

# A Policy Framework for International Cooperation in Space Biotechnology



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# Introduction

**B**iototechnology is emerging as an indispensable enabler for the future of sustainable human space exploration and the creation of long-term habitats in space. Microbes carefully engineered for outer space can potentially overcome challenges like radiation exposure, oxygen provision in closed-loop systems, space agriculture, habitat sustainability, and disease prevention, among many others. Humans—whether voyaging as part of space agencies or private companies—will be unable to go to the Moon for long periods of time or travel further to Mars without biotech. After all, it is biology that provides the environmental services that sustain life and economies on Earth.<sup>1</sup> In the next ten to fifteen years, biotech will have a major presence at the forefront of space exploration.

Yet, policymakers have not explicitly considered the potential social, geopolitical, and ethical consequences of biotech-enabled space exploration, and the need for frameworks and guidance to support its development within an international context. The decisions that we make—or fail to make—now, have important implications for our capacity as a species to explore the galaxy, ensure benefits for life on Earth, and protect against the risks already inherent in testing space-biotech on Earth. Without thinking ahead, plans already underway to return to the Moon, travel on to Mars, share (or withhold) technology with international partners, and build on the achievements of the International Space Station will be insufficient to safeguard human safety and protect the natural environment in space. For international cooperation to develop, and continually adapt, a shared policy roadmap is needed.

Only a small handful of international treaties exist to govern how countries cooperate in both domains—space exploration and biotech—individually. And forefront technologies in these domains are evolving far more rapidly than the rules governing them. At the same time, both space and biotech are areas of strategic competition between the United States and China. While such competition between nations can spur innovation, it also carries with it risks that may go unnoticed, unheeded, or even amplified in the competition for superiority.<sup>2</sup> Pursuing international cooperation at the same time, as occurred during the Cold War between the Soviet Union and United States, can mitigate these risks.

This report identifies the main areas of tension as well as the key issues for which it will be crucially important to expand space diplomacy and governance as the genomic and space revolutions collide. We argue for deeper and deliberate international and transnational cooperation.

Time is of the essence. The first unmanned starship launch to Mars could happen as soon as 2026, taking advantage of a launch window that opens approximately every 26 months. If successful, the first crewed missions to Mars could launch just four years later in 2030. While Mars is only the beginning of possible human expansion into space, landing humans on the red planet will certainly open up a radically new era in human space travel—with advances in biotech sitting at the heart of any such mission. We set forth key considerations in the effort to devise new policy and ethical frameworks and recommendations for a roadmap to lay the foundation for humans to live and work on the Moon, Mars, and beyond.

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<sup>1</sup><https://www.ipbes.net/>

<sup>2</sup>Emery-Xu et al. 2024 <https://journals.sagepub.com/doi/full/10.1177/00220027231214996> ; “In addition, revealing information about rivals’ capabilities has two opposing effects on risk: states discover either that they are far apart in capability and compete less or that they are close in capability and drastically reduce safety to win.”

# Biotech as a Tool for Space Exploration

Experts envision that biotech applications stand to increase resilience, flexibility, and efficiency of space missions, particularly because they enable more effective use of available materials (i.e. synthetic microbe-based habitats),<sup>3</sup> resources already present on Mars<sup>4</sup> or the Moon (i.e. making bricks out of regolith),<sup>5</sup> and those reclaimed from waste streams. In effect, biotechnology provides a means of enabling food, materials, and medical resources without relying on replenishing these supplies from Earth.<sup>6</sup> For example, using biotechnology on Mars to produce food, structural materials, therapeutics, and chemical feedstocks could increase autonomy, sustainability, and resilience, while at the same time freeing up payload capacity.<sup>7</sup>

Beyond bio-manufacturing to sustain life and ecosystems on celestial bodies, other scientists also envision more advanced interventions to re-engineer human genetics so that future astronauts can tolerate the extreme environments of space travel and sustainably inhabit other planets.<sup>8</sup> Naturally, both policymakers and technologists see compelling benefits to these applications, either in terms of enabling space missions or in terms of scientific, economic, or geopolitical

advantages. At the same time, experience with technological revolutions here on Earth suggest that thoughtfulness is warranted, especially when it comes to the fundamental technologies upon which society depends. But we must address now the questions that these short-term practical steps raise that might not be apparent over the longer term.

Moreover, if humans are to live in space for long periods of time, the goal should not only be to survive, but to flourish. This new era in space exploration is an opportunity to avoid replicating problems that now exist on Earth, many arguably the result of an absence of systems thinking and/or proper planning. Case studies from extreme environments on Earth, such as the deep sea, serve as warnings, for example. Recent research has shown the potential for deep sea submersibles to serve as a vector for invasive species—and the diseases that they carry—that were, surprisingly, able to survive in both extreme deep sea environments and in shallow habitats.<sup>9</sup> Similar concerns have been raised about the introduction of bioengineered microbes to extraterrestrial environments, as well as for the potential reintroduction of pathogenic microbes to

<sup>3</sup> <https://arxiv.org/pdf/2406.02522>, <https://www.nature.com/articles/s41467-023-37070-2>

<sup>4</sup> Warren, P., Raju, N., Ebrahimi, H., Krsmanovic, M., Raghavan, S., Kapat, J., Ghosh, R. 2022. Effect of sintering temperature on microstructure and mechanical properties of molded Martian and Lunar regolith. *Ceramics Int.* 48(23, Part B, 35825-35833. <https://doi.org/10.1016/j.ceramint.2022.07.329>. and Kruyer, N.S., Realff, M.J., Sun, W., Genzale, C.L., Peralta-Yahya, P., 2021. Designing the bioproduction of Martian rocket propellant via a biotechnology-enabled in situ resource utilization strategy. *Nat. Commun.* 12, 6166; <https://www.nature.com/articles/s41467-021-26393-7.epdf>

<sup>5</sup> Zuo, H.Y., Ni, S.S., Xu, M.Y., 2023. An assumption of in situ resource utilization for “bio-bricks” in space exploration. *Frontiers in Materials* 10. doi: 10.3389/fmats.2023.1155643; <https://spi.science.org/doi/10.34133/space.0037>

<sup>6</sup> Aversch, N.J.H., Berliner, A.J., Nangle, S.N. et al. Microbial biomanufacturing for space-exploration—what to take and when to make. *Nat Commun* 14, 2311 (2023). <https://doi.org/10.1038/s41467-023-37910-1>

<sup>7</sup> <https://www.nature.com/articles/s41526-023-00285-0>, <https://www.nature.com/articles/s41467-023-37910-1> Aversch, N.J.H., Berliner, A.J., Nangle, S.N. et al. Microbial biomanufacturing for space-exploration;” Cockell, C.S., 2022. Bridging the gap between microbial limits and extremes in space: space microbial biotechnology in the next 15 years. *Microbial Biotechnology* 15, 29-41; McNulty, M.J., Xiong, Y.G., Yates, K., Karuppanan, K., Hilzinger, J.M., Berliner, A.J., Delzio, J., Arkin, A.P., Lane, N.E., Nandi, S., McDonald, K.A., 2021. Molecular pharming to support human life on the moon, mars, and beyond. *Critical Reviews in Biotechnology* 41, 849-864; Mezhevikin, V.V., Okhonin, V.A., Bartsev, S.I., Gitelson, J.I., 1994. Indications and counterindications for applying different versions of closed ecosystems for space and terrestrial problems of life support, in: MacElroy, R.D., Mitchell, C.A., Andre, M., Blackwell, C.C., Tibbitts, T.W., Banin, A., Levine, J.S. (eds.), *Life Sciences and Space Research* Xxv, vol. 14, pp. 135-142.

<sup>8</sup> Mason, Christopher E. *The next 500 years: Engineering life to reach new worlds.* MIT Press, 2021.

<sup>9</sup> Miliotis, G., McDonagh, F., Singh, N.K., O’Connor, L., Tuohy, A., Morris, D., Venkateswaran, K., 2023. Genomic analysis reveals the presence of emerging pathogenic *Klebsiella* lineages aboard the International Space Station. *Microbiology Spectrum* 11. <https://conbio.onlinelibrary.wiley.com/doi/epdf/10.1111/j.1523-1739.2012.01864.x>; Van Dover, C.L., Ward, M.E., Scott, J.L., Underdown, J., Anderson, B., Gustafson, C., Whalen, M., Carnegie, R.B., 2007. A fungal epizootic in mussels at a deep-sea hydrothermal vent. *Marine Ecology* 28, 54-62; Voight, J.R., Lee, R.W., Reft, A.J., Bates, A.E., 2012. Scientific Gear as a Vector for Non-Native Species at Deep-Sea Hydrothermal Vents. *Cons. Biol.* 26, 938-942.

Earth that may have evolved during spaceflight.<sup>10</sup> Recent experimental work has even shown the ability of organisms such as lichens to survive under environmental conditions mimicking those of Mars. As we anticipate future space travel, it is imperative to practice maximal sustainability, environmentally friendly production, advanced manufacturing techniques, and protection of natural environments.

Much can be also learned from ongoing work in analog environments such as undersea habitats

used to prepare astronauts for space travel here on Earth.<sup>11</sup> In addition to simulating human experiences in space, underwater analog environments also serve as test beds for both equipment and as pilots for biological experimentation in space. The planning and execution of space-based biological experimentation thus has potential consequences for how initial studies are carried out here on our home planet, and provide an opportunity to carefully refine those procedures to avoid unintended consequences.

## The Gaps in Ethics & Policy

A specific framework that lays the foundation for humans to live and work on the Moon and Mars is necessary.<sup>12</sup> It should be a dynamic set of principles that is adaptable as science, technology, and policy evolve. A diverse range of interdisciplinary experts, including scientists, astronauts, space entrepreneurs, regulators, philosophers, governance scholars, and legal experts, should help to inform diplomats and policymakers in crafting and developing this Space-Biotech Framework. While some diplomatic processes and transnational policy arenas concerning space and biotech do already exist, there is still a need to set forth the framing within which these deliberations should take place. As cutting-edge technologies are rapidly moving forward in synergistic and unanticipated ways, what do policymakers need to know?

We identify policy and ethical gaps in biotech, space, and at the intersection of the two that should be addressed in order to craft such a dynamic roadmap for the future:

### The Policy-Ethics Gap: Biotech

There are several international treaties that seek to govern biotech. For example, the Cartagena Protocol on Biosafety, adopted in 2000, specifically addresses the safe handling, transport, and use of living modified organisms (LMOs), although it is not signed by the U.S. or Russia, among others. The International Treaty on Plant Genetic Resources for Food and Agriculture, adopted in 2001, focuses on the conservation and sustainable use of plant genetic resources for food and agriculture, but also includes provisions related to the exchange of germplasm for breeding purposes, which is relevant to biotech research. Again, it has only partial adoption as it is signed by the U.S., but not Russia or China. The 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, adopted in 2010, establishes a framework for the fair and equitable sharing of benefits derived from the utilization of genetic resources, including those used in biotech

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<sup>10</sup> McDonagh, F., Cormican, M., Morris, D., Burke, L., Singh, N.K., Venkateswaran, K., Miliotis, G., 2023. Medical Astro-Microbiology: Current Role and Future Challenges. *Journal of the Indian Institute of Science* 103, 771-796; Miliotis, G., McDonagh, F., Singh, N.K., O'Connor, L., Tuohy, A., Morris, D., Venkateswaran, K., 2023. Genomic analysis reveals the presence of emerging pathogenic *Klebsiella* lineages aboard the International Space Station. *Microbiology Spectrum* 11.

<sup>11</sup> Ricciardi, A., Cassey, P., Leuko, S., Woolnough, A.P., 2022. Planetary Biosecurity: Applying Invasion Science to Prevent Biological Contamination from Space Travel. *Bioscience* 72, 247-253; Sokol, M., Volf, P., Hejda, J., Leova, L., Hybl, J., Schmirler, M., Suchy, J., Prochazka, R., Charvat, M., Seitlova, K., Dolejs, M., Schneider, J., Kutilek, P., 2025. DIANA: An underwater analog space mission. *Acta Astronautica* 226, 349-360.

<sup>12</sup> Shannon N. Nangle et. al, "The case for biotech on Mars," *Nature Biotechnology*, vol 38, April 2020, pp. 401-407.

research. However, it is not ratified by the U.S., Russia, or China, among others.

Broadly, as an emerging field, biotechnology has received less attention from policy and ethics experts than other new technologies like artificial intelligence (AI) or renewable energy. The one exception to this is in the biomedical domain where vaccines, genetic therapy, and other medical applications are extensively regulated, discussed, and deployed. For example, the 1998 Paris Protocol to the Convention on Human Rights and Biomedicine aims to strengthen the protection of human rights in the field of biomedicine. It outlines specific provisions regarding topics such as organ transplantation, research on biological materials of human origin, and the protection of the human genome, although again the U.S. and China have not signed it.

Similarly, the 1975 Asilomar Conference on Recombinant DNA is seen as a paradigmatic example of self-regulation within the sciences. Here, researchers agreed to internal norms against genetically modifying viable human embryos along the germline for what they saw as ethical reasons including questions about who has the right to make genetic changes to the human race as a whole. The efficacy of these norms faced a significant challenge in 2018, however, when Chinese biophysicist He Jiankui genetically modified a pair of children with heritable traits, prompting a widening of conversations around what more formal regulations might look like in the field.<sup>13</sup>

Attention to novel biotechnologies for fields like agriculture, manufacturing, and energy are thus lacking. What does exist centers largely on the risks and benefits of using genetic technologies or materials for the creation and management of crops; the impact of the emerging field on sustainability efforts, including potential new green fuels and endangered species management; the governance of genetic databases or materials; and biomedicine. Much of the ethics literature leans into the

precautionary principle, with concerns about having enough information to make informed decisions.

Current ethical frameworks tend to emphasize a balance between considering the possible beneficial and detrimental outcomes, and the inherent rights of certain groups to not have their bodily autonomy or integrity threatened by the emerging technologies. It is generally accepted, for example, that humans ought to have control of their own genetic codes and how they are used, a principle that has been consistently violated by the medical community who have previously extracted genetic materials from Indigenous groups and people from other vulnerable communities without their knowledge. Similarly, there is concern about how genetic restoration of extinct species might encourage us to think of ecosystems as easily fixable with future technologies, rather than something to be preserved now. At the same time, there is a broadly accepted ethical principle that says we ought to be restoring ecosystems which have been degraded by human actions, up to and potentially including de-extinction. It is also worth noting that biotech, in contrast to many other areas of science, is prone to accusations of hubris or reactions of fear from the general public, who see it as a field “playing god” with nature.

In general, biotechnologies tend to represent a difference in ethical scale, however, rather than posing novel ethical issues by themselves. While genetic modification of animals, for example, can now be done at increased speed and scales, in many ways it simply represents an intensification of the ethical issues surrounding selective breeding which humans have engaged with for millennia. Similarly, issues of how and where we acquire and store genetic materials, including human genetic code, intersect heavily with existing debates in privacy and who has the right to own a genetic sequence.

Progress in biological science, coupled with accelerating developments in computing, automation, and AI, are unlocking new applications

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<sup>13</sup> <https://www.science.org/content/article/crispr-bombshell-chinese-researcher-claims-have-created-gene-edited-twins>

for health, manufacturing, agriculture, food, and energy. As a result, biotech is among other cutting-edge technologies seen to be key to future economic and national security.

## The Policy-Ethics Gap: Space

Outer space also has a dearth of international agreements—the main treaty governing actions in space is still the very first one: the 1967 Outer Space Treaty. To be sure, the international community has multiple levels and venues in which formal and informal space diplomacy take place, and attention to this key area is intensifying given the scientific, economic, and military implications. At the UN level, the most prominent venues are the Committee on the Peaceful Use of Outer Space (COPUOS), the International Telecommunications Union (ITU), and the Conference on Disarmament.

However, little progress has been made in terms of creating parameters of shared understanding related to human exploration of space, especially as it pertains to private company participation. New venues for space diplomacy, such as the Artemis Accords and the Combined Space Operations Initiative, are promising. And valuable processes of space diplomacy also happen more informally through project-based bilateral and multilateral cooperation that includes both the public and private sectors. In this sense, space benefits from a more active international and transnational landscape of collaboration and sharing of best practices compared to biotech, even if it falls short of formal agreements.

Given that space now represents a new frontier in research, with a unique set of challenges and opportunities, it is noteworthy that there is almost

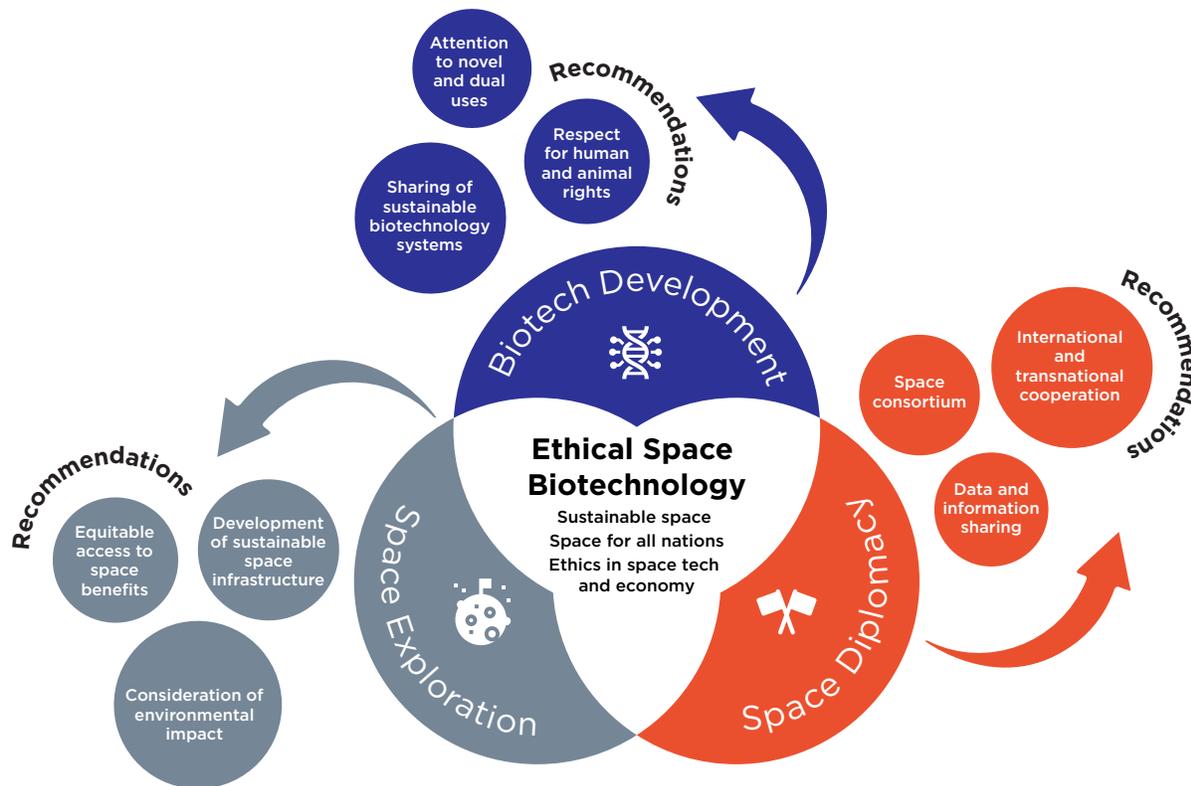


Figure 1. A conceptual framework illustrating the intersection of biotech development, space exploration, and space diplomacy within the domain of space biotechnology.

no serious literature on human space exploration from an ethics perspective. Of the literature that does exist, some portion of this work considers how to approach the discovery of alien life (SETI) or design ethical governance for off-world human civilizations, while other ethics work in this area focuses on a small handful of key issues relevant to the near term.

For example, one topic under consideration is the ethics of the environmental impact of space infrastructure on Earth, which can be highly polluting. This includes regions around rocket launch sites that are being significantly degraded by the emissions from rocket fuel,<sup>14</sup> leading to environmental and health concerns for local communities and loss of biodiversity.<sup>15</sup> Another issue is how the act of decommissioning satellites by burning them up in the atmosphere is increasingly leaving trace metals and plastics in the upper atmosphere.<sup>16</sup> Indeed, space junk in general is a growing international issue that will require significant ethics and policy work to solve.

There is also a growing conversation about how to ensure that the benefits of expansion into space are felt by everyone, rather than a select few. This would include opening up access to space for emerging economies, or the lower-income communities that are often asked to host space infrastructure but see little of the benefits. This, in turn, connects heavily to political agreements about who is able to launch and maintain objects in low-Earth-orbit and, eventually, who has the right to use other celestial bodies including the Moon, Mars, and asteroids. In

all these cases, ethics and policy experts are turning to parallel conversations on Earth for resources. The Antarctic Treaty is often viewed as a good model for what international cooperation ought to look like on the Moon given the sparsity of life and potentially high economic value of the interior of the continent (albeit with the additional recognition that the biodiversity of Antarctica is very rich in coastal regions). Recent discussions on deep sea mining are a close analog to discussions about mining of resource-rich extraterrestrial bodies including the Moon and asteroids, although here too much of these conversations center on impacts of mining on the biodiversity of deep sea ecosystems.<sup>17</sup>

The potential to make major breakthroughs in understanding the universe, inspiring future generations of scientists, and consolidating a burgeoning space economy is tremendous. But here too, some members of the public worry about wasted resources that could be better spent tackling challenges on Earth and the threat of militaries weaponizing space. For their part, scientists are rightly concerned about irrevocable contamination in space if explorers push too rapidly into new frontiers without considering the impact this might have on the ability to discover life on other celestial bodies.<sup>18</sup> What we learn in the process of developing new technologies for space exploration inevitably has consequences for life on this planet as well, and the implications of this connection are sometimes ignored or downplayed.

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<sup>14</sup> Cho, H. J., Burow, D., San Antonio, K. M., McCarthy, M. J., Herrero, H. V., Zhou, Y., ... & Jones, C. M. (2024). Satellite-Based Assessment of Rocket Launch and Coastal Change Impacts on Cape Canaveral Barrier Island, Florida, USA. *Remote Sensing*, 16(23), 4421.

<sup>15</sup> Ang, L.P., Kong, F., Hernández-Rodríguez, E., Liu, Q., Cerrejón, C., Feldman, M.J., Shu, L., Ye, L.-X., Gao, L., Ang, L.L., Yin, X., 2024. Rocket launches threaten global biodiversity conservation. *Communications Earth and Environment* 5, 799. <https://www.nature.com/articles/s43247-024-01963-x>

<sup>16</sup> Ryan, R. G., Marais, E. A., Balhatchet, C. J., & Eastham, S. D. (2022). Impact of rocket launch and space debris air pollutant emissions on stratospheric ozone and global climate. *Earth's Future*, 10(6), e2021EF002612.

<sup>17</sup> Holzheid, A., Zhao, H.B., Cabus, T., Fan, L., Kuhn, T., Sun, L.L., Tao, C.H., Haeckel, M., Hoang, D., Kelly, N., Kihara, T., Li, B., Li, J.T., Ma, J., Matz-Lück, N., Meyn, K., Molari, M., Petersen, S., Pollmann, K., Rudolph, M., Xu, X.X., Zhang, Y.J., 2024. Deep-sea mining of massive sulfides: Balancing impacts on biodiversity and ecosystem, technological challenges and law of the sea. *Marine Policy* 167. Niner, H.J., Ardron, J.A., Escobar, E.G., Gianni, M., Jaeckel, A., Jones, D.O.B., Levin, L.A., Smith, C.R., Thiele, T., Turner, P.J., Van Dover, C.L., Watling, L., Gjerde, K.M., 2018. Deep-Sea Mining With No Net Loss of Biodiversity-An Impossible Aim. *Frontiers in Marine Science* 5.

<sup>18</sup> Indeed, NASA and the National Academies of Science have already stood up a committee to examine planetary protection. <https://nap.nationalacademies.org/catalog/26714/planetary-protection-considerations-for-missions-to-solar-system-small-bodies>

## The Policy-Ethics Gap: Space-Biotech Intersection

Even where there are ethical considerations, policy frameworks, and tools available for issues arising in the areas of space and biotech individually, it is an open question whether they are adequate for addressing the issues raised at the intersection of these two domains. A common and costly mistake in emerging areas is to treat ethics solutions in other areas as off-the-shelf solutions to similar problems in new domains without adequate care to adapt them to ensure they are fit for their new purpose. While the underlying values we aim to protect and promote with policy and ethics interventions do not change, different contexts will call for different interventions. For example, standard best practices for decommissioning traditional space infrastructure might be inadequate for decommissioning space-biotech infrastructure, which will have a different risk profile than traditional infrastructure. Or, consider that the appropriate way to manage concerns and tradeoffs about genetic integrity on Earth might be very different than in an environment where baseline mutation rates are much higher. The standards for safety, security, sustainability, and other key values will be differentially implicated in the space-biotech context. These considerations raise a distinctive need for the parallel development of a specific space-biotech ethics and policy ecosystem.

So far, scientists are pursuing space-biotech as only a question of scientific capability. In taking into account public and societal considerations at the space-biotech intersection, new questions of concern emerge that go beyond considering space and biotech separately. We can roughly break these questions into near-, medium-, and long-term categories. In the near future: How do we decide who has the right to build on the few viable locations for infrastructure on the Moon, and eventually Mars? And under what principles can technology be transferred from country to country if ethical frameworks differ? If private companies are pervasive in space, how do we

sustain the financing of these endeavors in a way that respects the fundamental principle that space is for all humankind and bound by shared notions of morality? How should we handle the potential need for quarantine, both between space stations, and between planets?

In the medium-term future: How can a shared protocol be maintained off-world? What does it mean to live in a facility where the very air you breathe and food you eat is generated by a private company you work for? If a virus is introduced in one space habitat, do other actors have a responsibility of rescue? What resources must be present in space to monitor the impact and location of biotech-generated microbes? How do we preserve the scientific and natural value of other planets while also utilizing the resources they offer us?

And in the more distant future, a new set of questions emerge such as: Do we have a right to terraform or otherwise significantly alter other planets? Who gets to decide what these terraforming processes should look like? What kinds of genetic modification should we allow for people living and working in space, and should these modifications be heritable? How do we handle citizenship and rights for children conceived and born off-world? What does the governance and regulation of emerging technologies look like for an interplanetary species?

These are just a few of the key questions that require clear decision-making tools to enable policymakers to navigate through this difficult terrain. Both the space and biotech revolutions are at full-speed, coupled with simultaneous debates already taking place in policy and scientific circles—and increasingly, the public—across the world. Given these ethical gaps and policy considerations, the next section outlines recommended principles that can underpin a new roadmap for space and biotech.

# An International Space-Biotech Framework: Recommended Principles

**F**irst and foremost, we see long-term human exploration of space to be fundamentally grounded in international cooperation, as the required investment in this combined field is enormous and difficult. Moreover, the story of human space exploration, starting with the 1920s spaceflight movement and extending through to the International Space Station, has primarily been anchored in the idea that space is for all of humankind, not any single nation.<sup>19</sup> Indeed, this is codified in the Outer Space Treaty and fully integrated into the U.S.-led Artemis Accords, even while the latter provides room for private companies to operate profitably in space. Thus, our overarching recommendation for moving forward in the realm of space-biotech is to emphasize the tools and processes of international cooperation, rather than the efforts of any single nation on its own. In this respect, space diplomacy, as a rapidly emerging field that spans the public-private and formal-informal domains, is indispensable to shaping the future of long-term space travel and human presence in space.<sup>20</sup> The next step is to integrate biotech ethics and policy into these deliberations.

The **second** principle is proactive consideration of the ethical issues at stake, especially recognition of the dangers of ignoring or delaying these discussions. Important open questions include how to maximize the benefits of space biotech while minimizing the risks they pose to both space and Earth-based systems, how to predict and minimize the environmental impact of space-biotech, how to ensure the benefits of space-biotech are felt by a diverse range of communities at both the national and international levels, how biotechnologies developed for—and normalized by—space expansion will be used on Earth, and how to shape and enforce shared off-world protocols. Competition for leadership on

space regulation means that international cooperation becomes all the more important when deciding the ethical norms we want to establish for space. These norms need to be developed in conversation with a broad range of stakeholders.

The **third** principle should be to anchor deliberation in pre-existing venues and institutions. The 53 (as of February 2025) signatories of the Artemis Accords, for example, provide a strong platform to inspire fresh discussions on space-biotech. As Artemis signatories start to pin down more specific regulations in particular areas of space exploration, filling key ethical gaps will be paramount.

For example, the Council on Foreign Relations February 2025 task force report on space recommends that the U.S. convene a regular Space Summit and make space a national priority, recognized as critical infrastructure, and declared as part of the global commons.<sup>21</sup> This would marshal all existing tools, including soft power, to bring the global space community together. We argue that one of the themes of such an international Space Summit should be space-biotech, and it should include a range of actors from the private sector and space agencies, along with scientists and ethicists, among others. Both the Artemis Accords and a potential international Space Summit could serve as a fulcrum for the space and biotech communities to be brought together for fruitful deliberation.

**Fourth**, fostering the creation of transnational networks of experts who work in space-biotech-relevant areas can enable ongoing, knowledge-based deliberation that is dynamic as technologies change. These experts should be drawn from as wide a range of fields as possible including biotechnologists,

<sup>19</sup> Mai'a K. Davis Cross, "The Social Construction of the Space Race: Then & Now." 2019. *International Affairs* 95(6): 1403-1421.

<sup>20</sup> Mai'a K. Davis Cross and Saadia Pekkanen (eds), *Space Diplomacy*, *The Hague Journal of Diplomacy*, 18(2-3), 2023.

<sup>21</sup> Task Force Report, no. 82, "Securing Space: A Plan for US Action," Council on Foreign Relations, February 2025. <https://www.cfr.org/task-force-report/securing-space>

ethicists, social scientists, environmental scientists, biologists, space diplomats, and policy experts, as well as the wide range of people already working in space. Providing a platform for listening to these transnational networks, especially within Artemis Accords policy committees will be important. These expert networks can address key questions such as: What developments on Earth (climate and environmental degradation, etc.) do we want to avoid in space and what do we want to replicate (governance structures, rule of law, etc.)? What lessons can we learn from Antarctic and Arctic Treaties? Can ocean exploration analogies occurring right now, such as the Proteus underwater habitat project, help inform what should happen in outer space?<sup>22</sup> Just as in efforts to explore the deep sea, how can we minimize the negative impact of humans on other celestial bodies? How can we maximize the benefits of a growing space economy for the entirety of the human race?

Transnational networks of various sorts have long played a role in governing the global commons and establishing rules and norms that have ultimately been formally adopted by governments. In the emerging space-biotech field, they can already begin the work of crafting forward-looking vulnerability assessments and chart a path forward for the more than 90 countries today with space programs.

**Fifth**, we suggest an emphasis on continued data sharing and the free flow of information as long as there are no security risks. There is strong precedence

## Conclusion

**W**ithout a degree of thoughtfulness in considering the future trajectory of space exploration, we risk replicating in this domain some of the mistakes we have made on Earth. As the global space economy continues to expand, and space companies and agencies emerge and grow all over the world, there is an urgency to crafting sensible governance of space-biotech. Adaptable and ethical policy frameworks must come

for this, such as the 1957-58 International Geophysical Year, which included both the U.S. and Soviet Union as key participants, alongside over 60 other countries and thousands of scientists. Principles of scientific sharing and data diplomacy can shape longer-term ideas around living in space and terraforming, which will in turn, have a moderating influence through prioritizing science and safety. Some initial actions in space may become irreversible. For example, if a habitat on Mars becomes contaminated with harmful microbes it could be ruined for future scientists and explorers. The free flow of information is a good starting point and can generate agreed-upon innovations, such as the tagging of Earth-originating microbes that are brought to space by humans. Currently, some organizations, such as the Space Information Sharing and Analysis Center, work specifically with the commercial sector to encourage this.<sup>23</sup> However, it is crucial that such efforts include governments around the world.

**Sixth**, we also believe that it is important to inform the public through people-to-people interaction and public diplomacy initiatives. Biotech has public relations problems that space does not have in quite the same way. Academic and policy leaders can address both in a way that promotes understanding about the risks and opportunities. Space diplomats around the world can also play a role in informing the public of scientific advancements in real time, and engaging the public in discussions about the limits and ethical boundaries of these developments.

from the international community and encompass interdisciplinary expertise.

In preparing for a long-term human presence in space beyond low-Earth orbit, big questions about the meaning and value of life eventually come to bear and should be anticipated once a foundational roadmap is established. For example, what does life look like on Mars if a larger, diverse population is

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<sup>22</sup> <https://www.proteusoceangroup.com>

<sup>23</sup> <https://spaceisac.org>

present? If mining colonies on asteroids bring back valuable metals and minerals, how do we maximize their use on Earth for the common good of all? What form of space-based governance can embrace the different nationalities represented? The space ecosystem and the maintenance of human life in space is likely to become more complex rather than less.

In the even longer-range future, we can also imagine the significant cognitive shifts that can take place over time if humans are able to increasingly live safely in space. Even with relatively short trips to the International Space Station, astronauts report undergoing a transformative experience, the Overview Effect<sup>24</sup>—seeing planet Earth from space for the first time and realizing a common connection to all life on the planet, regardless of national boundaries. Even if future space-faring civilizations are too far away to see Earth, other cognitive shifts are possible, such as the reported Underview Effect experienced when living in the ocean—the combination of awe and anxiety that aquanauts feel

when confronted with a vast living ecosystem rarely seen.<sup>25</sup> Many generations from now, will our ethical frameworks be fit for purpose when questions emerge such as whether or not to terraform Mars or genetically engineer humans and other species to be more resilient far away from life on Earth?

In thinking ahead to these future possibilities, it is clear that now is the time to anticipate and prepare for near-future scenarios. Biotech innovation already has the capability to support long-term travel or settlement in outer space through the creation of self-sustaining, closed-loop systems, with oxygen and food production, and protection against radiation exposure, microgravity, dietary changes, and altered atmospheric gas composition, among many other dangers. While the cost of launches is decreasing dramatically and exponentially, the next major challenge is to keep astronauts safe and support security and prosperity while maintaining space as a realm of discovery for future generations.

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<sup>24</sup> Frank White, *The overview effect: Space exploration and human evolution*. AIAA, 1998.

<sup>25</sup> Kristen Kilgallen, Lily Turino, Angela Jones, Lisa Truitt, John Coley, Brian Helmuth, “The Underview Effect: Psycho-Social Impacts of Saturation Diving among Aquanauts,” under review

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