

The Tide of Regulation: Probiotics for Corals, Rules for Reefs

By Elisa Khoo (Year 5, Law and Life Sciences)

Introduction

A bottle of Yakult is about the size of the palm of my hand. Scientists have been exploring giving probiotics to corals to help them stave off diseases and resist environmental stresses. When I think about this, I imagine them enlarging a Yakult bottle by a few hundred folds and pouring the giant bottle into the oceans where reefs are. While that is not quite how probiotics are given to corals, it does raise some important scientific and legal questions. How can probiotics be effectively administered to corals? Will there be any effects on the surrounding microbial communities? Should probiotics be released into our oceans without complete certainty of their ecological impacts?

Before delving into these questions, let us briefly unpack the biology of coral reefs, their associated microbes, and where coral probiotics come in. Coral reef ecosystems house the most diverse marine life among all of earth's ecosystems¹, and provide major ecosystem services like food security, fisheries, coastal protection, and tourism.² Corals create stunning three-dimensional structures by building up their calcium carbonate skeletons.³ However, they cannot do this alone. Corals form intricate relationships with their associated microorganisms, together forming a "holobiont".⁴ One of the most crucial microorganisms is dinoflagellate (also known as zooxanthellae), microalgae, which lives within corals and photosynthesise to supply corals with energy to construct calcium carbonate skeletons.⁵ In addition to dinoflagellate, bacteria, viruses, and archaea inhabit corals' mucus, tissues, and skeleton.⁶

Reefs in Environmental Crisis

Unfortunately, reefs face incessant stresses such as ocean acidification, marine heatwaves, storms, and pollution.⁷ It is estimated that 99% of all coral reefs will face unsuitable living conditions by 2055.⁸ At the core of these stresses is global warming which is associated with ocean acidification caused by increased dissolved carbon dioxide, marine heatwaves, and intense storms that are destructive to reefs.⁹ To exacerbate matters, coral diseases such as White Band Disease (WBD)¹⁰ and Stony Coral Tissue Loss Disease (SCTLD)¹¹ are devastating reefs, causing severe tissue loss and mortality. WBD is linked to pathogens like *Rickettsia*-like bacteria and *Vibrio* species, which are thought to cause or contribute to the disease.¹² As for SCTLD, pathogens associated include *Flavobacteriales*, *Rhodobacterales*,

¹ Nancy Knowlton et al., "Coral Reef Biodiversity," *Life in the World's Oceans: Diversity Distribution and Abundance*, 2010, 65–74.

² Carlo Fezzi, Derek J. Ford, and Kirsten L.L. Oleson, "The Economic Value of Coral Reefs: Climate Change Impacts and Spatial Targeting of Restoration Measures," *Ecological Economics* 203 (January 2023): 107628, <https://doi.org/10.1016/j.ecolecon.2022.107628>.

³ Christian R. Voolstra, Raquel S. Peixoto, and Christine Ferrier-Pagès, "Mitigating the Ecological Collapse of Coral Reef Ecosystems: Effective Strategies to Preserve Coral Reef Ecosystems," *EMBO Reports* 24, no. 4 (April 5, 2023): e56826, <https://doi.org/10.15252/embr.202356826>.

⁴ Thomas CG Bosch and Margaret J McFall-Ngai, "Metaorganisms as the New Frontier," *Zoology* 114, no. 4 (2011): 185–90.

⁵ Charles Sheppard et al., *The Biology of Coral Reefs*, 2nd ed. (Oxford University Press/Oxford, 2017), <https://doi.org/10.1093/oso/9780198787341.001.0001>.

⁶ Raquel S. Peixoto et al., "Beneficial Microorganisms for Corals (BMC): Proposed Mechanisms for Coral Health and Resilience," *Frontiers in Microbiology* 8 (2017): 341.

⁷ Renee O. Setter, Erik C. Franklin, and Camilo Mora, "Co-Occurring Anthropogenic Stressors Reduce the Timeframe of Environmental Viability for the World's Coral Reefs," ed. Peter John Mumby, *PLOS Biology* 20, no. 10 (October 11, 2022): e3001821, <https://doi.org/10.1371/journal.pbio.3001821>.

⁸ Setter, Franklin, and Mora.

⁹ Maria Byrne et al., "Impacts of Climate Change Stressors on the Great Barrier Reef," in *Oceanographic Processes of Coral Reefs* (CRC Press, 2024), 323–40.

¹⁰ Sarah A Gignoux-Wolfsohn and Steven V Vollmer, "Identification of Candidate Coral Pathogens on White Band Disease-Infected Staghorn Coral," *PloS One* 10, no. 8 (2015): e0134416.

¹¹ Lorenzo Alvarez-Filip et al., "Stony Coral Tissue Loss Disease Decimated Caribbean Coral Populations and Reshaped Reef Functionality," *Communications Biology* 5, no. 1 (2022): 440.

¹² Gignoux-Wolfsohn and Vollmer, "Identification of Candidate Coral Pathogens on White Band Disease-Infected Staghorn Coral."

Peptostreptococcales-Tissierellales, and *Clostridiales*.¹³ Both these diseases can be exacerbated by the environmental stresses described above. While addressing global warming is vital for reef conservation, efforts are also shifting toward intervention strategies that enhance coral survival amid worsening conditions.

What are coral probiotics and how do they work?

In comes - coral probiotics! Coral probiotics are microorganisms that support coral health.¹⁴ In enclosed aquarium experiments, scientists have found that probiotics can boost coral health.¹⁵ Probiotics may boost nutrient uptake, alleviate stress, neutralise toxic substances, and suppress harmful microbes, among other benefits.¹⁶ But how do these experiments work? First, scientists isolate microorganisms from a target coral species. They then screen these microbes to identify ones with beneficial traits. Like assembling a team of microscopic bodyguards, they combine the best candidates into a tailored cocktail of probiotics and administer them to corals in a controlled setting. To test their effectiveness, scientists expose these treated corals to stresses such as high temperatures or pathogens.¹⁷

Deploying Coral Probiotics in Ocean Ecosystems

This happens in the laboratory, but how are coral probiotics actually delivered to corals? If we go back to the Yakult analogy, simply pouring probiotic liquid into the ocean would be ineffective. The microbes would not be concentrated on the target corals; worse, this could disrupt surrounding microbial communities. The indiscriminate release of probiotics into the sea might do more harm than good, raising regulatory concerns.

In a study published in *Nature* last year, scientists applied probiotics using syringes on cauliflower corals (*Pocillopora verrucosa*) in the Red Sea three times per week for 3 months.¹⁸ The probiotic mix included six bacterial strains: two *Pseudoalteromonas galathea*, two *Cobetia amphilecti*, one *Halomonas sp*, and one *Suctifella sp*. These strains were chosen for their beneficial traits, such as fighting off harmful *Vibrio* bacteria (which is linked to coral diseases like WBD), reducing harmful reactive oxidative molecules, and aiding phosphate absorption (which is important for coral metabolism).

The results showed that the probiotics successfully reshaped the coral's microbial community without causing any noticeable effects on the surrounding microbiome. Notably, the study could not track major health improvements as both treated and non-treated corals remained healthy throughout the experiment. Interestingly, a reduction in *Vibrio* bacteria was observed in treated corals, suggesting that probiotics may help suppress opportunistic coral pathogens. Still, the nuance is that not all *Vibrio* species are harmful, highlighting the need for further research.¹⁹

¹³ Stephanie M Rosales et al., "A Meta-Analysis of the Stony Coral Tissue Loss Disease Microbiome Finds Key Bacteria in Unaffected and Lesion Tissue in Diseased Colonies," *ISME Communications* 3, no. 1 (December 1, 2023): 19, <https://doi.org/10.1038/s43705-023-00220-0>.

¹⁴ Raquel S. Peixoto et al., "Coral Probiotics: Premise, Promise, Prospects," *Annual Review of Animal Biosciences* 9, no. 1 (February 16, 2021): 265–88, <https://doi.org/10.1146/annurev-animal-090120-115444>.

¹⁵ Peixoto et al. "Beneficial Microorganisms for Corals (BMC): Proposed Mechanisms for Coral Health and Resilience."

¹⁶ Peixoto et al.

¹⁷ Peixoto et al.

¹⁸ Nathalia Delgadillo-Ordoñez et al., "Probiotics Reshape the Coral Microbiome in Situ without Detectable Off-Target Effects in the Surrounding Environment," *Communications Biology* 7, no. 1 (April 9, 2024): 434, <https://doi.org/10.1038/s42003-024-06135-3>.

¹⁹ Michael Sweet et al., "Insights into the Cultured Bacterial Fraction of Corals," ed. Nick Bouskill, *mSystems* 6, no. 3 (June 29, 2021): e01249-20, <https://doi.org/10.1128/mSystems.01249-20>.

Besides syringes, some researchers are exploring the use of "mini aquariums" created by wrapping corals in plastic bags to isolate them for probiotic application.²⁰ One promising naturally occurring probiotic, *Pseudoalteromonas sp.* strain McH1-7, has shown broad-spectrum antibacterial properties (works against a wide range of bacteria), particularly against the bacteria linked to SCTLD.²¹ In laboratory trials, McH1-7, administered into a plastic canopy, successfully slowed or halted disease progression in 68.2% of infected coral fragments and completely prevented disease transmission in all cases.²²

Sailing the Legal Seas: Regulatory Considerations of Coral Probiotics

As these methods evolve, it is essential to establish legal frameworks that protect both coral reefs and the surrounding environment while allowing for innovative solutions to combat coral degradation. At the moment, there is no universal set of rules governing the use of probiotics for coral conservation. The International Scientific Association for Probiotics and Prebiotics offers guidance by defining probiotics as "live microorganisms that, when administered in adequate amounts, confer a health benefit on the host".²³ This definition is crucial as it establishes clear criteria for what qualifies as probiotics, ensuring that only strains scientifically proven to have positive effects are recognised as such. Thus far, the discourse on probiotics has revolved primarily around food, and this leaves policymakers in a grey area when it comes to deploying probiotics for reef conservation.

Still, we can turn to our bread-and-butter legal principles in international environmental law. The first port of call would be the *Precautionary Principle*. First introduced in the 1992 Rio Declaration, a document adopted at the United Nations Earth Summit held in Rio de Janeiro, Principle 15 states that "Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation".²⁴ The critical threat to coral conservation is global warming and its associated challenges, leaving us racing against time. If we demand complete scientific certainty, we risk critical time enforcing our corals with necessary defences. On the other hand, if we are too lenient in our regulations, we risk disrupting the microbial communities that play an intricate role in maintaining coral health. Nonetheless, it is encouraging that research thus far has shown little off-target effects²⁵ in the environment, and "enclosed" methods such as plastic canopies²⁶ appear to contain probiotic use.

Another important consideration is the *Principle of Transboundary Harm*, a form of customary international law. Customary international law can be described as the unwritten rules between countries that countries follow because they have been doing so for a long time and believe they are supposed to. The principle here is that states have a duty to prevent, mitigate, and address environmental damage that causes harm to other states.²⁷ This principle is

²⁰ Blake Ushijima et al., "Chemical and Genomic Characterization of a Potential Probiotic Treatment for Stony Coral Tissue Loss Disease," *Communications Biology* 6, no. 1 (April 6, 2023): 248, <https://doi.org/10.1038/s42003-023-04590-y>.

²¹ Ushijima et al.

²² Ushijima et al.

²³ Food and Agriculture Organization of the United Nations, "Report of a Joint FAO/WHO Expert Consultation on Evaluation of Health and Nutritional Properties of Probiotics in Food Including Powder Milk with Live Lactic Acid Bacteria," October 1, 2001, <https://openknowledge.fao.org/server/api/core/bitstreams/382476b3-4d54-4175-803f-2f26f3526256/content>.

²⁴ United Nations, "Report of the United Nations Conference on Environment and Development: Annex I - Rio Declaration on Environment and Development," 1992, https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_CONF.151_26_Vol.I_Declaration.pdf.

²⁵ Delgadillo-Ordoñez et al., "Probiotics Reshape the Coral Microbiome in Situ without Detectable Off-Target Effects in the Surrounding Environment."

²⁶ Ushijima et al.

²⁷ Owen McIntyre, "The Current State of Development of the No Significant Harm Principle: How Far Have We Come?," *International Environmental Agreements: Politics, Law and Economics* 20, no. 4 (December 2020): 601–18, <https://doi.org/10.1007/s10784-020-09501-8>.

relevant as coral probiotics could shift across borders, affecting coral reefs shared by multiple countries. For instance, the Coral Triangle (also known as the “Amazon of the seas” because of its incredible biodiversity) borders the waters of six countries, with ocean currents playing a role in the movement of not just water but organisms across national boundaries.²⁸ Here, the duty to conduct *Environmental Impact Assessments* (EIAs) become relevant. In the 2010 *Pulp Mills*²⁹ ruling, the International Court of Justice held that EIAs should be conducted when an activity poses a risk of causing transboundary harm. Here, risk assessments need to be conducted before large-scale probiotic operations.

The Path Ahead

As of yet, scientific research focuses on isolating existing microorganisms from coral, creating a cocktail of the most beneficial ones, amplifying them and re-introducing them to corals. This theoretically has little risk as the microorganisms introduced are ones that are already found in the environment. Furthermore, the existing treatment methods – syringe and plastic canopy – appear to limit treatment to target corals effectively, reducing off-target effects. In considering legal principles, it seems worthwhile to equip corals to face impending environmental stresses. Moreover, risks can be mitigated through rigorous assessments that mirror the structure of clinical trials. We could start with controlled laboratory experiments to evaluate probiotic safety and efficacy, and then progress to carefully monitored in situ trials³⁰ on small coral populations. This stepwise approach allows for the early detection of unintended effects and the refinement of methods before any large-scale application.

However, we are also reminded of Article 8(h) of the Convention on Biological Diversity, a major international treaty adopted at the Earth Summit in Rio, which urges to “[p]revent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species.”³¹ New developments are on the horizon, such as introducing strains from one coral reef to an entirely different reef or even genetically modifying probiotics to increase coral resistance to stresses.³² Regulation needs to develop with scientific advancement.

Ultimately, the goal is not to stifle innovation but to ensure that emerging conservation methods are guided by sound legislation to avoid irreversible damage. As we step into the next chapter, we face the grim reality that coral health is declining at an unprecedented rate. The pressures on coral ecosystems are immense, and we must equip ourselves with both scientific innovation and legal gusto to move coral conservation forward.

²⁸ Franciska von Heland, Beatrice Crona, and Pedro Fidelman, “Mediating Science and Action across Multiple Boundaries in the Coral Triangle,” *Global Environmental Change* 29 (2014): 53–64.

²⁹ *Pulp Mills on the River Uruguay (Argentina v. Uruguay)* (International Court of Justice April 20, 2010). The Court held that: “it may now be considered a requirement under general international law to undertake an environmental impact assessment where there is a risk that the proposed industrial activity may have a significant adverse impact in a transboundary context, in particular, on a shared resource.”

³⁰ *In situ* means on-site, in this case referring to the study of probiotics in the natural coral reef environment.

³¹ Convention on Biological Diversity, “Article 8. In-Situ Conservation” (United Nations, 1992), 8, <https://www.cbd.int/convention/articles/default.shtml?a=cbd-08>.

³² Jie Li et al., “Microbiome Engineering: A Promising Approach to Improve Coral Health,” *Engineering* 28 (September 2023): 105–16, <https://doi.org/10.1016/j.eng.2022.07.010>.

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