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Plant Cultivation: Plant Systems in Sustainable Space Exploration and Earth Applications

A core principle of any scientific endeavor is achieving results with efficiency, completing the task while conserving resources for future endeavors. One of the longest goals for humanity is cosmic exploration but despite the moon having been visited by people and Mars by robots, not even the International Space Station (ISS) can sustain people indefinitely as they utilize probes to send provisions and data. This is bad news because the Moon is 1000 times farther away than the ISS's orbiting height, and Mars an even greater 500,000 times farther away. Probes to sustain missions would be an incredibly difficult, expensive, and time consuming option for supplying missions. As someone who has always been fascinated by plants, thanks to my family's enjoyment of gardening, I've come to appreciate their incredible potential. This personal interest grew even more when I participated in a NASA research camp, where I had worked on Mars habitat design but didn't explore the role plants might play in space exploration. One of the key challenges of long-duration space missions is ensuring habitable living conditions, particularly when it comes to air quality and food supply. Astronauts need clean, dry air and fresh, nutritious food to maintain both their health and mental well-being.

Another issue with exploration currently is habitable living conditions, specifically air and food. The air must be clean and dry while the astronauts would not only gain nutrients but also an improved mental state with fresh food. There is a solution that if properly utilized and carefully maintained, can solve all of these issues: Plants. They can provide fresh food, boosting morale and reducing the need for resupply missions. Additionally, plants could purify the air by absorbing excess carbon dioxide and converting it into oxygen. This would improve the quality of the atmosphere inside spacecraft or habitats. Plants could also help manage waste, recycling organic material into usable resources and reducing space pollution. Plants could be one of the most efficient ways to reduce issues in the journey of space exploration. Not only that but plants offer similar benefits on Earth. I utilized primary research in the form of an interview with Makena McLaughlin, a Landscape Architecture major, Horticulture minor, and Horticulture club leader with seven questions. I also reviewed many articles that explored how plants fared in space and what they could do with given resources. In this essay, I argue that cultivating selected plant species in simulated regolith and special conditions is crucial to developing mission resources and processes creating arable dirt.

Methods

To explore how agriculture could be applied in space, this paper relies on both primary and secondary sources. The primary data was collected via an interview with Makena McLaughlin. She is a student at Virginia Tech who is studying Landscape Architecture as her major, while also minoring in Horticulture. I reached out to her because of her extensive past with plants and her leadership in the Virginia Tech Horticulture Club. The purpose of this interview was to gain insight into how an expert in horticulture, managing projects, and land in general would respond to issues in her scientific life as well as her experience. The interview included questions on a range of topics, such as issues in agriculture, global food security, research and data, and initiatives regarding projects. By analyzing the responses, I was able to garner a nuanced understanding of challenges, methods, practices, and ideas within the horticulture club.

In addition to primary research, I conducted secondary research through a review of existing literature relating to plant processes as well as conducted experiments relating to plant growth on the Moon and Mars. This research consisted of scientific journals and web articles that explored a variety of topics including the impact of plant growth in space. One such journal was *Can plants grow on Mars and the Moon: A growth experiment on Mars and moon soil simulants,* by Wieger Wamelink and others which examines a experiment conducted by them regarding the growth of plants in Martian and Lunar regolith (loose, unconsolidated rock and dust that covers a layer of solid bedrock; soil is regolith that can support plant life), allowing some theoretical processes for growing plants on foreign planets to be formed.

Research Findings

Long term space exploration or habitation missions face a number of challenges. One of the most pressing challenges is the need for sustainable food and air. Given the distance from Earth, resupply probes are not cost-effective or efficient enough for extended periods. Experimenting with plants in a variety of special conditions, including simulated regolith and low-space areas, can provide a possible solution for sustaining astronauts by offering fresh food, boosting morale, and revitalizing air within confined habitats.

A prominent benefit to growing plants in space is their ability to provide fresh food. Currently, astronauts rely on packaged, long-lasting food, which lacks the nutritional diversity and psychological benefits that come with fresh produce. Studies by Wamelink et al., have displayed that plants can grow in conditions found on Mars, suggesting that with proper conditions and adaptations, crops such as water cress and rye could be grown on Mars itself (3). By integrating plant cultivation into missions, astronauts could have a sustainable food source, reducing their dependence on Earth-based supplies and ensuring nutritional diversity for long-duration missions. Drawing from Caporale et al., enriching Martian or lunar soil simulants with organic fertilizers such as manure improves enzymatic activity, nutrient availability, and crop yields, making it a practical approach to achieving sustainable food production in space (3).

Having plants on missions such as these provide significant psychological benefits as well. Growing food in space provides more than just sustenance—it also helps maintain mental health. The presence of living, growing plants offers astronauts a sense of normalcy and connection to Earth, which can be crucial for maintaining morale during long missions. The act of tending to plants, watching them grow, and consuming the fruits of one’s labor can provide a therapeutic outlet for astronauts, helping combat feelings of isolation, stress, and monotony. As Wheeler found in their research, creating viable agricultural systems in space has the potential to improve astronauts' well-being, both physically and mentally, through the interaction with nature in a highly controlled environment (6). In her work with the Horticulture Club, McLaughlin emphasized the benefits of nurturing diverse plant life and cultivating environments that support mental and physical health (1).

Plants also act as natural air revitalizers. During photosynthesis, plants absorb carbon dioxide and release oxygen, which is vital for life support systems in space habitats. On Mars, the atmosphere is composed mostly of carbon dioxide, and creating a sustainable and habitable environment will require a consistent and efficient method of oxygen generation. As some studies note, bioregenerative life support systems (BLSS) that incorporate photosynthetic organisms—like plants—could effectively recycle air, transforming carbon dioxide into oxygen, which is essential for astronauts' survival (Wheeler 25). This natural air purification system reduces the reliance on complex and costly mechanical systems, making long-term missions more feasible.

In addition to providing food, plants in space habitats can play a role in nitrogen fixation. Nitrogen is a vital nutrient for plant growth, but Martian regolith lacks the necessary forms of nitrogen to support crops. To address this, certain plant species, such as Festuca Rubra (Red Fescue) or Vicia Sativa Sativa (Common Vetch), have the ability to fix nitrogen from the atmosphere and convert it into a usable form for other plants while also being a source of food themselves (Wamelink 3). Integrating nitrogen-fixing plants into space agriculture could help create a more self-sustaining ecosystem by reducing the need for external nitrogen sources. In terrestrial agriculture, McLaughlin highlighted similar principles, advocating for sustainable practices like avoiding monocultures and promoting plant diversity to reduce chemical use and enhance soil health (2). Research on nitrogen management will be critical for adapting these processes to Martian conditions, ensuring that plants can thrive without the need for constant resupply from Earth.

Moreover, waste management is a key challenge for long-duration missions. Plants offer a natural solution by recycling organic waste into valuable resources. For example, astronaut waste—such as food scraps and human waste—can be composted and used as organic fertilizer to enrich the Martian soil simulants (Caporale 2). By incorporating organic matter into the regolith, plants not only benefit from improved soil fertility but also help close the loop on waste, reducing the need to transport and store large amounts of waste material. This process of bioregenerative life support, where waste is transformed into a resource, aligns with the goal of reducing reliance on Earth-bound supplies and making space habitats more self-sufficient.

The development of space agriculture has broader implications for global food security, particularly in extreme or degraded environments on Earth. According to McLaughlin, protecting and restoring fertile soils, as well as employing sustainable cultivation practices, are critical to food security challenges (2). Research on space-based solutions, such as nitrogen fixation and improving soil composition, can improve efforts to optimize crop growth in challenging climates (Eckert 5; National Geographic 2). By developing robust systems for growing food in harsh conditions, space agriculture research contributes valuable insights that can be applied to Earth-based farming, ultimately enhancing resilience and sustainability for populations facing food insecurity.

The findings of this study display the role of cultivating plants in simulated regolith and other special conditions, supporting the thesis that this approach is essential for developing sustainable mission resources and creating arable dirt for future space exploration and colonization. By utilizing plant-based systems, space missions can achieve more than just survival; they can create semi-closed ecological loops that make long-term human habitation in extraterrestrial environments both viable and resource-efficient.

A potential counterargument is the high initial cost of developing, testing, and deploying plant cultivation systems for space missions. Indeed, establishing such systems requires significant investment in infrastructure, research, and adaptation to hostile space conditions. However, this argument overlooks the substantial long-term benefits and cost savings associated with plant-based regenerative systems. Unlike mechanical systems that require costly and frequent repairs or replacements, plants offer a self-renewing solution for air revitalization, food production, and waste recycling. Once established, plant-based systems become largely self-sustaining, reducing resupply needs and lowering mission costs over time. These established technologies can also support people on Earth, leading to an expansion of growth in extreme conditions such as deserts or areas of high heat. Applying techniques learned from experiments such as these can also lead to more regenerative farming practices, enhanced soil fertility, and reduced need for synthetic fertilizers.

Conclusion

In conclusion, cultivating selected plant species in simulated regolith and special conditions represents a transformative strategy for developing mission resources and creating arable dirt, essential for the feasibility of long-term space missions and planetary colonization. The findings of this study highlight how plant-based systems provide sustainable solutions for producing fresh food, revitalizing air, and managing waste, all of which are critical for maintaining human health and well-being in extraterrestrial environments. The integration of nitrogen-fixing plants, waste-to-resource systems, and innovative soil enrichment techniques offers a blueprint for creating self-sustaining ecosystems in space.

Given the pressing timelines, ranging from the time required to establish viable colonies on Mars to the looming threats posed by Earth's changing climate and degradation of agricultural land, the need for efficient, self-sustaining cultivation systems becomes even more apparent. While current costs of developing and deploying these plant-based systems may appear high, the long-term benefits far outweigh the initial investment. Over time, these systems will reduce reliance on costly resupply missions and lower mission expenses by creating renewable and sustainable life support structures.

Looking toward the future, this research holds the potential to not only make human life on Mars and other planets feasible but also revolutionize sustainable agriculture on Earth. By scaling these experiments and integrating diverse plant species for resilient and adaptable agricultural strategies, we can develop innovative solutions for food production and environmental sustainability. This dual impact emphasizes the interconnectedness of space exploration and terrestrial needs, showcasing how advancements in one realm can lead to groundbreaking improvements in the other. As humanity moves closer to colonizing new planets and addressing Earth's environmental challenges, the cultivation of plants in controlled, resource-limited environments will play a pivotal role in shaping our future.

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