Significance of Biological Design-based Strategies Towards Sustainability and Security in Space Biology Research: A Partial Taxonomy and Exploration

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Abstract: Biological design offers a promising framework for addressing the sustainability and security challenges associated with long-duration space exploration. By drawing upon biological principles such as resource cycling, modularity, hierarchical feedback, self-repair, and adaptive response, biological design can support the development of regenerative life-support systems, resilient infrastructure, and closed-loop operational architectures beyond Earth. As biological and digital systems become increasingly integrated within future mission environments, however, new cyberbiosecurity challenges emerge at the interface between living systems, automation, artificial intelligence, and cyber-physical infrastructure. This perspective paper examines the role of biological design in advancing sustainable and secure space biology. Through an exploratory review of relevant literature and the development of a partial taxonomy of biological design domains, the paper evaluates applications including autonomous biosafety, space bioprocess engineering, in-situ biomanufacturing, biologically grown architecture, and astro-ecological systems. Particular attention is given to Digital-to-Biological Attack Vectors, defined as pathways through which compromise of digital systems may produce unintended biological consequences within mission-critical environments. The paper offers the consideration that biological design should be considered as a sustainability strategy as well as a cyberbiosecurity imperative for future deep-space missions. By integrating biological resilience with secure digital architectures, biological design can contribute to the development of adaptive, regenerative, and cyber-resilient extraterrestrial ecosystems capable of supporting long-term human presence beyond Earth.

Keywords: Biological design, Cybersecurity, Space biology, Sustainability

1. Introduction

Biological design plays a foundational role in space biology by enabling both the investigation of cellular processes in extraterrestrial environments and the development of living systems to support long-duration missions. This imperative is driven by an increasing number of calls for sustainable space exploration, rejecting the current disposable mentality which relies on expensive, non-regenerative solutions that are environmentally and economically unsustainable for deep-space endeavors (Losch et al., 2024; Zimon et al., 2024). Products and solutions in space biology research and utility significantly impact the 17 Sustainable Development Goals. Therefore, there is a need for sustainable space development to be regarded as a goal, perhaps SDG 18, which in turn impacts the other remaining SDGs (Figure 1). This paper argues that biological design provides the critical conceptual toolkit for this required architectural shift, by leveraging inherent biological attributes, such as resilience, modularity, and self-repair, to secure the vital bio-digital interfaces that govern all future deep-space critical infrastructure.

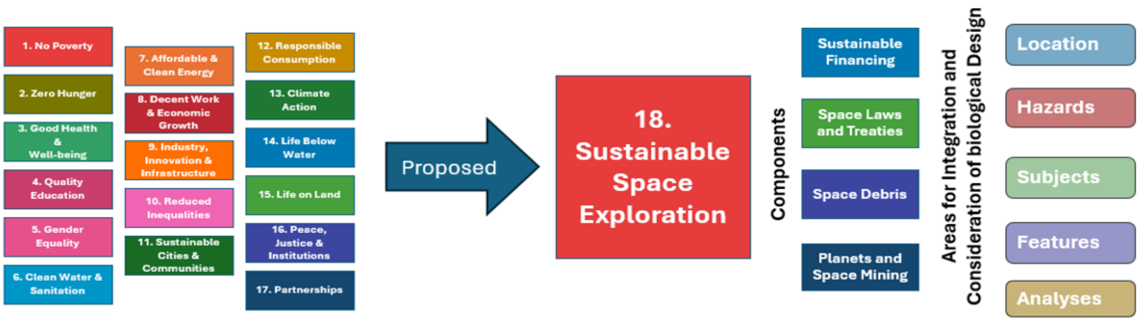

Figure 1: This figure was shown in poster form by Subramanian and Palmer at the 2025 American Society of Space and Gravitational Research Conference (Subramanian and Palmer, 2025) and illustrates the additional space-focused considerations within the proposed 18th SDG vs SDGs 1-17. It draws inspiration from figures in works by Afshinnekoo et al. (2020), Losch et al. (2024), and Zimon et al. (2024)

In this context, biological design is defined as the intersection of biomimicry and biodesign, integrating both concepts within products, architectures, and processes to support sustainability. Biomimicry solves design challenges by modeling nature's systems, forms, and functions (Verbrugghe et al., 2023), as demonstrated by optimization algorithms inspired by slime mold movement (Li et al. 2020) and ant colony navigation (Zhang et al. 2022). Biodesign, by contrast, incorporates living components directly into products (Myers 2012), including bio-concrete containing self-repairing bacteria (Seifan et al., 2016) and mycelium-based construction materials (Myers 2012). While biomimicry primarily promotes efficiency, biodesign emphasizes sustainability through regenerative materials and processes (Myers 2012).

As these technologies become autonomous components of life-support and habitation systems, they introduce cyber-physical resilience challenges through embedded digital control and monitoring. Cyberbiosecurity addresses vulnerabilities arising at the intersection of biological systems, digital technologies, and cyber-physical infrastructures (Greenbaum, 2023; Potter and Palmer, 2023). In space biology, it focuses on protecting digitally controlled biological systems supporting life support, bioprocessing, environmental monitoring, habitat maintenance, and in-situ resource utilization. In this paper, a Digital-to-Biological Attack Vector refers to any pathway through which manipulation of digital or cyber-physical systems produces unintended biological outcomes, including compromised bioprocesses, contamination events, degradation of biological materials, or broader mission-critical failures.

To explore biological design through a cyberbiosecurity framework, Section 2 presents a partial taxonomy of five domains: Autonomous Biosafety and Digital-to-Biological Attack Vectors; Space Bioprocess Engineering and Cyber-Resilient Digital Twins; On-Demand In-Situ Biomanufacturing and Responsive Diagnostics; Cyber-Physical Resilience in Biologically Grown Architecture; and Specialized Applications in Interplanetary Systems and Astro-Ecologies. This taxonomy provides a framework for identifying Digital-to-Biological Attack Vectors across each domain and links biological design to cyber defense requirements for deep-space infrastructure.

2. Potential Areas for new Biological Designs and Development

2.1 Autonomous Biosafety and the Digital-to-biological Attack Vector

As missions extend beyond low Earth orbit and into deep space, microbial contamination has emerged as a critical concern in habitat design and life-support systems. Contaminating microbes pose a dual threat: they can compromise astronaut health and degrade biologically integrated infrastructure. The management of microbial colonization must be an integral aspect of both the architecture and its maintenance systems. Addressing this concern requires the incorporation of new biological design strategies that are adaptive, self-monitoring, and capable of autonomous remediation (Dove et al, 2025). A simple and efficient way to address water contamination in hydroponic systems is to use a biological design approach where the water system itself mimics natural ecological niches, and at the same time integrates biological systems themselves into the product design. For example, using single-cell organisms such as ciliates that consume bacteria in freshwater systems (Dopheide et al., 2011). Due to the non-invasive and non-pathogenic nature of these ciliated organisms, no additional modifications need to be made to the system; regular maintenance of hydroponics, including improved filtration and UV sterilization, may be sufficient to maintain these mini-ecosystems. A growing field of micro and nanostructured surface engineering addresses several impacts on biomedical applications. The modifications performed to the surfaces of these materials are known to influence cell-material interactions (Luong-Van et al, 2013). However, an integration of principles of biological design will be required to increase the efficacy, durability, sustainability, and cost-effectiveness of the above products. For example, mimicking structures such as shark skin, cicada wings, etc., which are known to have anti-microbial properties due to their inherent design, will be crucial for product design (Jin et al., 2024). Additionally, adding a biodesign element to the product by using sustainable compounds such as chitosan that are both structurally robust and also biodegradable will be crucial to the sustainability of these surfaces. Studies are underway to program microbes to perform specific tasks, such as detecting contamination or releasing antimicrobial compounds in response to environmental triggers. For example, engineered biosensors embedded within habitat walls or air filtration matrices could be designed to fluoresce, change color, or alter conductivity in the presence of harmful microbial metabolites or biofilms. These sensors could interface with remediation strains programmed to produce biofilm-disrupting enzymes, antimicrobial peptides, or quorum-quenching molecules to inhibit microbial proliferation (Reed and Dunaway, 2019). This design strategy allows the architecture itself to become a dynamic participant in biosafety, shifting the burden of microbial control from manual to autonomous systems. However, a compromise of the digital interface governing these sensors and remediation strains could weaponize engineered organisms or disable critical remediation functions, turning a safety system into a significant vulnerability.

Microfluidics, specifically Lab-on-a-Chip (LoC) platforms, are crucial for the next phase of space exploration, which demands rapid, *in-situ* analytical measurements on other planets (Covone et al., 2021). Traditional analytical chemistry methods are ill-suited for remote space applications due to their requirement for advanced machinery, sterile conditions, and large sample volumes. LoC biosensors, offering miniaturization, a low chemical footprint, high sensitivity, and low payload requirements, are ideal for space biology (Cinti et al., 2023). A sustainable biological design strategy involves using microorganisms, such as the single-cell eukaryote *Tetrahymena*, as biological microbots for LoC systems. The well-studied chemotaxis, galvanotaxis, and artificial magnetotaxis in *Tetrahymena* can be leveraged under varying gravity conditions to gather complex information from Lunar and Mars samples using minimal fluid volumes (Kim et al., 2009, Kim et al., 2010; Kim et al., 2012; Hellung-Larsen et al., 1990). Furthermore, by feeding *Tetrahymena* ferromagnetic nanoparticles, these biological microbots can be used in artificial magnetotaxis experiments to establish ciliated cell substrates in fluid channels, potentially assisting microfluidic flow in LoCs by mimicking fluid movement in human tissue via ciliary wave motion. Hypothethically, as these biological microbots or analogues become integrated with autonomous sensing and analytical platforms, manipulation of sensor inputs, control algorithms, or communication pathways could alter sampling behavior and analytical outputs, creating additional Digital-to-Biological Attack Vectors within future space-based diagnostic systems.

2.2 Space Bioprocess Engineering (SBE) and Cyber-resilient Digital Twins

A burgeoning sub-field of space biology is the interdisciplinary area of design known as space bioprocess engineering (SBE). The goal of SBE is to develop and integrate biological systems that support the nutritional, medical, and environmental needs of astronauts during interplanetary missions and long-term habitation (Berliner et al., 2024). This includes not only producing oxygen and food but also fabricating pharmaceuticals, recycling waste, and maintaining air and water quality using biological processes. In this context, biological design becomes foundational; its principles enable the construction of systems that are not only functional but regenerative, self-maintaining, and adaptable to changing mission conditions. Rather than viewing biological components as isolated tools, SBE treats them as integrated modules that work in concert to reduce reliance on Earth-based resupply and enhance mission autonomy.

Biological design, as applied in SBE, draws on evolutionary strategies such as modularity, hierarchical feedback, and resilience to develop systems that can self-repair, grow in situ, and respond dynamically to environmental stressors. For instance, engineered microbial consortia may be programmed to switch metabolic pathways in response to carbon dioxide concentrations or radiation levels, supporting both air recycling and real-time diagnostics (Menezes et al., 2015). Similarly, growable biostructures such as fungal mycelium for habitat insulation offer low-mass, high-efficiency solutions for construction in off-Earth environments (Jones et al., 2017). The integration of biodesign with automation, synthetic biology, and material science in SBE ensures that bioprocessing platforms are not only robust and scalable but also capable of contributing to closed-loop life-support systems. As missions push beyond low Earth orbit, the relevance of SBE continues to grow, embodying a shift from passive environmental control to proactive, biologically driven adaptation. Securing the digital control systems governing these elements of modularity, hierarchical feedback, and self-repair is paramount to prevent catastrophic system failures that could arise from malicious interference.

Digital twins of complex biological systems can initialized with initial parameters and continuously updated with real-time sensor data, enabling predictive maintenance and autonomous control in simulated space missions (Homaei et al., 2024; Abraham et al., 2025). These sophisticated models can integrate sub-modules for factors like zero-G fluid dynamics and radiation-damage, allowing for the refinement of repair-pathway predictions and shielding designs. Furthermore, the use of closed-loop machine-learning controllers and advanced analytical sensors allows for dynamic adjustment of life support systems, while generative algorithms facilitate *in silico* evolution for trait optimization. These digital twins can be indispensible for cyberbiosecurity defense, enabling continuous, dual-domain anomaly detection by comparing real-time biological and cyber-physical signals against expected models, thereby flagging both compromised software and emergent bioprocess failures.

2.3 On-Demand In-situ Biomanufacturing and Responsive Diagnostics

Advances in synthetic biology, as described earlier, will be imperative to manufacturing fuels, self-repairing polymers, metabolizing products, and even generating energy and light. An integrated loop system, for example, exemplifies efficiency that can be achieved through combining biological factories with the precision of synthetic chemistry. Wallace and Balskus (2015) demonstrated that through pairing styrene-producing *E. coli* with designer micelles, complex chemical reactions can occur in a safe, water-based environment, eliminating the need for toxic solvents. This 'green' approach minimizes the hardware footprint while enabling the on-demand synthesis of high-value materials from fuels to self- repairing polymers. This work has since been built upon by numerous teams for other products. These can promote the creation of valuable components in a sustainable way for long-duration space habitation.

Engineered organisms and biomaterials can be integrated into spacecraft interiors or environmental control systems to detect and respond to threats such as toxic gas buildup, microbial contamination, or equipment failure. For instance, synthetic gene circuits can be encoded into bacteria to fluoresce in the presence of specific contaminants or radiation levels, offering real-time bio-indicators for system health (Llorente et al, 2022; Koehle et al., 2023). By functioning as intelligent, living diagnostics, these responsive materials can enhance autonomy and reduce the operational burden on human crews. Their skillful, integration supports proactive risk management, particularly during missions operating in communication-limited environments. However, because these manufacturing and diagnostic systems rely on digitally controlled biological processes, they can be inherently exposed to Digital-to-Biological Attack Vectors. Compromise of sensor networks, control software, or genetic programming may suppress warning signals, manipulate outputs, or generate unintended biological outcomes within autonomous mission environments.

2.4 Cyber-Physical Resilience in Biologically-grown Architecture

Beyond low Earth orbit, biologically grown architecture offers a promising strategy for reducing launch mass while enabling adaptive, self-repairing infrastructure. Mycelium-based composites, algae-derived materials, and engineered living systems can support long-duration habitation through autonomous growth, repair, and environmental adaptation (Myers, 2012; Jones et al., 2017; Brandić Lipińska et al., 2022; Mitchell et al., 2025). In parallel, digital twin technologies and closed-loop biosensing systems increasingly used in terrestrial biomedical and industrial environments can be adapted for space habitats. These digital counterparts of biological systems enable real-time monitoring of growth rates, structural integrity, and biosafety conditions. Applied to space architecture, they could facilitate autonomous detection of stress fractures, environmental degradation, and biological contamination while supporting the targeted deployment of structural reinforcements and remediation measures. The integration of predictive modeling, artificial intelligence, adaptive biomaterials, and cyberbiosecurity-by-design principles can represent a significant advancement in the development of resilient infrastructure (Potter, Mossberg and Palmer, 2023; DiEuliis, Imperiale and Berger, 2024; Dove et al., 2025). By combining continuous monitoring with autonomous response capabilities, such systems can improve operational reliability while reducing dependence on human intervention in communication-limited environments.

By embedding adaptability, autonomy, and self-repair into structural materials, biological design strategies offer a transformative approach to off-Earth habitation. These approaches not only address the practical requirements of space biology but also extend the frontier of architecture toward systems that are responsive, regenerative, and inherently alive. Such concepts reflect an emerging vision of “living structures” capable of maintaining their own bio-integrity through continuous interaction between biological processes and digital control systems. Beyond operational functions, biophilic and bio-integrated habitats may also improve astronaut psychological well-being and cognitive performance during prolonged missions, particularly under conditions of isolation and confinement (Firth, 2022). Feedback derived from microbial colonization and environmental monitoring can reveal vulnerabilities in surface geometry, material porosity, and airflow patterns, informing iterative design improvements in habitats intended to grow, self-assemble, or adapt to extraterrestrial conditions.

However, the reliance on digital feedback introduces a critical cyber-physical vulnerability. Corrupted sensor data or compromised control systems could undermine autonomous resilience by providing inaccurate information regarding a habitat’s structural or biological condition. On Earth, contamination control in biomanufacturing environments often depends on resource-intensive sterilization protocols; in space, such approaches must evolve into lightweight, decentralized, and autonomous systems. Consequently, future biological designs may incorporate genetic sensors, self-healing biofilms, and cyber-physical interfaces capable of detecting and mitigating contamination in real time. In this context, microbial contamination management becomes a core design function within regenerative and responsive habitats (Greenbaum, 2023).

2.5 Specialized Applications: Interplanetary Systems and Astro-ecologies

Biodesign-based strategies for in-situ product synthesis include integrating products into spacewear, such as the 'Wanderers' collection by Oxman's research group, designed for astrobiological exploration. A key example is *Living Mushtari*, a 3D-printed wearable embedded with synthetic microorganisms to enhance biological function and generate energy from sunlight (Mediated Matter Group, 2017). This biodesign utilizes a symbiotic association where photosynthetic cyanobacteria convert sunlight into sucrose, which then fuels other microorganisms (like *E-coli* or yeast) to produce pigments, drugs, food, fuels, or scents. The design's biomimetic aspect is a 3D-printed structure resembling the human intestine (58 meters of channels) that facilitates cyanobacteria flow via peristaltic-like movement. Transparent sections ensure sunlight access for the microorganisms. Other 'Wanderers' products share a similar goal: to interact with the destination environment to produce biomass, water, air, light, energy, bio-mineralized human bone, or fluorescence. Research, notably from Dr. Neri Oxman's former MIT Media Lab group, has explored biological design for space applications. The "Maiden Flight" project is a key example, sending queen and nurse bees within a metabolic support capsule aboard Blue Origin's New Shepard (Mediated Matter Group, 2021). This capsule, a 'synthetic astro-ecology,' combined human-made components with natural honeycomb-like structures built by the bees, offering a familiar, sustainable, and evolving environment. This biomimetic and biodesign approach is crucial for understanding crop pollination beyond Earth by addressing questions like the viability of reproduction and subsequent function upon Earth reintroduction (Strom, 2019). Integrating biological systems with wearables, autonomous habitats, and astro-ecologies requires complex interactions between living organisms and digital platforms. These bio-digital interfaces introduce Digital-to-Biological Attack Vectors through which compromised software or sensor systems may disrupt biological performance, ecological stability, and mission outcomes. Consequently, cyberbiosecurity is helpful as a foundational element in the design of future astro-ecological systems.

3. Discussion on Challenges in Sustainable Interplanetary Exploration

The integration of biological design principles offers a path for tackling the entrenched, systemic challenges of interplanetary endeavors. Beyond the immediate technical hurdles, missions face critical policy, economic, and ethical dilemmas, all of which are encapsulated by issues of long-term sustainability and planetary security that biological systems have navigated quite well over the course of evolution. Closed-loop material cycles, decentralized decision-making, and emergent robustness are all hallmarks of design and function found in biology that stakeholders can use to fundamentally shift away from an extractive, terrestrial-dependent model. The bio-inspired approaches mentioned as used towards modeling mission architectures on principles of biological resilience directly address the financial viability through resource circularity (e.g., in-situ resource utilization and waste recycling), strengthen legal and governance regimes by embedding self-repair and adaptability into protocols, and critically enhance planetary protection measures by fostering ecosystemic responsibility and minimizing biological contamination risks through contained, balanced systems. Dedicated and substantial funding for research into interplanetary sustainability and mission architectures is paramount. Nations that prioritize and achieve breakthroughs in these areas can gain a profound strategic, economic, and geopolitical advantage. This leadership will not only define the future of space exploration but also foster domestic technological innovation with broad applications, as they connect to many bio-adjacent industries with deep skill sets that have been left out of recent space-related economic growth initiatives. Blending expertise here provides the potential to position shrewdly led nations to the forefront of the next era of human endeavor.

4. Conclusion

Biological design offers a transformative framework for sustainable and secure space exploration by aligning mission systems with the adaptive logic of life itself. This paper's core contribution is the establishment of a partial taxonomy across five critical domains, systematically linking the promise of biological design directly to the necessity of cyber defense in deep-space critical infrastructure. The reliance on evolutionary strategies such as modularity, resource recycling, and self-repair must be coupled with robust cyberbiosecurity protocols to ensure resilient infrastructure. We illuminated how bio-integrated systems like Space Bioprocess Engineering and Biologically-Grown Architecture introduce critical Digital-to-Biological Attack Vectors that must be secured against malicious interference. Beyond technical security, this biologically driven approach offers models for tackling systemic policy, economic, and ethical challenges in interplanetary endeavors, promoting resource circularity and critically enhancing planetary protection measures. Ultimately, this requires a fundamental shift in human systems thinking from previous versions of seeking total environmental control to designing in harmony with ecological processes. Astronauts and mission specialists must be trained to steward these living systems and recognize emergent failure modes. By fusing imagination with ecological intelligence and embedding biological design into the fabric of future missions, humanity can build resilient, regenerative, and resource-aware extraterrestrial ecosystems, positioning ourselves as explorers of space, and more importantly, co-evolving participants in its living potential.

Ethical Approval: This study does not use human subjects. Therefore, ethical approval is not applicable.

AI Statement: This paper utilized tools within Google Docs, ChatGPT, and Grammarly for grammar checks & organization of pre-written text.

References

Abraham, D., Erceylan, G., Gkioulos, V. and Houmb, S.H. (2025) 'Towards enhanced cybersecurity in industrial control systems: a systematic review of context-based modeling, digital twins, and machine learning approaches', International Journal of Information Security, 24, 243. Available at: https://doi.org/10.1007/s10207-025-01158-1

Afshinnekoo, E. et al. (2020) 'Fundamental biological features of spaceflight: advancing the field to enable deep-space exploration', Cell, 183(5), pp. 1162–1184. Available at: https://doi.org/10.1016/j.cell.2020.10.050

Berliner, A.J., Zezulka, S., Hutchinson, G.A., Bertoldo, S., Cockell, C.S. and Arkin, A.P. (2024) 'Domains of life sciences in spacefaring: what, where, and how to get involved', npj Micrograviy, 10(1), 12. Available at: https://doi.org/10.1038/s41526-024-00354-y

Brandić Lipińska, M., Maurer, C., Cadogan, D., Head, J., Dade-Robertson, M., Paulino-Lima, I. G., Liu, C., Morrow, R., Senesky, D. G., Theodoridou, M., Rheinstädter, M. C., Zhang, M. and Rothschild, L. J. (2022). Biological growth as an alternative approach to on and off-Earth construction. *Frontiers in Built Environment*, *8*, p. 965145. Available at: https://doi.org/10.3389/fbuil.2022.965145

Cinti, S., Singh, S., Covone, G., Tonietti, L., Ricciardelli, A., Cordone, A., Iacono, R., Mazzoli, A., Moracci, M., Rotundi, A. and Giovannelli, D. (2023). Reviewing the state of biosensors and lab-on-a-chip technologies: Opportunities for extreme environments and space exploration. *Frontiers in Microbiology*, *14*, 1215529. Available at: https://doi.org/10.3389/fmicb.2023.1215529

Covone, G., Ienco, R.M., Cacciapuoti, L. and Inno, L. (2021) 'Efficiency of the oxygenic photosynthesis on Earth-like planets in the habitable zone', Monthly Notices of the Royal Astronomical Society, 505(3), pp. 3329–3335. Available at: https://doi.org/10.1093/mnras/stab1357

DiEuliis, D., Imperiale, M.J. and Berger, K.M. (2024) 'Biosecurity assessments for emerging transdisciplinary biotechnologies: Revisiting biodefense in an age of synthetic biology', Applied Biosafety, 29(3), pp. 123–132. Available at: https://doi.org/10.1089/apb.2024.0005

Dopheide, A., Lear, G., Stott, R. and Lewis, G. (2011). Preferential Feeding by the Ciliates Chilodonella and Tetrahymena spp. and Effects of These Protozoa on Bacterial Biofilm Structure and Composition. *Applied and Environmental Microbiology*, *77*(13), 4564–4572. https://doi.org/10.1128/AEM.02421-10

Dove, D., Chamberland, K., Karathanasis, S.F., Potter, L. and Palmer, X.-L. (2025) 'Integrating ethical, legal, and technological safeguards in space-focused cyberbiosecurity: AI, cloud, and crew considerations', in Proceedings of the 6th International Conference on AI Research (ICAIR 2025). Reading: Academic Conferences International, pp. 687–695. Available at: https://doi.org/10.34190/icair.5.1.4391

Firth, A. (2022). *Biophilic Interventions in Crew Quarters for Deep Space Transit Habitats to Improve Cognitive and Physiological Health Measures*. Master's thesis, Oklahoma State University.

Greenbaum, D. (ed.) (2023) *Cyberbiosecurity: A New Field to Deal with Emerging Threats.* Cham: Springer Nature. Available at: https://link.springer.com/book/10.1007/978-3-031-26034-6

Hellung-Larsen, P., Leick, V., Tommerup, N. and Kronborg, D. (1990). Chemotaxis in Tetrahymena. *European Journal of Protistology*, *25*(3), 229–233. https://doi.org/10.1016/S0932-4739(11)80174-4

Homaei, M., Mogollón-Gutiérrez, Ó., Sancho, J.C., Ávila, M. and Caro, A. (2024) 'A review of digital twins and their application in cybersecurity based on artificial intelligence', Artificial Intelligence Review, 57, 201. Available at: https://doi.org/10.1007/s10462-024-10805-3

Jin, E., Lv, Z., Zhu, Y., Zhang, H. and Li, H. (2024) 'Nature-Inspired Micro/Nano-Structured Antibacterial Surfaces', Molecules, 29(9), 1906. Available at: https://doi.org/10.3390/molecules29091906

Jones, M., Huynh, T., Dekiwadia, C., Daver, F. and John, S. (2017) 'Mycelium composites: a review of engineering characteristics and growth kinetics', Journal of Bionanoscience, 11(4), pp. 241–257. Available at: https://www.researchgate.net/publication/318942381_Mycelium_Composites_A_Review_of_Engineering_Characteristics_and_Growth_Kinetics

Koehle, A. P., Brumwell, S. L., Seto, E. P., Lynch, A. M. and Urbaniak, C. (2023). Microbial applications for sustainable space exploration beyond low Earth orbit. *npj Microgravity*, *9*(1), 47. https://doi.org/10.1038/s41526-023-00285-0

Kim, D., Brigandi, S., Kim, P. and Kim, M. (2012) 'Control of Tetrahymena pyriformis as a microrobot', in Kim, M.J. and Abbott, J.J. (eds.) Microbiorobotics. Oxford: Elsevier, pp. 277–287. Available at: https://doi.org/10.1016/B978-1-4557-7891-1.00011-6

Kim, D.H., Casale, D., Kőhidai, L. and Kim, M.J. (2009) 'Galvanotactic and phototactic control of Tetrahymena pyriformis as a microfluidic workhorse', Applied Physics Letters, 94(16), 163901. Available at: https://doi.org/10.1063/1.3123254

Kim, D.H., Cheang, U.K., Kőhidai, L., Byun, D. and Kim, M.J. (2010) 'Artificial magnetotactic motion control of Tetrahymena pyriformis using ferromagnetic nanoparticles: a tool for fabrication of microbiorobots', Applied Physics Letters, 97(17), 173702. Available at: https://doi.org/10.1063/1.3497275

Li, S., Chen, H., Wang, M., Heidari, A.A. and Mirjalili, S. (2020) 'Slime mould algorithm: a new method for stochastic optimization', Future Generation Computer Systems, 111, pp. 300–323. Available at: https://doi.org/10.1016/j.future.2020.03.055

Llorente, B., Williams, T.C., Goold, H.D., Pretorius, I.S. and Paulsen, I.T. (2022) 'Harnessing bioengineered microbes as a versatile platform for space nutrition', Nature Communications, 13(1), 6177. Available at: https://doi.org/10.1038/s41467-022-33974-7

Losch, A., Galli, A. and Schildknecht, T. (2024) 'History, concepts and challenges of proposing an 18th UN Sustainable Development Goal related to Space', Space Policy, 68, 101631. Available at: https://doi.org/10.1016/j.spacepol.2024.101631

Luong-Van, E., Rodriguez, I., Low, H.Y. et al. Review: Micro- and nanostructured surface engineering for biomedical applications. Journal of Materials Research 28, 165–174 (2013). Available at: https://doi.org/10.1557/jmr.2012.398

Menezes, A. A., Cumbers, J., Hogan, J. A. and Arkin, A. P. (2015). Towards synthetic biological approaches to resource utilization on space missions. *Journal of the Royal Society Interface*, *12*(102), 20140715. Available at: https://doi.org/10.1098/rsif.2014.0715

Mediated Matter Group (2017) Living Mushtari. MIT Media Lab. Available at: https://www.media.mit.edu/projects/living-mushtari/overview/

Mediated Matter Group (2021) Maiden Flight. MIT Media Lab. Available at: https://www.media.mit.edu/projects/maiden-flight/overview/

Mitchell, A., Potter, L., Palmer, X.L. and Barnett, M. (2025) 'Exploring the Intersection of Cybersecurity, Neurocapitalism, and Biodesign', in Proceedings of the 19th International Conference on Cyber Warfare and Security. Reading: Academic Conferences International, pp. 273–283. Available at: https://doi.org/10.34190/iccws.20.1.3444

Myers, W. (2012) Bio Design: Nature, Science, Creativity. New York: Museum of Modern Art.

Potter, L., Mossberg, K. and Palmer, X.-L. (2023) 'A reflection of typology and verification flaws in consideration of biocybersecurity/cyberbiosecurity: Just another gap in the wall', in Andreatos, A. and Douligeris, C. (eds.) Proceedings of the 22nd European Conference on Cyber Warfare and Security. Reading: Academic Conferences International, pp. 358–365. Available at: https://doi.org/10.34190/eccws.22.1.1271

Potter, L. and Palmer, X.L. (2023) 'Mission-aware differences in cyberbiosecurity and biocybersecurity policies: prevention, detection, and elimination', in Greenbaum, D. (ed.) Cyberbiosecurity: A New Field to Deal with Emerging Threats. Cham: Springer Nature, pp. 37–69. Available at: https://doi.org/10.1007/978-3-031-26034-6_4

Reed, J.C. and Dunaway, N. (2019) 'Cyberbiosecurity Implications for the Laboratory of the Future', Frontiers in Bioengineering and Biotechnology, 7, 182. Available at: https://doi.org/10.3389/fbioe.2019.00182

Seifan, M., Samani, A. K. and Berenjian, A. (2016). Bioconcrete: Next Generation of Self-Healing Concrete. *Applied Microbiology and Biotechnology*, *100*(6), 2591–2602. https://doi.org/10.1007/s00253-016-7316-z

Strom, S. (2019). Six Suborbital Research Payloads from MIT Fly to Space and Back. *MIT News | Massachusetts Institute of Technology*. Available at: http://news.mit.edu/2019/space-and-back-six-suborbital-research-payloads-mit-media-lab-0503 (Accessed: 29 May 2026).

Subramanian, A. and Palmer, X. (2025) 'Biological design-based strategies towards sustainability and security in space biology research'. Poster presented at the American Society for Space and Gravitational Research Annual Meeting, Phoenix, Arizona, USA, December 3-6.

Verbrugghe, N., Rubinacci, E. and Khan, A. Z. (2023). Biomimicry in Architecture: A Review of Definitions, Case Studies, and Design Methods. *Biomimetics*, *8*(1), 107. https://doi.org/10.3390/biomimetics8010107

Wallace, S. and Balskus, E.P. (2015) 'Interfacing microbial styrene production with a biocompatible cyclopropanation reaction', Angewandte Chemie International Edition, 54(24), pp. 7106–7109. Available at: https://doi.org/10.1002/anie.201502185

Zhang, C., Zhang, D., Zhang, M., Zhang, J. and Mao, W. (2022) 'A three-dimensional ant colony algorithm for multi-objective ice routing of a ship in the Arctic area', Ocean Engineering, 266, 113241. Available at: https://doi.org/10.1016/j.oceaneng.2022.113241

Zimon, D., Lysenko-Ryba, K. and Szocik, K. (2024) 'SDG 18 for sustainable space exploration', European Journal of Futures Research, 12, 22. Available at: https://doi.org/10.1186/s40309-024-00243-3