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Mushrooms to Mars: Harnessing Fungi for Sustainable Human Settlements

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Abstract: Fungi can play a crucial role in humanity's efforts to colonize Mars. Already, fungi, including mushrooms, have been featured in experiments conducted in low Earth orbit. In the establishment and maintenance of a large colony on Mars, fungi could fulfil vital roles in forming structural components and habitats, building and detoxifying soils, and providing foodstuffs, textiles, and pharmaceuticals. Enhancing our understanding of fungi could not only benefit space exploration but also yield more immediate benefits here on Earth.

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1. Introduction

In Boca Chica, Texas, SpaceX is developing a prototype of a "Starship," which could more aptly be described as a "Planet-ship." The company's vision entails an armada of hundreds of interplanetary Starships flocking to Mars to establish a city-sized colony [1-2]. While the timelines may seem ambitious, it's foreseeable that someone will eventually succeed in establishing a human presence on the Red Planet. Let's imagine this to be more than a mere base or cluster of domes; rather, it would be an advanced and robust settlement, in stark contrast to the makeshift base depicted in Andy Weir's novel, "The Martian" (2014). Envision a colony effort of significant scale, with long-term habitation and a substantial permanent population, albeit not yet poised for full-scale terraforming or replication of Earth-like conditions across the entire planet. Fungi, including mushrooms, offer numerous benefits to civilization here on Earth. But what about beyond? Are there fungal species we should bring along to aid the colony's survival, or would they merely add unnecessary weight, with luxuries like mushroom pizza toppings remaining an irrelevant dream for our intrepid colonists?

Some fungi are likely to accompany us to Mars, whether intentionally or not. These resilient microbes thrive in space habitats, adapting readily to low gravity and higher radiation levels. Fungal contaminants posed significant challenges on the Mir space station (1986–2001), degrading circuit boards and attacking rubber seals [34]. Among the fungi isolated from Mir were *Penicillium chrysogenum* and *Aspergillus versicolor* [3]. Similarly, fungi have been discovered on the International Space Station (ISS), including *Malassezia* sp. (found on human skin), *Aspergillus sydowii*, *A. niger*, *Penicillium palitans*, and *Rhodotorula mucilaginosa* [4-5]. An experiment aboard the ISS demonstrated that spores of *A. sydowii*, *A. versicolor*, *P. aurantiogresium*, and *P. expansum* could survive direct exposure to space on the exterior of the orbital station [7-8]. Moreover, experiments on the ISS have investigated the growth of several potential contaminants: *A. niger*, *Basipetospora halophile*, and

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Cladosporium herbarum **[8]**. These studies revealed that the anamorphic ascomycete *Ulocladium chartarum*, an indoor mold capable of degrading various materials, undergoes complex morphological adaptations in microgravity and may pose a threat to space travelers **[9]**. Fungal pigments may also play a crucial role in space; another experiment showed that melanized forms of *Cryptococcus neoformans* survive better on the ISS compared to non-melanized forms.

But what about Mars? A hypothetical Mars colony would likely harness microfungi in many of the same ways we do on Earth. Domesticated yeasts would be utilized for food, brewing, and the production of useful chemicals such as solvents, drugs, and biopolymers. The growth of *Saccharomyces cerevisiae* in bioreactors has already been observed experimentally on Space Shuttle missions and at the ISS **[8]**. Other microfungi might include arbuscular mycorrhizal types to enhance the productivity of hydroponic gardens or extremophiles like *Debaryomyces hansenii* and *Purpureocillium lilacinum*, capable of tolerating the high perchlorate levels in Martian soils **[10]**, thereby aiding in their processing for plant growth. Even without immediate concerns about terraforming, there would likely be in-situ studies of cryptoendolithic fungi like *Cryomyces antarcticus* and *Cryomyces minteri*. Both fungi are extremophiles found in the McMurdo Dry Valleys of Antarctica's Victoria Land and have survived simulated Martian environments in ISS experiments **[11]**. The potential applications of microfungi are extensive, contingent upon the colony's size, available resources, and desired capabilities. But what about mushrooms?

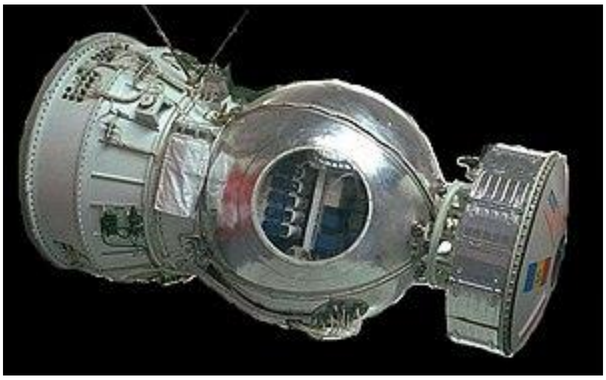

Figure-1 Kosmos 690 (Bion Spacecraft) [Image Courtesy: NASA]

Mushrooms have already been successfully grown in space. *Polyporus brumalis*, *Pleurotus ostreatus*, and *Pleurotus pulmonarius* were cultured aboard the Kosmos 690 (Bion 2) satellite in 1974 **[12]**, launched from the USSR. P. *brumalis* was also cultivated during experiments on the USSR Salyut–5 and Salyut–6 missions from 1976 to 1978 **[13]**. NASA launched cultures of *Flammulina filiformis* (= *F. velutipes*, "Enokitake") aboard a NASA Spacelab shuttle mission **[14]**, finding that Enokitake mushrooms exhibit irregular growth patterns in microgravity **[15]**. Stock cultures for any mushrooms transported to Mars would likely endure months of interplanetary travel before reaching their destination. Practically, we could carry inoculum for various species in relatively small spaces, storing them cryogenically until required. This approach would offer flexibility should our needs evolve. Opinions may vary regarding where to begin, but the following sections outline some ways fungi (and mushrooms specifically) could aid in establishing and maintaining a colony on the Red Planet.

2. Structural Components of Habitats

The concept of utilizing fungi for constructing structures on Earth has been a longstanding idea. Techniques have been developed to leverage the capability of fungal mycelium to create a matrix that actively binds various substrates together into a solid, composite building material. By incorporating organic substrates into the material, hyphae are able to grow, branch out, encase, and fuse substances within the matrix. Depending on the intended application, the fungi can either be maintained alive, allowing for self-repair, or cured and solidified.

On Earth, fungal composites can comprise sustainable substrates such as hemp shives, rapeseed straw, or poplar wood chips, bound together by the hyphae of fungi like *Fomes fomentarius* **[48]**. The strength of these composite materials varies based on factors like the species of fungi, the materials used, size, measurement methods, and more. For instance, the compressive strength of certain fungal bricks has been reported as 0.2 Megapascals (Mpa) for composites weighing 43 kg m^{-3} **[55]**. Research exploring materials suitable for building extraterrestrial structures has identified even higher compressive strength values, such as 1.57 Mpa for *Phellinus* *linteus*, 5.05 Mpa for *Annulohypoxylon* sp., and 26 Mpa for *Ganoderma lucidum* **[33]**. For comparison, the compressive strength of cement is 27.6 Mpa with a weight of 2400 kg m^{-3}. These materials could prove valuable for constructing habitats on Mars, where gravity is approximately 38% that of Earth.

Figure-2 Mushroom Plantation on Mars [Image Courtesy: AI with additional craft work]

At NASA's Ames Research Center, efforts are focused on exploring the potential use of fungal composites for constructing Martian "myco–architecture" **[46]**. On Mars, fungal composites might incorporate Martian regolith (soil) as part of the structure, with growth occurring within frameworks designed to contain the fungi. The matrix could fulfill multiple functions, such as water filtration, mineral extraction, humidity regulation, and providing bioluminescent lighting. Habitats built with these composites could incorporate exterior ice to supply water for the fungi and associated algae, which would utilize solar energy to fix CO_2 from the Martian atmosphere into carbon substrates to nourish the fungi. Some researchers have proposed forming these composites through the deposition of inoculated feedstock using macro-scale 3-D printing techniques **[43]**, while others have suggested using regolith combined with chitosan derived from fungi **[47]**. Amid concerns about the environmental impact of cement-based construction, which contributes significantly to CO_2 emissions implicated in global warming, the development of these composite technologies could offer benefits for Earth as well.

Regarding smaller structural materials and components, bioreactors can be employed in ABE (Alcohol, Butanol, Ethanol) fermentation to produce valuable "feedstock chemicals" for plastics **[44]**. While ABE fermentation typically involves bacteria like *Clostridium* spp., fungi could also play a role. For instance, research has demonstrated that a white-rotting *Phlebia* sp. can interact with *Clostridium saccharoperbutylacetonicum* to effectively produce butanol from cellulose **[50]**.

3. Building and Detoxifying Soils

Current and advanced plans for Lunar and Martian settlements involve the implementation of tunnel-like greenhouses designed to support crop growth. These greenhouses utilize sophisticated aeroponic systems Granath 2017 to cultivate crops along the floor and walls. Such soil-free systems significantly reduce water usage and offer the potential for scalability potentially evolving into "vertical gardens" to optimize space utilization within purpose-built habitats However the reliance on complex technical equipment and construction poses challenges for scaling up to sustain city-sized colonies Additionally the cultivation of root crops and larger plants such as fruit trees presents further obstacles using these methods. Until the colony can establish a substantial industrial base for producing and maintaining such technology, greenhouses or biodomes with relatively large-scale production would likely rely on readily available resources including some form of soil medium. Most depictions of future Mars colonies feature biodomes where plants could be grown in soil, assuming absence of hazardous life-forms in Martian soils These biodomes would not only cultivate essential food crops but also incorporate flora for recreational miniature parks offering inhabitants a semblance of Earth on an alien world. Transporting Earth soil and food to Mars in large quantities is fundamentally illogical, impractical, and prohibitively costly due to weight constraints and limited mass transfer capabilities Moreover, the soils on Mars' surface (technically fine regolith) are devoid of organic matter and are inhospitable to plant growth due to high levels of toxic chlorine-containing compounds like calcium perchlorate. These compounds are a result of surface radiation exposure. Potential methods to mitigate this issue include leaching and chemical separation of perchlorates from soils **[16]** as well as exploring biological methods involving plants and microbes to detoxify Martian soils. Studies suggest that certain plant/microbe combinations such as willow (*Salix nigra*) with dissolved organic carbon and bacteria **[17-18]** or microfungi like *Rhizopus stolonifera Pennicillium* sp and *Aspergillus* sp **[19]** possess the capability to eliminate perchlorates. Furthermore strains of fungi like *Penicillium spinulosum* have shown promise in degrading perchlorate soil contaminants (e.g. 2,4,6-Trinitrotoluene (TNT) combined with natural phosphate-bearing material) [20] indicating potential avenues for soil remediation on Mars. Fungi known for their pivotal role in decomposing organic matter and building soil fertility are poised to play a central role in transforming Martian regolith into a conducive medium for plant growth. Reminiscent of Robert A. Heinlein's 1950s vision of soil formation in agricultural colonies [21], current research explores the potential utilization of fungi such as *P. ostreatus* to digest organic compounds found in asteroids to facilitate soil formation [22]. Additionally fungi contribute to mineral weathering and soil formation on Earth. For instance, mycorrhizal fungi like *Scleroderma citrinum* enhance soil fertility through nutrient-cycling processes [23] Future Martian colonies may leverage fungal capacity to recycle organic wastes produced by the colony, converting them into organic soil components akin to terrestrial ecosystems [24]. Species like *Pisolithus arhizus* and *Agaricus bisporus* are examples of fungi capable of breaking down organic wastes while accumulating minerals. That is a property that could aid in soil amelioration on Mars. However the nutrient composition of Martian soils varies and may necessitate fertilization or amendment to support plant growth [25]. Mushrooms known for accumulating minerals, including toxic elements, offer avenues for soil improvement through bioaccumulation and sequestration processes Species like *Boletus edulis* and *Tricholoma matsutake* exhibit capabilities to absorb harmful elements while promoting soil development through enzymatic activities [26-27]. These fungal interactions with Martian regolith represent promising avenues for sustainable agriculture in extraterrestrial habitats.

Addressing the management of organic wastes from crops, human activities, and other sources will be a critical challenge for future Martian colonists. Fungi are anticipated to play a pivotal role in recycling these organic wastes within the colony, transforming them into organic soil components via processes that mirror those observed on Earth [24]. For instance, the mycorrhizal mushroom *Pisolithus arhizus* (= *P. tinctorius*), known as a cold-tolerant "earthball," demonstrates resilience in harsh soil conditions and has been shown to decompose sewage sludge, thereby enhancing the growth of host plants like *Pinus taeda* (loblolly pine) and *Pinus echinata* (shortleaf pine) [56]. Similarly, saprotrophic fungi such as *Agaricus bisporus* and *Coprinus comatus* could contribute to the breakdown of organic wastes while also yielding foodstuffs.

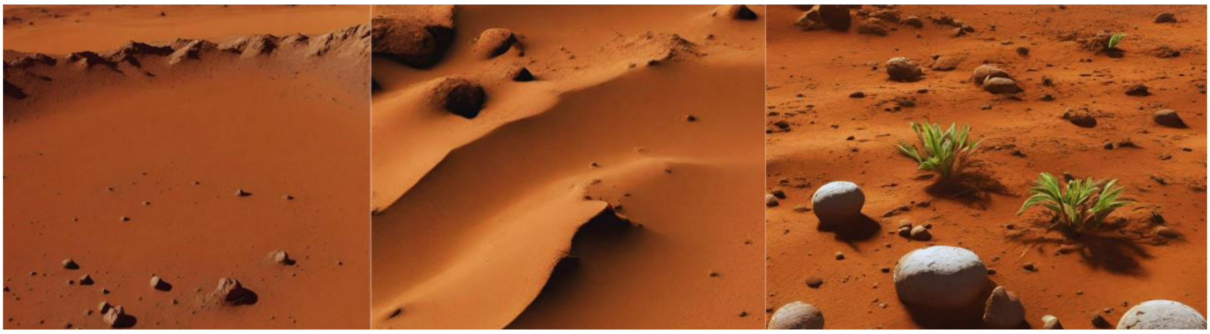

Figure-3 Detoxifying Martian soils to increase soil fertility [Image Courtesy: AI with additional works]

Concerns also arise regarding the availability of nutrients. Martian soils, resembling volcanic soils on Earth, contain essential mineral elements necessary for plant growth. However, the concentrations of these minerals can vary significantly **[36]**, necessitating fertilization or soil improvement for cultivation. Mushrooms have a propensity to accumulate minerals, including toxic elements and heavy metals, in their fruiting bodies, thereby aiding in soil improvement through the actions of mycorrhizal fungi. Ectomycorrhizal fungi have the ability to uptake and concentrate compounds detrimental to plant growth, a process known as bioaccumulation, with the option to harvest and remove harmful elements once they accumulate. Various mushrooms, such as A. *bisporus* and C. *comatus*, are known for their capacity to accumulate specific metals like cadmium, silver, aluminum, barium, mercury, nickel, and vanadium [42, 53, 57].

In conjunction with cold-tolerant trees, mycorrhizal mushrooms can serve as effective scavengers for harmful elements. For instance, *Thelephora terrestris*, known for its stress tolerance, can accumulate metals like silver and copper while contributing to soil development through the promotion of mineral weathering [58]. *P. arhizus* is reported to accumulate chromium, manganese, and nickel [59]. In more developed, warmer soils, fungi such as boletes, including *Boletus edulis*, demonstrate the capability to accumulate mercury and selenium while producing compounds that bind and sequester toxic elements [26, 60]. Another noteworthy fungus is the mycorrhizal species *Tricholoma matsutake*, which forms colonies associated with complex mycelial mats where biogeochemical activities occur. This species can assist in managing aluminum toxicity, a concern in Martian regolith, by binding aluminum into safe complexes suitable for plant and fungal growth [27, 40].

4. Food Production

Knowledgable mycophiles will have recognized the inclusion of several species of edible fungi in the preceding text: *A. bisporus*, *A. campestris*, *B. edulis*, *C. comatus*, *F. filiformis*, *P. ostreatus*, *P. pulmonarius*, and *T. matsutake*. Clearly, fungi can serve diverse roles within our Mars colony. Therefore, introducing these fungi could potentially allow for the inclusion of *A. bisporus* slices on Martian pizzas (assuming the production of organic substrates for mushroom growth, alongside the cultivation of tomatoes for sauce, wheat for flour, and suitable alternatives for mozzarella cheese and pepperoni). However, the allocation of effort and space by colonists towards incorporating mushrooms into their diet requires careful consideration, particularly in relation to the timeframe involved.

In the short term, cultivating mushrooms from organic waste in colony greenhouses may be viable. But their suitability for immediate survival situations is debatable, making them a lower priority. Mushrooms offer relatively low calorie content, and their high fiber levels could potentially limit carbohydrate availability and impede fat digestion. Given the anticipated activity levels of colonists during the colony's establishment phase, it would likely be more practical to prioritize the cultivation of foods with higher caloric value initially.

Conversely, a different perspective emerges when considering the long-term scenario. Recent research indicates that "mycoprotein" or 'mushroom meat' is as effective as animal protein for muscle-building during resistance training **[28].** Mycoprotein is derived from the liquid fermentation of the *Fusarium venenatum* fungus **[29]**. Given the eventual establishment of infrastructure to support bioreactor operations within the colony, this method of protein production could offer significant advantages. Additionally, proteins from various mushroom crops could prove beneficial. Mushrooms serve as a convenient source of minerals, essential amino acids, and Vitamin D, which may not be readily available in other plants grown within colony biodomes. Moreover, their flavor could enhance dietary variety and boost colony morale. Overall, incorporating mushrooms into the colony's diet appears to be a favorable proposition.

5. Textiles

Let's consider the practicalities of clothing and fabric use in a Mars colony, where the necessity for attire extends beyond mere modesty to encompass thermal comfort and safety (as famously described by Elton John, it's "cold as hell" there). While some fabrics may need to be sourced from artificial polymers or plant fibers, it may surprise some to learn that fungal mycelia can be transformed into artificial leather—a versatile material suitable for belts, shoes, jackets, and more. Remarkably, various commercial enterprises like MuSkin, MycoWorks, and Bolt Threads are already manufacturing fungal leather products. This innovation could prove highly valuable in larger colonies, eliminating the need for livestock rearing.

Several fungi species, including *P. ostreatus*, *T. versicolor*, and *Schizophyllum commune*, have been identified as viable sources for fungal leather. MycoWorks' **[38]** recent patent encompasses Polyporales and all fungi capable of degrading lignin or cellulose, including *Ganoderma* spp. and *Trametes* spp (one assumes that that their Reishi™ product, under proprietary of "Fine Mycelium™" technology, involves *G. lucidum*). MuSkin utilizes *Phellinus ellipsoideus*, a tropical polypore known for producing the largest fruiting body on record. Additionally, a scientific study comparing 14 species in the Polyporales identified *Fomitella fraxinea*, an ash-tree pathogen, as having optimal characteristics for growing fungal leather products **[30]**

Regarding textiles, it's worth noting that if *P. arhizus* is already being cultivated for other purposes, it also produces natural pigments useful for dyeing various plant-based fabrics, earning it the monikers "Dyeball" or "Dyemaker's Puffball." This underscores the potential for synergy within the colony's resource utilization strategies.

6. Pharmaceuticals

In the computer game "Deliver Us Mars," players stumble upon 'fungal growth chambers' containing cultures of *Psilocybe* spp. The implication is that these hallucinogenic mushrooms are being studied for their potential in developing drugs to address depression among overworked colonists. While we hope real Martian colonists won't face such severe mental health challenges, there may still be significant medical needs where fungal-derived therapies could offer solutions.

One pressing concern on Mars relates to its elevated radiation levels, posing a considerable health risk and potentially increasing the likelihood of cancer among colonists. Given that certain fungi, such as *Ganoderma* *lucidum*, *Tramates versicolor*, and *Sparassis crispa*, have demonstrated anti-cancer properties in laboratory experiments and even human clinical trials, it stands to reason that any long-term colonization effort would be keen on exploring their medicinal potential. Additionally, fungi could play a role in extracting metallic nanoparticles from regolith, which have been reported to possess anti-cancer or other medical applications **[31-32]**

While immediate cures may be elusive, it would be prudent for colonists to investigate promising anti-cancer therapies derived from mushrooms and other fungi as part of their ongoing medical research endeavors.

7. Facing the Future

Considering all the information presented, it becomes evident that fungi could serve significant roles in any theoretical Martian colony. As the establishment of such a colony may lie far in the future (Figure 4), some might argue that it's premature to delve into specifics. However, the sounterpoint suggests that preparedness is key, particularly in the inherently risky domain of space exploration. Thus, endeavors aimed at mitigating risks will invariably take precedence.

Figure-4 Left panel: Hypothetical image of a fungal Mars colony. Center and right panels: Artistic depiction of culturing and consuming mushrooms on Mars. The image at left was composed by AI (Dall–E–2) with additional artwork by R. Winder. Other images were composed by AI with additional artwork.

Both on Earth and beyond, there remains much to be discovered concerning fungi and their potential applications. Questions abound: How can fungi be optimally utilized as sustainable architectural components and textiles? Which fungal species and strains are most effective for soil-building and remediation? In what ways can fungi contribute to enhanced organic waste recycling? What nuances govern fungal associations with plants, soils, and other organisms, and how might these interactions be leveraged in remote habitats? Moreover, which fungal candidates hold promise for the production of dietary proteins and pharmaceuticals? The exploration of these inquiries holds immense value, not only for terrestrial endeavors but also for ventures throughout the solar system.

8. Conclusion

In conclusion, the exploration of the potential role of fungi in Martian colonization reveals a plethora of opportunities for leveraging these organisms in various aspects of settlement establishment and sustainability. From their resilience in space habitats to their ability to detoxify soils and provide essential resources such as food, textiles, and pharmaceuticals, fungi emerge as versatile allies in humanity's extraterrestrial endeavors. While the realization of a thriving Martian colony may still be distant, the proactive consideration of fungi underscores the importance of preparedness in mitigating the risks inherent in space exploration. Furthermore, the study of fungi not only promises to advance our understanding of extraterrestrial ecosystems but also holds the potential for significant terrestrial benefits, ranging from sustainable agriculture to medical advancements. As we continue to navigate the complexities of space exploration, fungi stand as compelling subjects for further research and exploration, offering valuable insights and solutions for both planetary and earthly challenges **[61-64]**.

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10. Biography

Richard Winder is a retired Forest Biologist with a distinguished career spanning several decades. His expertise encompasses a diverse range of disciplines including botany, ecology, and microbiology. Throughout his career, he has been involved in multidisciplinary research programs aimed at understanding and managing forest ecosystems. Winder's research interests have focused on various aspects of forest biology, including biological control, soil microbiology, and plant pathogen ecology. He has also made significant contributions to the study of Non-Timber Forest Products (NTFPs) and mushroom ecology, exploring their ecological roles and potential applications.

With over 65 publications to his name, Winder's work has been influential in advancing our understanding of forest dynamics, soil microbes, and microbial ecology. His expertise extends to areas such as biocontrol, nitrogen-cycling, and diazotrophy, where he has conducted groundbreaking research on diazotrophic niches and nitrogen fixation. Richard Winder's academic journey includes a Doctorate and a Master's degree from North Carolina State University, where he honed his expertise in forestry and related disciplines. He completed his Bachelor's degree at Slippery Rock State College in Pennsylvania, laying the foundation for his illustrious career in forest biology. Throughout his career, Richard Winder has been a dedicated scholar and researcher, contributing significantly to the field of forest biology and leaving a lasting impact on our understanding of forest ecosystems.

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