SPACE BIOMANUFACTURING: INTERSECTION OF SPACE RESOURCE UTILIZATION AND TERRESTRIAL INNOVATION. D. Northroup-Kuder[1], L.E. Fackrell[1], H.J. Mills[1], and O. Gamez Holzhaus[1], [1]Rhodium Scientific, Houston, Texas USA (daven@rhodiumscientific.com)

Introduction: As space exploration extends beyond low Earth orbit (LEO), leveraging space resources will be critical to developing sustainable mission architectures and infrastructure. This applies not only to in-situ re-source utilization (ISRU) but also to potential terrestrial applications of space-derived innovations. Biology plays an indispensable role in long-duration space missions, intersecting with resource extraction, utilization, manufacturing, and infrastructure development. This work explores the advances in space biomanufacturing and its pivotal role in supporting space resource utilization and mission sustainability [1,2].

The Role of Biomanufacturing in Space Exploration: As missions travel farther from Earth, reliance on terrestrial resupply becomes increasingly impractical due to logistical and economic constraints. To address this challenge, NASA is prioritizing in-situ resource production, with biomanufacturing emerging as a key technology due to its versatility and resilience [3]. On Earth, biomanufacturing is widely used to produce food, pharmaceuticals, industrial chemicals, and construction materials [4]. In space, it can serve additional critical functions, such as enhancing life support systems by capturing carbon, generating oxygen, purifying water, and providing radiation shielding [5].

NASA's Artemis initiative, while still dependent on Earth-based resupply, will require in-situ production of essential resources such as food and fuel in early-stage habitats. Biomanufacturing systems provide a robust, adaptable solution for meeting these needs and will become increasingly essential for long-term human presence in space [1].

Beyond supporting space habitation, space biomanufacturing offers transformative terrestrial applications, particularly in pharmaceuticals and regenerative medicine. The unique stressors of microgravity have been shown to enhance bioproduction rates, accelerate cell growth, and induce the formation of novel secondary metabolites [6]. Space-based research has already led to the discovery of anti-cancer compounds and advancements in stem cell therapies and synthetic tissue production [7]. Given the rising importance of biologic medicines, access to space environments could drive breakthroughs in drug development and therapeutic innovation [8].

Rhodium Scientific's Biomanufacturing Program: Rhodium Scientific is the industry leader for space biomanufacturing, testing production systems across all phases of spaceflight—during launch, in microgravity, and upon return to Earth. These systems are subjected to unique stressors, including radiation exposure, altered gravity conditions, cold chain logistics, and biological preservation challenges. Previous research has demonstrated that microgravity imposes selective pressures on microbes, leading to both genotypic and phenotypic adaptations [1,6]. Recent findings from Rhodium's Biomanufacturing Program indicate that space-induced genetic mutations can enhance microbial growth rates, increase cell densities, and improve production yields [5]. Moreover, these adaptive advantages persist after the microbes return to Earth, suggesting potential applications for optimizing terrestrial biomanufacturing [7].

Transcriptomic analyses of microbes exposed to space conditions have revealed previously uncharacterized cellular adaptations that could enhance biomanufacturing efficiency. However, standardization of methodologies is needed to ensure reproducibility and scalability of these biological processes for industrial applications [3]. The overarching goal of the Rhodium Biomanufacturing Program is to establish reliable and reproducible bioproduction platforms for manufacturing critical chemical products in space while simultaneously improving terrestrial production processes.

Rhodium's central hypothesis is that genetic and transcriptomic data obtained from space-adapted biological systems can guide the development of more efficient biomanufacturing processes. These insights have broad implications, including potential applications for the Department of Defense and biotech industries seeking to enhance production efficiencies for strategic and economically valuable products [10]. Additionally, Rhodium's Quality, Industry-Compatible Space Process™ (QuIC Space Process™) provides the necessary quality assurance and logistical framework to ensure the reproducibility and reliability required for the commercialization of space-based biomanufacturing [8].

Challenges and Future Directions: Despite its promise, space biomanufacturing remains an emerging field with numerous challenges. Rhodium Scientific is actively developing streamlined methods for characterizing how different organisms and bioproduction systems adapt to microgravity, lunar gravity, and Martian gravity. However, significant hurdles remain, particularly in demonstrating scalability and transitioning

from laboratory-scale experiments to operational production systems [2,3].

One of the primary constraints is the logistical difficulty of accessing space. However, through multiple ISS missions in collaboration with Rhodium, advances have been made in optimizing biomanufacturing pipelines, such as eliminating the need for cold-chain logistics [5]. The next phase of research will focus on scaling up production volumes, characterizing diverse biomanufacturing systems in microgravity, and optimizing biological transport logistics for space deployment [1,6].

Conclusion: Biomanufacturing is poised to become a cornerstone of sustainable space exploration, enabling long-term human habitation by reducing dependence on terrestrial resources. As research advances, these technologies will not only revolutionize space resource utilization but also drive transformative innovations in medicine, materials science, and industrial biomanufacturing on Earth. By integrating cutting-edge biological and chemical engineering approaches, Rhodium Scientific is laying the groundwork for a new era of space-based bioproduction, unlocking unprecedented opportunities for both space exploration and terrestrial applications [7,8].

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