

Molecular Pharming to Support Human Life on the Moon, Mars, and Beyond

Matthew J. McNulty^{1,2}, Yongao (Mary) Xiong^{1,2,#} and Kevin Yates^{1,2,#}, Kalimuthu Karuppanan^{1,3}, Jacob M. Hilzinger^{1,4}, Aaron J. Berliner^{1,4}, Jesse Delzio^{1,2}, Adam P. Arkin^{1,4}, Nancy E. Lane⁵, Somen Nandi^{1,2,6}, and Karen A. McDonald^{1,2,6,*}

¹Center for the Utilization of Biological Engineering in Space (CUBES), Berkeley, CA, USA, <https://cubes.space/>

²Department of Chemical Engineering, University of California, Davis, CA, USA

³Radcliffe Department of Medicine, Oxford University, Oxford, UK

⁴Department of Bioengineering, University of California, Berkeley, CA, USA

⁵Center for Musculoskeletal Health, School of Medicine, University of California, Davis, CA, USA

⁶Global HealthShare® Initiative, University of California, Davis, CA, USA

#These authors contributed equally for this manuscript

* Corresponding author: kamcdonald@ucdavis.edu, (707) 548-8314

Abstract

Space missions have always assumed that the risk of spacecraft malfunction far outweighs the risk of human system failure. This assumption breaks down for longer duration exploration missions and exposes vulnerabilities in space medical system. Space agencies can no longer buy down the majority of human system risk through the crew member selection process and emergency re-supply or evacuation. No mature medical solutions exist to close the risk gap. With recent advances in biotechnology, there is promise in augmenting a space pharmacy with a biologically-based space foundry for on-demand manufacturing of high-value medical products. Here we review the challenges and opportunities of molecular pharming, the production of pharmaceuticals in plants, as the basis of a space medical foundry to close the risk gap in current space medical systems. Plants have long been considered an important life support object in space and can now also be viewed as programmable factories in space. Advances in molecular pharming-based space foundries will have widespread application in promoting simple and accessible pharmaceutical manufacturing on Earth.

Keywords: life support for space, plant molecular pharming

1. Re-Thinking Human Health for Deep Space Missions

Humanity has collectively returned its gaze to the stars as space agencies and companies around the world work to develop new strategies to extend human presence farther into the universe. To get there, we need to transition from Earth-reliant to Earth-independent mission architecture. Agencies like the National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) have developed exceptional life support systems for Earth-reliant human missions into space¹. Carefully planned medicine, food, and environmental control re-supply shuttles working in concert with on-board environmental control and life support systems maintain a habitable environment for astronauts in the International Space Station (ISS)².

But as space missions get longer and probe deeper into the solar system – to the Moon, to Mars, and beyond – frequent re-supplies for life support systems will become increasingly burdensome. Current exploration medical capabilities are particularly vulnerable to this paradigm shift. The list of necessary supplies to address persistent exposures of space travel adds up quickly: including countermeasures for increased radiation^{3,4}, bone loss^{5,6}, kidney stones^{7,8}, vision impairment⁹, and adverse behavioral conditions¹⁰ to name a few. The list of supplies begins to look unmanageable when you add in intermittent, or even unanticipated, exposures such as microbial infection^{11–13}, and implications of spaceflight-induced genome instability and metabolic changes¹⁴. As mission duration increases, the risk of a low probability medical condition is amplified; when an astronaut is on Mars and the closest hospital or medical re-supply is at least 200 days of interplanetary travel away¹⁵, it is critical that astronauts are prepared for self-sufficiency.

Furthermore, recent literature highlights systemic vulnerabilities in space-flown pharmaceutical life support in the biased and underreported historical data of in-flight pharmaceutical use and efficacy, limited fidelity of current ground-analog models, and in-flight instability of drug formulations¹⁶. Of the small molecule solid formulations tested thus far, three-quarters will have degraded by the end of the proposed first Mars mission duration¹⁵. There has been no spaceflight testing of biologics, a critical category of pharmaceuticals known to be less stable than small molecule drugs^{17,18}.

2. Defining a Medical Foundry for Space Exploration

The medical systems of future space exploration will need to be reconfigured to guarantee astronaut health. The contemporary standard is the NASA-provided ISS crew health care system (CHeCS) consisting of three sub-systems: 1) the countermeasures system (CMS) composed of exercise hardware and monitoring devices, 2) the environmental health system (EHS) composed of hardware for environmental monitoring, and 3) the health maintenance system (HMS) composed of a medical kit for supporting routine minor medical needs for up to 180 days¹⁹. Earth-reliant medical systems like CHeCS will need to be augmented with medical foundries for self-sufficiency in Earth-independent space mission architectures. A space medical foundry will expand mission capabilities to include high-value medical product manufacturing, of which pharmaceuticals will be a critical product class. This is particularly important for extended duration exploration, and settlement, of extraterrestrial bodies such as the Moon and Mars.

A space foundry, of which a medical foundry is a subset, must be capable of utilizing a limited set of inputs (ideally *in situ* resources with minimal flown resources) to generate a wide spectrum of outputs and must be able to do so in a simple, closed loop. Recent literature have detailed a

compelling narrative for the use of biotechnology to answer these challenges^{15,20,21}. The Center for Utilization of Biological Engineering in Space (<https://cubes.space>) is a multi-university effort to realize the inherent mass, power, and volume advantages of space biotechnology and advance the practicality of a nearly closed loop, photoautotrophic factory for production of food, pharmaceuticals, and materials on a Mars mission.

An alternative method for pharmaceutical production is chemical synthesis. In producing small molecule pharmaceuticals, chemical synthesis is often advantageous on Earth. However, as stereochemical complexity and size of the target pharmaceutical increases, chemical synthesis often becomes dramatically less feasible and attractive. For perspective, there are examples of chemical synthesis used commercially to produce pharmaceuticals as large as peptides (5-50 amino acids)^{22,23}, but antibodies, an example class of life-saving pharmaceuticals produced only in biological systems (termed “biologics”), are two orders of magnitude larger (~1,400 amino acids) than that. Chemical synthesis of pharmaceuticals can also be contrasted with biological production as having highly reaction-specific inputs and complex synthesis steps, often requiring use of organic solvents and generating substantial waste by-products, all of which are undesirable attributes for space applications. Chemical synthesis may be necessary for a robust medical foundry for space, indeed it will likely be required to synthesize nucleic acids to mobilize biological production in space²⁴, but it will not be sufficient.

Space biotechnology has primarily focused on microbes^{15,20}, fungi²⁵, and plants^{20,26}. From this perspective, we review the promise in expanding the utility of plants as a molecular medical foundry for production of pharmaceuticals in deep space and contrast this with the capabilities of alternative biological organisms.

3. Plants in Space

Plants are an established facet of space mission architecture, with research dating back to the 1950s²⁷. Most recently, a study on red romaine lettuce grown in the International Space Station (ISS) using the Vegetable Production System (Veggie) has reported that leafy vegetable crops can be grown and consumed safely in the ISS as a dietary supplement²⁸.

Resource flexibility is essential in the confined environments of a space mission, and researchers have shown that plants serve as versatile assets in a space mission life support system. Up to this point, studies have focused on the value of plants to harness solar energy and provide nutrients, water treatment, air treatment, and behavioral health^{27–31}. Accordingly, research into advancing the capabilities of plants for space has primarily focused on those key areas. What has not been captured in published research is the potential of plants to provide astronauts with pharmaceuticals and other high value products, which is formally known as molecular pharming (Figure 1)³².

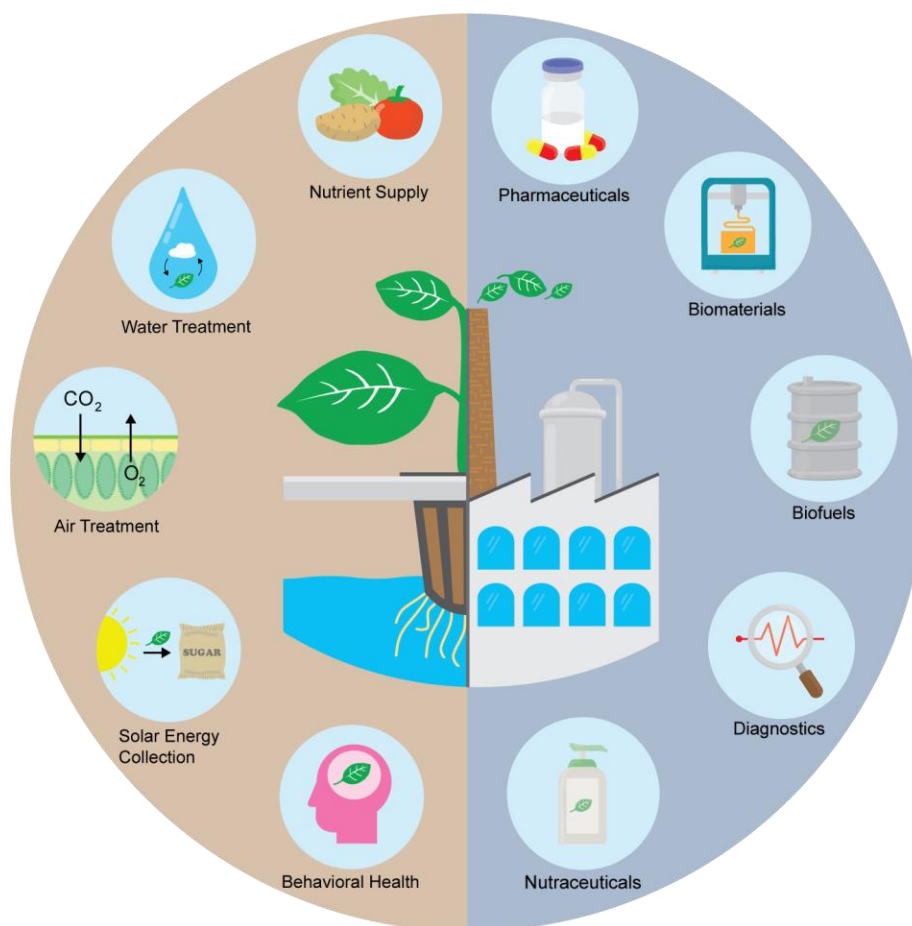


Figure 1. Molecular pharming embodies the perspective that plants are chemical factories. Viewing plants as factories vastly expands the bioregenerative life support capabilities of plants in space. Here we focus on molecular pharming of pharmaceuticals.

4. Supporting Life with Molecular Pharming

Humans have looked to plants as a source of healing for thousands of years³³. To date, there are over 120 commercially available drugs consisting of distinct chemical substances that have been derived from plants³⁴. This list includes widely used medications such as Paclitaxel³⁵, which is used to treat various forms of cancer, and Artemisinin³⁶, an antimalarial compound.

The breadth of therapeutically-relevant molecules that we can now produce in a plant to support human life has exploded with recombinant DNA technology. Plants have been used to produce a wide variety of complex products for supporting human life – ranging from products as diverse as diagnostic reagents and therapeutic proteins, to biomaterials and biofuels. Continuing those advances, we focus on producing pharmaceuticals as a high-priority application of molecular pharming to mitigate human health risks in extended deep space exploration.

The first commercial therapeutic protein to be produced recombinantly in plant cells (Elelyso[®]) was approved for enzyme replacement therapy in 2012^{37,38}. While this product is produced in plant cell culture, it has established a regulatory pathway for addressing concerns with plant-based production in general. There is currently a wide range of whole plant-produced pharmaceuticals

in commercial pipelines; perhaps most notably, Medicago's clinical program consists of an influenza vaccine in Phase 3 trials (ClinicalTrials.gov Identifier: NCT03739112) and several other vaccine candidates in earlier stages. Molecular pharming has also found commercial success in other application areas – for example in diagnostic reagents, with avidin produced in maize³⁹, veterinary medicine, with canine interferon-alpha produced in strawberry⁴⁰, nutraceuticals, with human growth factors produced in barley⁴¹, and commodity chemicals, with cell culture media components produced in rice⁴².

4.1 Pairing Production Strategies with Disease States

Molecular pharming with whole plants can be performed by using one of two strategies: transient production using gene delivery systems to introduce genes for the plant to temporarily transcribe and translate on-demand, or transgenic production using plants with recombinant genes inserted into the genome for stable translation. As depicted in Figure 2, either strategy can be executed to produce recombinant products using a simple process flow.

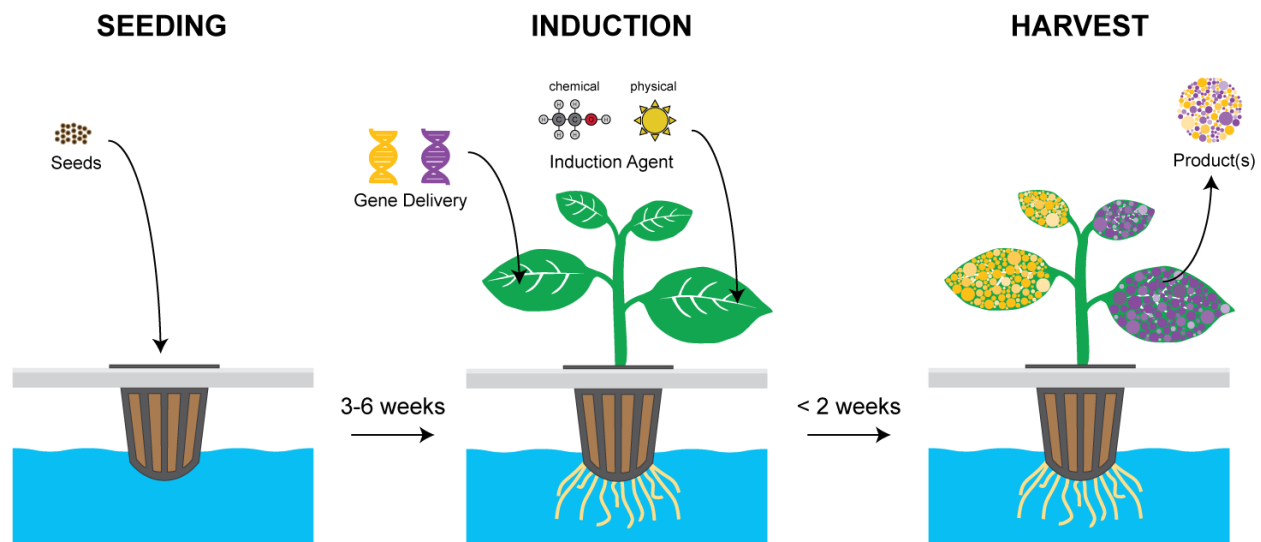


Figure 2. The simplicity of molecular pharming, illustrated. Producing recombinant products can be induced via gene delivery (transient production) or an induction agent (inducible transgenic production). Recombinant products accumulate in constitutive transgenic production without an induction step.

Transient production is a strategy that can provide on-demand transformation of food into a medical (or some other high-value product) resource. This enables rapid response countermeasures, in which initiation of production is linked to the exceeding of some risk threshold, be it triggered by the emergence of a diagnosed disease state or an increased probability of occurrence. This allows stockpiles to be minimized for low frequency disease states, and perhaps most importantly, builds capability to respond to unanticipated disease states. Key parameters of transient production to meet these capabilities are the production lead time (how fast can a dose of medicine be produced), the specific productivity (how much biomass is needed for a dose of medicine), and the manufacturing resources (which equipment and materials are needed for production). There are a variety of established transient production systems that employ both biotic and abiotic methods as shown in Figure 3. Table 1 summarizes key process differences in these transient production systems. Selecting the most effective transient production system

depends on the disease state (e.g. a small time-to-treatment window) and the exploration mission architecture (e.g. available resources).

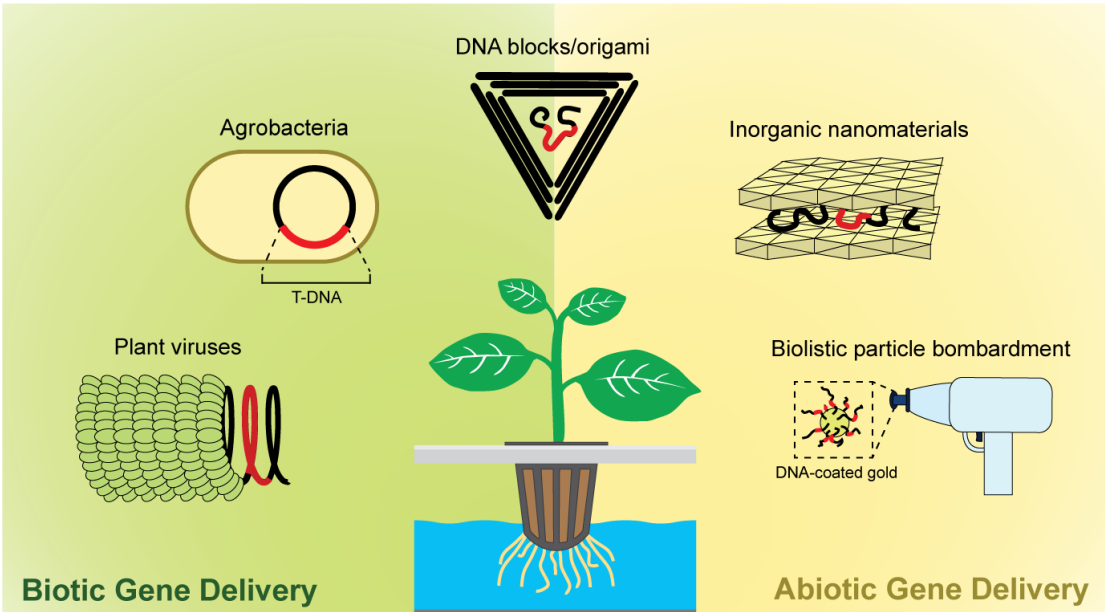


Figure 3. A look at previously established biotic and abiotic methods (also referred to as indirect and direct methods, respectively) for transient expression of recombinant products in plant systems.

Table 1. A comparison of key attributes between molecular pharming-based transient production methods.

	Plant viruses	Agrobacteria	DNA blocks/origami	Inorganic nanomaterials	Biolistic particle bombardment
Mode of Administration	Mechanical transmission	Vacuum, syringe, spray	Vacuum, syringe	Root drenching	Gas-pressured gene gun
Vehicle Size	10 – 500 nm	1,000 – 3,000 nm	100 – 500 nm	1 – 60 nm	500 – 1,600 nm
Host Range	Virus-specific by plant family (can be more; TMV infects 11 families)	Dicot and certain monocot species	Unrestricted*	Unrestricted*	Unrestricted*
Insert Size	<10 kbp	<120 kbp	Unrestricted*	Unrestricted*	<25 kbp*
Level of Expertise	Low	Medium	Medium	Low	Low
Equipment Requirements	Low	Medium	Low	Low	Medium

*Based on limited research data available; potential limitations may be uncovered with further investigation.

Transgenic production is the simplest form of molecular pharming. Pharmaceutical production capability hardwired into the genome of the plant through either nuclear or plastid engineering⁴³. No additional manufacturing resources beyond those used for plants as a traditional

bioregenerative life support object are needed, except an induction agent (e.g. heat, ethanol) for inducible promoter-controlled transgenics. This allows for simple and sustained production of pre-determined molecular target(s) for which a consistent demand is anticipated. Transgenic plants for medical countermeasure production will most likely be distinct resources from food crops unless strategies such as inducible promoters or tissue-specific expression (e.g. pharmaceuticals produced only in inedible biomass) are employed.

Combined, transient and transgenic production systems have the potential to cover the breadth of pharmaceutical production needs for deep space missions. Anticipated human health-impacting exposures in deep space missions include intermittent and persistent modes, within which both acute and chronic disease states are possible.

Chronic disease states needing a constant supply of medical countermeasures are most likely best addressed by using the simpler manufacturing of transgenic production. Transient production is also a viable strategy for meeting the medical needs of chronic disease states; it often yields higher specific productivity on a product per biomass basis⁴⁴. However, the higher resource demand of production and concerns of long-term pharmaceutical stability (if stockpiles were generated using transient production) raise potential disadvantages in transient production for chronic disease states, such as microgravity-induced osteopenia.

For acute disease states above a certain risk level, defined by both likelihood of occurrence and severity of mission impact, it may be valuable to generate transgenic plants to produce countermeasures. On the other hand, transient production may be a more cost-effective strategy for reducing mission risk associated with a slough of lower risk, and unanticipated, disease states. Here we reiterate that the significance of being able to provide medical countermeasures for unanticipated disease states should not be underestimated.

The delineation of best use cases for transgenic and transient production system selection depends on mission architecture and the specific resource availability. The decision tree shown in Figure 4 provides a foundational logic framework for evaluating and selecting an appropriate molecular pharming production system on a situational basis. A detailed walk-through of the decision tree for two test cases is included in Supplementary Information.

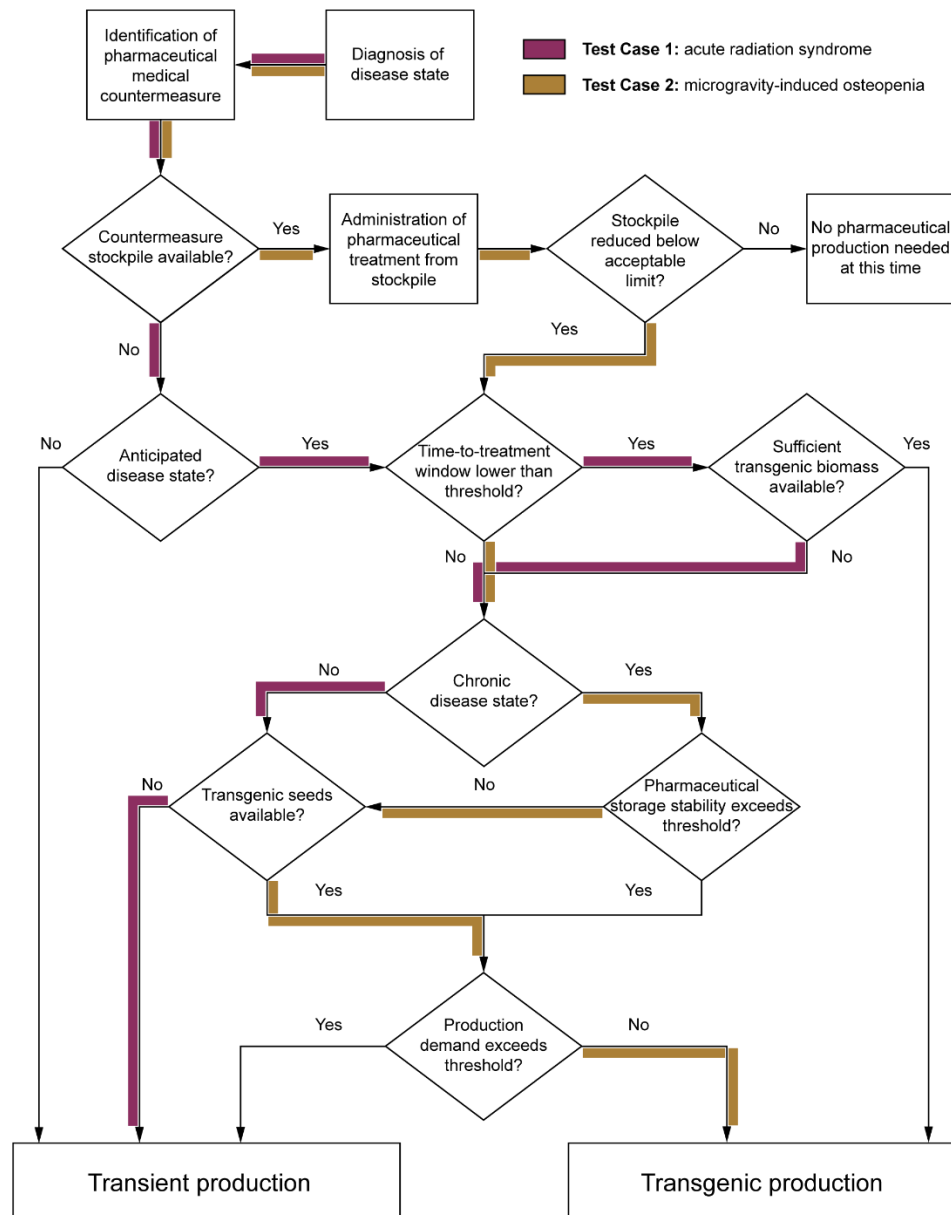


Figure 4. A decision tree for selecting a molecular pharming production strategy. This assumes that transient production is a more cost-efficient strategy above some threshold pharmaceutical demand, which is driven by the notion that transient production tends to yield higher product accumulation. This threshold depends on mission architecture, available resources, and the impact of the disease state to mission outcome. Two test cases of hypothetical disease state diagnoses are included; supporting information for the test cases are included in Supplementary Information.

4.2 A Test Case for Molecular Pharming in Space

Consider a deep space exploration mission in which plants are grown for their previously established utilities and a crew of six astronauts subsists on a diet supplemented with a single serving, 100 g fresh weight (FW), of lettuce or potato per crew member per day. The primary purpose for growing this single serving of plant-based food per day on an extended space mission is to meet the Food and Nutrition Board of the Institute of Medicine's Recommended Dietary Allowance (RDA) of nutrient. The current stated shelf life of pre-packaged space food is only 18

months⁴⁵, and degradation of key nutrients such as thiamine (vitamin B1) is well documented^{46–48}. Just as when sailors suffered the effects of missing vitamin C on long sea voyages, it will be critical to avoid vitamin deficiencies as we explore deep space. Figure 5 shows the macronutrient and labile vitamin contributions of the daily single serving of lettuce or potato as a percentage of recommended dietary allowance. A supplement selected from a variety of food crops would be most effective to meet the RDA, as well as to minimize menu fatigue and negative crew responses⁴⁹.

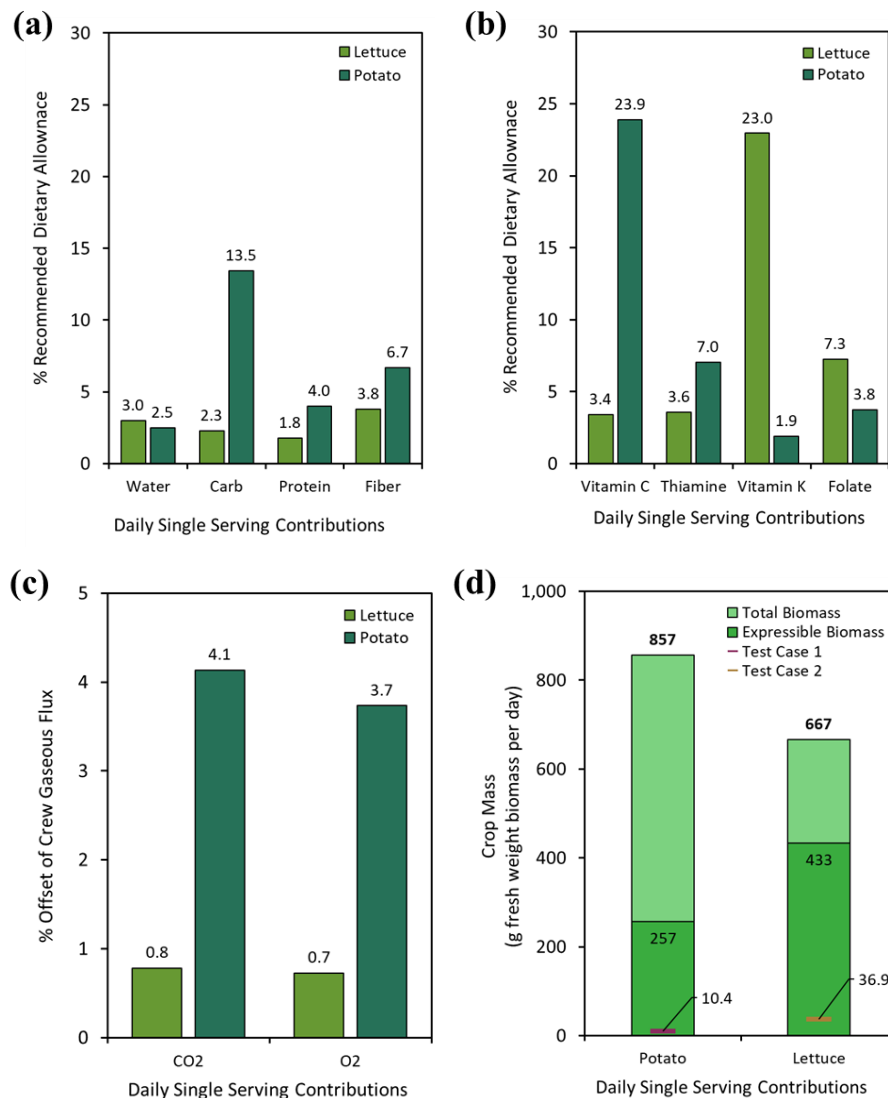


Figure 5. Cultivating a daily single serving (100g fresh weight) of crop, either lettuce or potato, to supplement an astronaut's diet. Contributions of the daily single serving to Recommended Dietary Allowance are shown for select (a) macronutrients and (b) labile vitamins. (c) The biomass for a daily single serving supports air revitalization by partially offsetting human gaseous metabolic flux. (d) The biomass for a daily single serving could be more than sufficient for molecular pharming production of pharmaceutical-based medical countermeasures, as illustrated by crop mass requirements of Test Case 1 (granulocyte stimulating colony factor, 1 dose, produced in potato) and Test Case 2 (parathyroid hormone residue 1-34, 6 doses, produced in lettuce).

Growing a daily single serving supplement of plant-based food is estimated to occupy 4.6 and 5.7 m² of cultivation area for lettuce and potato, respectively. This considers the plant inventory needed for sustained production of a single serving per day. The actual cultivation footprint is expected to be significantly smaller than the cultivation area, as hydroponic cultivation is typically done with multi-layered growth stages. The plant cultivation calculations were performed according to values listed in NASA's Baseline Values and Assumptions Document⁵⁰. Supporting information for the assumptions and calculations can be found in Supplementary Information.

In addition to supplying nutrients, this single serving will assist in other aspects of life support. The plant growth assists in air revitalization, offsetting crew carbon dioxide and oxygen flux by ~1% (lettuce) and ~4% (potato) (Figure 5c). It also serves to revitalize water as 9.7 (lettuce) and 22.8 (potato) liters per day of clean water are released in gaseous form via transpiration, most of which can be recycled for crop cultivation unless needed in other operations, such as for pharmaceutical formulation. These simple calculations highlight the auxiliary value of plants for bioregenerative life support.

The contributions to all aspects of life support depend highly on the crop species and cultivation environment. For example, a previous study using a closed human/plant system has shown experimentally that 11.2 m² of wheat grown at high light intensity (1,500 $\mu\text{mol m}^{-2} \text{s}^{-1}$) supplies sufficient oxygen for one person⁵¹. Wheat is one of the most productive crops for oxygen production, which is amplified by the high light intensity used and its tolerance of a 24-hour light cycle. This crop cultivation strategy has been demonstrated to provide ~13 times (lettuce) and ~3 times (potato) more oxygen for a given cultivation area.

Now we look at two test cases in which the biomass generated for this daily single serving can be applied to molecular pharming for manufacturing of pharmaceutical-based medical countermeasures:

Test Case 1: Transient production of one dose of granulocyte stimulating factor (G-CSF) in less than a single serving's worth of potato leaves (42 g FW/crew member) as a countermeasure to acute radiation syndrome, representative of an acute disease state.

Test Case 2: Transgenic production of a single dose per crew member (six doses) of parathyroid hormone residue 1-34 (PTH) in less than a single serving's worth of lettuce leaves (100 g FW/crew member) as a countermeasure to microgravity-induced osteopenia, representative of a chronic disease state.

Table 2 summarizes the key assumptions that were built into the two test cases. The logic for selection of the production method is shown in Figure 4 and further described in Supplementary Information.

Table 2. A list of assumptions used in the molecular pharming test case calculations. BLA, biologics license application. NDA, new drug application.

	Test Case 1	Test Case 2
Disease State	Acute radiation syndrome (acute disease)	Microgravity-induced osteopenia (chronic disease)
Countermeasure	Granulocyte stimulating factor	Parathyroid hormone residue 1-34
FDA-Approved Product	NEUPOGEN® (filgrastim) BLA: 103353	FORTEO® (teriparatide) NDA: 021318
Medication Demand	300 µg (1 doses; 300 µg/dose)	120 µg (6 doses; 20 µg/dose)
Production Method	Transient production in potato leaves	Transgenic production in lettuce leaves
Expression Level	250 µg drug/g potato leaf fresh weight	10 µg drug/g lettuce leaf fresh weight
Expressible Biomass	23% total biomass fresh weight	65% total biomass fresh weight
Drug Delivery	Intravenous injection (50% drug loss in purification processes)	Intravenous injection (50% drug loss in purification processes)

From the perspective of molecular pharming, lettuce^{52,53} serves as a fast-growing crop with a small cultivation footprint in which the edible biomass is also the expressible biomass capable of producing pharmaceuticals. Potato^{54,55} represents a slow-growing crop that has the advantage of distinct edible biomass (tubers) and expressible biomass (leaves); molecular pharming would not significantly impact the total available food resource. Leaves detached from the intact plant are capable of providing comparable pharmaceutical yield to those from the intact plant^{56–58}. Production of pharmaceuticals in inedible biomass is one way to create physical separation of the food and pharmaceutical streams while maintaining resource flexibility. However, there are situations in which it may be advantageous for merged food and pharmaceutical streams; there are reports in literature on oral delivery of pharmaceuticals in both lettuce and potato^{59–61}. While promising, this technology is still in nascent stages of development.

As shown in Figure 5d, only 10.4 g FW (1.2% of the total crop biomass FW, 4.0% expressible biomass FW, 0% food resource biomass FW) is needed for the Test Case 1 acute disease state countermeasure in potato, while 36.9 g FW (5.5% of total crop biomass FW, 8.5% expressible biomass FW, 5.8% food resource biomass FW) is needed for the Test Case 2 chronic disease state countermeasure in lettuce. While these test cases are driven by conservative assumptions of performance well-established in literature, it is important to note that biomass requirements are highly dependent on the rate of pharmaceutical accumulation (i.e. expression level), medication dose size, and drug delivery modality. Figure 6a illustrates how the total crop biomass demand differs between the two test cases based on the medication demand (dose size and number of doses) and over a range of conservatively estimated molecular pharming expression levels, while Figure 6b shows how the biomass requirements demands depend on drug delivery modality.

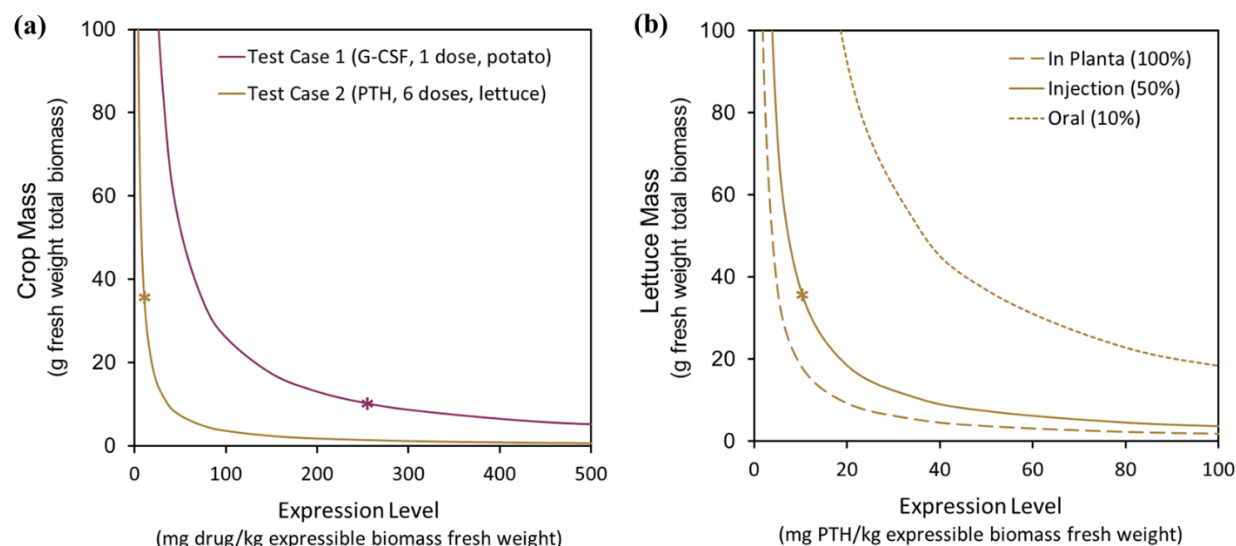


Figure 6. Plant cultivation requirements for molecular pharming are largely controlled by the product expression level, medication dosage, and medication delivery modality. (a) Test Case 1 and Test Case 2 sensitivity of crop mass demands to variation in pharmaceutical expression level. (b) Test Case 2 sensitivity of lettuce mass demands to selection of drug delivery modality, which we are representing as an approximated % availability of the produced drug. * signifies the expression level assumed in the test cases. G-CSF, granulocyte colony stimulating factor; PTH, parathyroid hormone residue 1-34.

5. Comparing Molecular Medical Foundries for Space

Since the founding of modern biotechnology with Cohen and Boyer's discovery of recombinant DNA technology in 1973⁶², biological organisms have risen to prominence as the primary means for producing high-value pharmaceutical proteins and other products, most of which are too complex to be economically and sustainably produced using current chemical synthesis approaches. In the half-century since inception of recombinant DNA technology, a plethora of biological platforms have been engineered as factories of recombinant products – microbial culture, eukaryotic (mammalian, insect, yeast, plant) cell culture, live animals, cell lysates, and whole plants. Table 3 shows a comparison of current pharmaceutical production platforms based on attributes relevant to their deployment for human health in space. Details of the category definition and system rankings are included in Supplementary Information. There are also new platforms on the horizon for production (e.g. microbiome engineering⁶³, gene therapy⁶⁴) and drug delivery (e.g. microneedle-based transdermal⁶⁵).

Table 3. A comparison of key characteristics for space exploration of biological platforms for pharmaceutical production.

System		In-Situ Resource Utilization	Just-In-Time Response	Operational Simplicity	Product Range	Crew & Planetary Safety
Bioreactor systems	Insect cell	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★
	Mammalian cell	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★
	Plant cell	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★
	Bacteria, autotrophic	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★
	Bacteria, heterotrophic	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★
	Yeast	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★
	Cell-free expression	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★
Non-bioreactor systems	Transgenic animals	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★
	Transgenic plants	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★
	Transient plants	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★	★ ★ ★ ★ ★

Commercial biopharmaceutical manufacturing on Earth is dominated by microbial fermentation and mammalian cell culture. Spread across over 1,700 production facilities globally, there is a commercial production capacity of 4.8 million liters for microbial fermentation and 15.0 million liters mammalian cell culture (online database; <http://top1000bio.com/>). Regulatory pathways have been well established, decades of intensive research have seen orders of magnitude increase in productivity, and billions of dollars have been poured into developing culture-based system infrastructure.

However, this established dominance of culture-based systems does not easily translate into implementation for human health in space for several reasons. The most glaring difficulty is with cell culture behavior, both with the cell biology⁶⁶ and fluid dynamics⁶⁷, in altered gravity; operation will need to be compliant across microgravity for in-flight production and reduced gravity for a Moon or Mars mission. There is a growing body of literature on development of bioreactors with alternative containment and mixing for microgravity^{68–70}. Main existing technical difficulties of culture-based systems in limited resource environments are the expensive and complex equipment requirements and the need for aseptic operation for growing the production host cells. Microbial fermenters and cell culture bioreactors are made of glass and/or a special grade (316L) stainless steel for durability and corrosion resistance⁷¹. Bioreactors are generally designed with a suite of capabilities, including culture agitation, aeration, sampling, in-line sensing, feedback control systems (for pH, temperature, dissolved oxygen, foaming), cleaning, and sterilization. This complex process equipment lowers general accessibility and increases workforce specialization of operators, which in turn forms another barrier to application in limited resource environments.

The equipment burden of culture-based systems is largely a result of the need to maintain a sterile cultivation environment during operation. Without adequate environmental protection, cultures are susceptible to contamination by undesired organisms. Compromised sterility of processing can lead to significant product and patient impact⁷²⁻⁷⁴.

In addition to complexity, stainless steel bioreactors impose significant mass and volume penalties that might prohibit adoption in a space mission. For example, a typical glass and stainless steel stirred tank reactor for 1L working volume (HyPerforma Glass Bioreactors, ThermoFisher Scientific) of culture weighs 3.7 kg, not including liquid culture mass and auxiliary reactor components (e.g. probes, spargers, agitator, heating jacket).

A growing trend in culture-based systems is to employ single-use technology for cost-savings in cleaning validation, capital costs, and time⁷⁵. Single-use technology for culture-based systems typically consists of a multi-layered plastic bag used in lieu of, or with support of, a stainless steel vessel. Of specific importance to space missions, these savings could also translate into significant reductions in mass and volume requirements. However, as the name “single-use” states, these plastic bioreactor housings are only used once, introducing significant consumable and waste streams to the pharmaceutical foundry. Therefore, single-use technology may introduce reliance on a stable supply chain for consumables that could strain feasibility in a limited resource environment. The use of recyclable materials (e.g. biopolymers) for single-use technology has not been commercially implemented but would serve to alleviate these concerns. The hindrance of consumable waste is offset by reduced cleaning requirements and should be evaluated within a mission architecture. For example, if pharmaceutical production is projected to be below a threshold capacity, then the extra consumables required to be flown may be acceptable.

Exceptional to the typical culture-based system vulnerabilities, microbial, oxygenic photoautotrophic cultures (i.e. microalgae^{76,77} and cyanobacteria^{78,79}) represent a promising subset of culture-based systems that may be better equipped for supporting human life in space. They share many of the same benefits of molecular pharming; these organisms are able to use available *in situ* resources (i.e. light and CO₂) as feedstocks, and some have been shown to be quite tolerant to a range of water qualities (e.g. polluted water)⁸⁰. Additionally, some of these species have unique advantageous characteristics: they can serve as a food resource, grow under conditions that minimize probability of contamination, and even be used as biofertilizer to improve soil quality and crop productivity⁸¹⁻⁸³.

A subset of these organisms, including the microalgal species *Chlamydomonas reinhardtii* and *Chlorella vulgaris*, and the cyanobacterial species *Arthrospira platensis* (commonly sold under the name spirulina), is categorized by the U.S. Food and Drug Administration as being Generally Recognized as Safe (GRAS), whereby these organisms are considered edible and are sold commercially as food and nutritional supplements^{83,84}. The edible nature of these organisms presents a potential boon to pharmaceutical foundries in space in that if the target production molecules are bioavailable through simply eating the wet or dry biomass of the production host, no downstream purification is needed.

The microbial nature of these organisms provides potential advantages to plant systems. First, microalgae (in particular *C. reinhardtii*) and cyanobacteria have genetic tools that are typically more advanced than those of plants^{84–86}. Although tools for engineering *A. platensis* have been reported⁸⁷, engineering this organism has remained a challenge in the field. To this end, we have recently developed a genetic toolkit for creating stable mutants of *A. platensis* (Hilzinger, Arkin, *et al.* Unpublished) that will help unlock this organism for metabolic engineering goals. Second, these organisms have faster growth rates than plants, which enable shorter times to reach the biomass necessary for molecular harvesting. Third, the larger metabolic diversity of microalgae and cyanobacteria compared to plants could help to metabolically engineer target molecules that are difficult or impossible to produce in plants using current technologies⁸⁴.

Therefore, these organisms may be well suited for pharmaceutical production, or for enhancing nutritional load through vitamin supplementation. Thus, GRAS-status microbial oxygenic photoautotrophs are poised to become edible molecular pharming hosts for space missions. As these technologies continue to mature, a detailed techno-economic comparison between plants, microalgae, and cyanobacteria will be needed.

It may be that a robust pharmaceutical foundry for space ends up being less about selecting one system and more about selecting a network of systems. It is important that interconnectivity and synergy of different platforms be considered for biological-based production of pharmaceuticals and other high-value products to support human life (e.g. biomaterials).

A main distinguishing feature of whole plants as a pharmaceutical production platform is the freedom from complex equipment housing during operation; the supracellular structure of a plant serves as its own natural “bioreactor” for operational control (e.g. nutrient distribution) and protection against contamination. This effectively means that molecular pharming can be employed with lower complexity process control systems and equipment. Figure 7 illustrates the simplicity and linear scalability of producing pharmaceuticals in whole plants. However, an equivalent system mass (ESM) comparison of molecular pharming and culture-based systems for spaceflight is needed to rigorously evaluate the perceived advantage of molecular pharming simplicity.

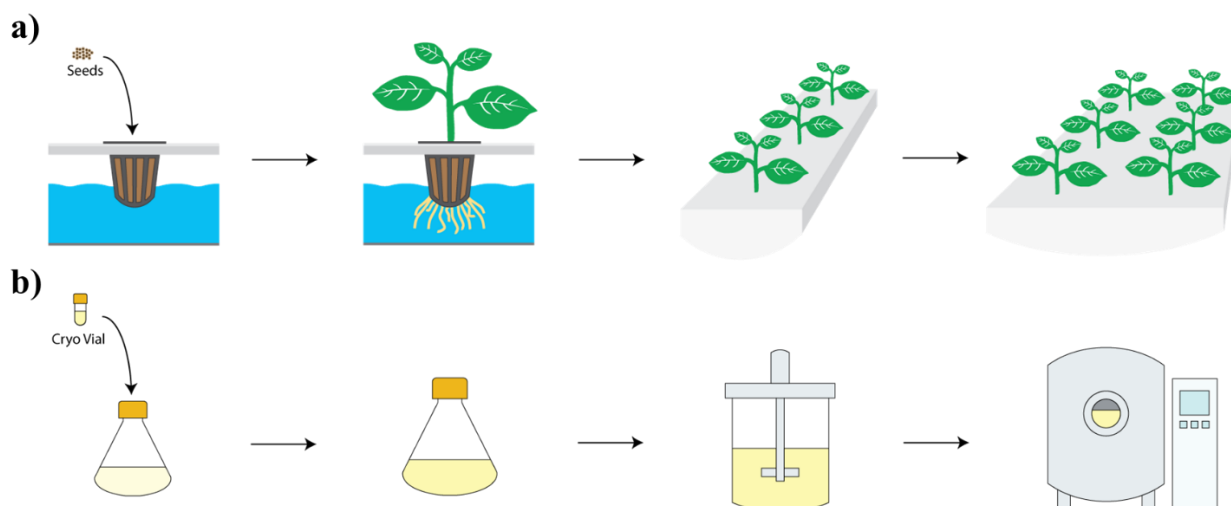


Figure 7. An illustration of the upstream manufacturing processes required for (a) whole plant molecular pharming, and (b) cell culture or fermentation-based biopharmaceutical production. Whole plant molecular pharming uses hydroponic or soil-based plant growth receptacles that scale linearly with demand, whereas cell culture and fermentation-based manufacturing use a series of bioreactors whose geometries are dependent on scale.

This self-regulating behavior also suggests that plants may serve as a more robust production platform with higher tolerance to input quality variation for a given output product quality. In literature, the strength of molecular pharming production tolerance as compared to culture-based systems is yet unproven, but would be a valuable avenue of research to directly investigate.

6. The Future of Plant-Based Foundries in Space

For decades, plants have been identified as important life support objects for human health in space. Here we have presented the need for an Earth-independent pharmaceutical life support system and identified molecular pharming as a strategy to tap into the power of plants to serve as a pharmaceutical (and other high-value product) foundry to meet that need. Molecular pharming in space has the potential to provide manufacturing capacity to respond to both acute and chronic disease states in space with a relatively small amount of plant biomass. Selecting the set of the most appropriate molecular pharming-based production strategies should be done within a reference mission architecture, which considers key attributes that we have laid out.

There are many ways to envision pharmaceutical foundries for interplanetary use. Chemical synthesis is limited in production targets and in reagent supply but may be necessary when biology is not sufficient or capable (e.g. nucleic acid synthesis). Translating culture-based systems from Earth to space utility face challenges of cell biology, fluid dynamics, feedstock sustainability, and mass/volume penalties. Their relatively high productivity may position them as an effective platform for settlement missions to sustain larger populations. Autotrophic cultures are exceptional to several challenges of traditional culture-based systems and have more potential as a nearer-term platform.

More thorough investigation is needed to select an appropriate set of pharmaceutical foundries. Process mass intensity (PMI) is a metric recently adopted by the biopharmaceutical industry to measure the environmental footprint of production⁸⁸. It is defined as the total mass in kg of raw

material and consumable inputs to produce 1 kg of active pharmaceutical ingredient. PMI can serve as a useful reference point when performing ESM analyses of pharmaceutical foundries in space. ESM analyses are typically performed to evaluate and optimize space mission payloads to minimize launch cost (or mission objective success) as a function of mass, volume, power, cooling, and crew time needs⁸⁹. Pharmaceutical foundry considerations will also need to include medical risk and outcomes. NASA's exploration medical system trade study tools have the potential to serve as a foundation for this analysis⁹⁰.

There are many obstacles ahead before making pharmaceutical foundries in space a reality.

What has not been thoroughly discussed in this review is the downstream processing of a molecular medical foundry, which will depend on the purity needed for the pharmaceutical formulation, delivery method, production host, etc. Downstream processing, the purification of the target molecule from the production host, is a resource-intensive aspect of biopharmaceutical production across all platforms. There is a lack of downstream processing technology that translates well from Earth-based constraints to those of space, such as a high quantity of consumables, raw materials, equipment, and cleaning costs. This bottleneck will need to be addressed for pharmaceutical foundries in space to succeed. One approach is to conduct research on novel drug delivery modalities (e.g. plant-encapsulated oral administration⁹¹) to reduce the need for downstream processing, and another is to diminish the resource demands of the processing itself (e.g. bioregenerative and recyclable processing reagents). A growing emphasis on distributed and just-in-time pharmaceutical production for healthcare on Earth is already driving solutions to these downstream challenges⁹².

The other major hurdle is in regulatory compliance. Production and administration of pharmaceuticals in space will require extensive quality control; manufacturing a small molecule might have 50 critical tests, while manufacturing a biologic may have over 250⁹³. Here, the advent of personalized medicine on Earth will illuminate a path forward. The shift from mass produced to individualized patient-specific medicine hinges on re-structuring the path to regulatory approval and quality control⁹⁴.

While there are many challenges ahead to pave the way for Earth-independent life support, the rewards of this pursuit will include great insights into supporting life on Earth and beyond. Understanding this value, we aim to highlight the critical importance (and long lead time) of developing Earth-independent systems in the future of human exploration. In addition to advocating for molecular pharming as a synergistic asset of space life support systems, we focus on the need for multi-faceted utilization of resources in limited environments like space and extraterrestrial bodies.

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