. "'iDentity' and Governance in Synthetic Biology: Norms and Counter Norms in the 'International Genetically Engineered Machine' (iGEM) Competition," January. https://ro.uow.edu.au/articles/journal_contribution/_iDentity_and_governance_in_synthetic_biology_norms_and_counter_norms_in_the_international_genetically_engineered_machine_iGEM_competition/27778068/1.

Munck, Christian, Ravi U. Sheth, Daniel E. Freedberg, and Harris H. Wang. 2020. "Recording Mobile DNA in the Gut Microbiota Using an Escherichia Coli CRISPR-Cas Spacer Acquisition Platform." Nature Communications 11 (1): 1–11. https://doi.org/10/gghn9x.

Nguyen, Peter Q., Xiaoning Huang, Daniel S. Collins, James J. Collins, and Ting Lu. 2023. "Harnessing Synthetic Biology to Enhance Ocean Health." Trends in Biotechnology 41 (7): 860–74. https://doi.org/10.1016/j.tibtech.2022.12.015.

Nielsen, Jens, Christian Brix Tillegreen, and Dina Petranovic. 2022. "Innovation Trends in Industrial Biotechnology." Trends in Biotechnology 0 (0). https://doi.org/10.1016/j.tibtech.2022.03.007.

Pakostova, Eva, Carmen Falagan, and Ruiyong Zhang. 2024. "The Geomicrobiology of Biomining." In Geomicrobiology: Natural and Anthropogenic Settings, edited by Lucian C. Staicu and Larry L. Barton, 171–94. Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-54306-7_9.

Parker, Michael T., and Aditya M. Kunjapur. 2020. "Deployment of Engineered Microbes: Contributions to the Bioeconomy and Considerations for Biosecurity." Health Security 18 (4): 278–96. https://doi.org/10.1089/hs.2020.0010.

Parsons, Meg, Karen Fisher, and Johanna Nalau. 2016. "Alternative Approaches to Co-Design: Insights from Indigenous/Academic Research Collaborations." Current Opinion in Environmental Sustainability, Sustainability challenges, 20 (June):99–105. https://doi.org/10.1016/j.cosust.2016.07.001.

Post, David M., and Eric P. Palkovacs. 2009. "Eco-Evolutionary Feedbacks in Community and Ecosystem Ecology: Interactions between the Ecological Theatre and the Evolutionary Play." Philosophical Transactions of the Royal Society B: Biological Sciences 364 (1523): 1629–40. https://doi.org/10.1098/rstb.2009.0012.

Power, Mary E. 2021. "Synthetic Threads through the Web of Life." Proceedings of the National Academy of Sciences 118 (22): e2004833118. https://doi.org/10.1073/pnas.2004833118.

"Real Vegan Cheese." n.d. Real Vegan Cheese. Accessed January 13, 2025. https://www.realvegancheese.org.

Reichman, Jay R, Gwendolyn McClung, Khoa Nguyen, Amanda Pierce, Wiebke Striegel, and Christopher Wozniak. 2022. "Research Needs for Novel Engineered Microbes & Biopesticides Intended for Open Release into the Environment."

Reynolds-Cuéllar, Pedro, and Daniela Delgado Ramos. 2020. "Community-Based Technology Co-Design: Insights on Participation, and the Value of the 'Co.'" In Proceedings of the 16th Participatory Design Conference 2020 - Participation(s) Otherwise - Volume 1, 75–84. PDC '20. New York, NY, USA: Association for Computing Machinery. https://doi.org/10.1145/3385010.3385030.

Ricciardi, Anthony, Tim M. Blackburn, James T. Carlton, Jaimie T. A. Dick, Philip E. Hulme, Josephine C. Iacarella, Jonathan M. Jeschke, et al. 2017. "Invasion Science: A Horizon Scan of Emerging Challenges and Opportunities." Trends in Ecology & Evolution 32 (6): 464–74. https://doi.org/10.1016/j.tree.2017.03.007.

Roy, Helen E., Aníbal Pauchard, Peter Stoett, Tanara Renard Truong, Sven Bacher, Bella S. Galil, Philip E. Hulme, et al. 2024. "IPBES Invasive Alien Species Assessment: Summary for Policymakers." Zenodo. https://doi.org/10.5281/zenodo.11254974.

Rubin, Benjamin E., Spencer Diamond, Brady F. Cress, Alexander Crits-Christoph, Yue Clare Lou, Adair L. Borges, Haridha Shivram, et al. 2022. "Species- and Site-Specific Genome Editing in Complex Bacterial Communities." Nature Microbiology 7 (1): 34–47. https://doi.org/10.1038/s41564-021-01014-7.

Saak, Christina C, Cong B Dinh, and Rachel J Dutton. 2020. "Experimental Approaches to Tracking Mobile Genetic Elements in Microbial Communities." FEMS Microbiology Reviews 44 (5): 606–30. https://doi.org/10/gg5hb9.

Sacchi, Simona, Marina Lotti, and Paola Branduardi. 2021. "Education for a Biobased Economy: Integrating Life and Social Sciences in Flexible Short Courses Accessible from Different Backgrounds." New Biotechnology 60 (January):72–75. https://doi.org/10.1016/j.nbt.2020.10.002.

Schoenberg, Kelsey. 2022. "Creating a Science-Engaged Public." Issues in Science and Technology (blog). September 28, 2022. https://issues.org/creating-science-engaged-public-renoe-nelson/.

Skariyachan, Sinosh, Neha Taskeen, Alice Preethi Kishore, and Bhavya Venkata Krishna. 2022. "Recent Advances in Plastic Degradation – From Microbial Consortia-Based Methods to Data Sciences and Computational Biology Driven Approaches." Journal of Hazardous Materials 426 (March):128086. https://doi.org/10.1016/j.jhazmat.2021.128086.

Szyjka, Shawn J., Shovon Mandal, Nathan G. Schoepp, Briana M. Tyler, Christopher B. Yohn, Yan S. Poon, Steven Villareal, Michael D. Burkart, Jonathan B. Shurin, and Stephen P. Mayfield. 2017. "Evaluation of Phenotype Stability and Ecological Risk of a Genetically Engineered Alga in Open Pond Production." Algal Research 24 (June):378–86. https://doi.org/10.1016/j.algal.2017.04.006.

Weinreb, Caleb, and Daphne S. Sun. 2023. "To Dismantle Structural Racism in Science, Scientists Need to Learn How It Works." Neuropsychopharmacology 48 (4): 579–82. https://doi.org/10.1038/s41386-023-01534-2.

Wen, Amy, Keira L. Havens, Sarah E. Bloch, Neal Shah, Douglas A. Higgins, Austin G. Davis-Richardson, Judee Sharon, et al. 2021. "Enabling Biological Nitrogen Fixation for Cereal Crops in Fertilized Fields." ACS Synthetic Biology 10 (12): 3264–77. https://doi.org/10.1021/acssynbio.1c00049.

Wolf, Clark. 2021. "PUBLIC TRUST AND BIOTECH INNOVATION: A THEORY OF TRUSTWORTHY REGULATION OF (SCARY!) TECHNOLOGY." Social Philosophy and Policy 38 (2): 29–49. https://doi.org/10.1017/S0265052522000036.

Wong, Sarah H.M., Faye Gishen, and Amali U. Lokugamage. 2021. "'Decolonising the Medical Curriculum': Humanising Medicine through Epistemic Pluralism, Cultural Safety and Critical Consciousness." London Review of Education 19 (1). https://doi.org/10.14324/LRE.19.1.16.

Yaashikaa, P. R., M. Keerthana Devi, and P. Senthil Kumar. 2022. "Engineering Microbes for Enhancing the Degradation of Environmental Pollutants: A Detailed Review on Synthetic Biology." Environmental Research 214 (November):113868. https://doi.org/10.1016/j.envres.2022.113868.

Yeom, Soo-Jin, Thien-Kim Le, and Chul-Ho Yun. 2022. "P450-Driven Plastic-Degrading Synthetic Bacteria." Trends in Biotechnology 40 (2): 166–79. https://doi.org/10.1016/j.tibtech.2021.06.003.

Zahed, Mohammad Ali, Elaheh Movahed, Arezoo Khodayari, Saba Zanganeh, and Maryam Badamaki. 2021. "Biotechnology for Carbon Capture and Fixation: Critical Review and Future Directions." Journal of Environmental Management 293 (September):112830. https://doi.org/10.1016/j.jenvman.2021.11283.

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