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Advancing Research, Development, and Innovation in Space Farming - A Brazilian Experience

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Abstract

The Brazilian Space Agency (AEB) and the Brazilian Agricultural Research Corporation (EMBRAPA) have signed a protocol of intentions under the Artemis Project to develop research, innovation, and technological solutions related to Space Farming. This initiative, known as "Space Farming Brazil," brings together nearly 45 researchers from 12 Brazilian research institutions and a U.S. university. The interdisciplinary team will focus on two key areas: space plant breeding and the development of self-sustaining agricultural production systems tailored to lunar conditions. The initial focus will be on two plant species—chickpeas and sweet potatoes—chosen for their nutritional value and ability to thrive in harsh environments. Both are high in protein and energy, and biofortified genetic variants rich in antioxidants, such as anthocyanins, may help mitigate the negative effects of space stressors, including ionizing radiation, on human health during long-term missions. A primary objective of the project's first phase is to enhance crop tolerance to the Moon's extreme abiotic stresses, including ionizing radiation, limited liquid water availability, energy use efficiency, and nutrient scarcity. Additionally, the project aims to induce mutations in these plants under space conditions, seeking to create genetic material better suited not only for lunar agriculture but also for terrestrial challenges, such as global climate change. Establishing the first lunar bases will require significant adaptations to controlled-environment agricultural systems currently used on Earth. This will involve advancements in energy generation and storage, biogenerative life support systems for space conditions, and materials engineering to improve efficiency in water and energy use. The program will also explore the use of microorganisms to enhance crop productivity in space and develop automated systems to reduce the workload of astronauts. All research under Space Farming Brazil will be

conducted in accordance with international quality standards, ensuring that findings can support both space exploration and potential applications on Earth.

Keywords: Space Plant Breeding, Chickpea, Sweet Potato, Plant in Space, Space Biology, Vertical Farming, Space Biology, Closed-Loop Systems, Deep Space Missions, Food Security in Space

Acronyms/Abbreviations
AEB - Brazilian Space Agency
Embrapa - Brazilian Agricultural Research Corporation
NASA - National Aeronautics and Space Administration
IPCC - Intergovernmental Panel on Climate Change
ISO - International Standardization Organization

1. Introduction

1.1. Overview of Space Farming

After the Apollo Missions, we are now witnessing a new Space Age, where various countries are striving to return to space for the construction of permanent bases in deep space, whether on the Moon, Mars, or other celestial bodies. While governments and their space agencies still play a crucial role in this new journey, they are increasingly sharing responsibilities with new players from the private sector, a phenomenon known as the New Space Economy. As a result, space has become an even more prominent arena for the development of new technologies that benefit life on Earth, leading to numerous spin-offs across various fields such as medicine and agriculture.

The Artemis Accords, conceived by the United States, primarily aim to return humans to the Moon and begin the construction of a permanent base there, with the long-term goal of establishing a base on Mars (NASA, 2022). These exploratory missions will generate a vast amount of data and knowledge, some of which are still unimaginable.

1.2. Significance of Brazilian Involvement in Space Agriculture

In 2021, Brazil signed the Artemis Accords, enabling participation in peaceful space exploration research alongside 42 other countries. In 2022, the objectives of the Artemis Accords were published (https://www.nasa.gov/press-release/nasa-s-stakeholder-collaborations-help-inform-moon-to-mars-planning).
Among these, several objectives align with the capabilities of Brazilian research institutions and international partners. These include:

- HBS-1LM: Understanding the effects of short- and long-term exposure to lunar, Martian, and deep-space environments on biological systems and health, including humans, model organisms, human physiological systems, and plants.
- AS-3LM: Characterizing accessible lunar and Martian resources, collecting scientific data, and analyzing potential reserves to meet science and technology goals, while enabling in-situ resource utilization (ISRU) for successive missions.
- AS-4LM: Conducting applied scientific research essential for developing bioregenerative life support systems.
- AS-5LM: Defining cultivated plant species, including methods for their growth and production, capable of providing sustainable sources of nutritious food on the Moon, during deep-space transit, and for habitation on Mars.
- AS-6LM: Advancing the understanding of how physical systems and fundamental phenomena are affected by partial gravity, microgravity, and the environments of the Moon, Mars, and deep-space transit.

Nutrition plays a role far beyond merely providing sustenance. Psychological and social aspects are highly relevant, making this a fundamental topic as humanity seeks to sustain itself for extended periods away from Earth. However, plant cultivation on Earth traditionally occurs in field conditions, with natural light and seasonal cycles, adhering to ambient temperatures. In space environments, plant cultivation will require designing a new artificial environment with controlled and sustainable light, temperature, atmosphere, water, and fertilizers. The closed-loop system must ensure that nothing is wasted and everything is reused.

Moreover, the development of space-bound technologies must undergo rigorous testing and validation to comply with safety and operational standards. This is particularly critical for projects that launch hardware aboard rockets and integrate them into satellites or space stations. The "do no harm" principle is essential, ensuring that any deployed technology poses no threat to its host environment (NASA-STD-7001B). Compliance strategies must include a structured roadmap toward technological readiness, alongside environmental testing such as vibration, shock, and thermal vacuum tests (ISO 19683:2017).

It is also necessary to assess which plants can best adapt, in their current forms, to human-made environments on the Moon, Gateway, or Mars. Generating genetic variability and selecting plants that thrive in these new conditions is essential. To achieve these goals, a long-term research program will be initiated. A group of 45 Brazilian researchers from 13 internationally recognized institutions has formed the Space Farming Brazil Network. This network plans to carry out research in three major phases.

The first phase will involve experiments simulating deep-space conditions. Experiments will include: 1) computer simulations of energy deposition in seeds, cells, or plants exposed to space radiation, and validation of these simulations, 2) experiments to generate new genetic variability, select new plants, and observe their genetics, physiology, and nutrition, simulating, as closely as possible, conditions observed in deep space, particularly ionizing radiation and efficient water and energy use, and 3) adapting plants to enclosed environments using aeroponics technology in vertical farms. The results of this phase will be crucial for refining research methodologies and addressing the challenge of fully replicating extraterrestrial environments in laboratories (i.e., simultaneously subjecting biological components to ionizing radiation, microgravity, etc.).

The second phase will focus on trials in Earth's orbit, such as on the ISS, Gateway, the Moon, or during deep-space transit. Seed or cell samples will be exposed to these environments, as well as plants selected in the first phase. The environmental conditions will be adequately monitored and recorded. Once the samples are retrieved, further research will be conducted in laboratories or under controlled conditions to evaluate their development, physiology, and adaptation. Promising materials will then advance to the third, long-term phase, involving experiments in lunar, Martian, or deep-space transit environments.

All these steps will contribute to the advancement of Space Farming—cultivating plants in space. Selecting plants best adapted to these conditions will be crucial for the success of future human exploration and the construction of bases beyond Earth. This includes designing a suitable environment for their full growth and development in deep space.

Plants with traits suitable for space environments may also be of great interest on Earth. Characteristics such as increased nutritional value, compact plant structure, and tolerance to stresses like water scarcity, higher temperatures, and radiation could be invaluable in addressing challenges on Earth, such as those posed by the climate crisis (IPCC, 2023) and the rising demand for vertical farms (Butturini & Marcelis, 2020) in urban or peri-urban areas. Vertical farming technology could significantly boost plant growth in deserts, areas undergoing desertification, sub-zero temperatures, flood-prone areas, or where native vegetation must be conserved.

Thus, advances in the development of new cultivars and innovative production systems could significantly impact both the Artemis Program and the future of innovative food production, biomass, and biomaterial technologies. Although the program's primary goal is to expand knowledge for deep-space exploration, numerous spin-offs can be expected, similar to those seen with the Apollo Project (Corrado et al., 2023). Since 1976, NASA has identified over 2,000 technologies that originated from mission spin-offs (https://spinoff.nasa.gov/).

One such impact could be generating new genetic variability that may lead to cultivars with unique traits in Brazil, leveraging Space Breeding techniques or space mutagenesis. China has already achieved similar advances through Earth-orbit programs (http://glo.bo/3oIotvE?fbclid=IwAR0yvKAoaoTrEp20QONa-Ret2Y-DTegnAXt_mwBIyEcFpCP_wCO7PMIJk4s). Expertise in computational simulation of space radiation environments and experimental characterization of radiation could also lead to spin-offs for other projects and knowledge domains.

Given the globally recognized leadership of Brazilian agricultural research institutions, Brazil’s involvement in the Artemis Accords is timely. Leading projects in Space Farming, Brazil is well-positioned to contribute to selecting plants adapted to conditions found in human bases in deep space. These efforts could result in plants serving multiple purposes—human food, energy, biomass, or biodegradable materials—necessary to sustain human life in these new environments.

2. Research Objectives

2.1. Goals of the Space Farming Brazil Initiative

It is known that the environment outside Earth's atmosphere is composed of various factors, such as ultra-vacuum conditions, ionizing radiation such as gamma rays, protons, heavy ions, and neutrons, non-ionizing radiation, and microgravity. Exposure to such factors or even their combined effects over a certain period has been shown to favour the occurrence of DNA mutations in seed embryos, leading to potential anomalies in plant development, chromosomal aberrations, somatic mutations, etc (Mei et al., 1998). The technique of mutation induction in the space environment has been used for at least 25 years (Liu et al, 2008) in genetic improvement programs, primarily by Chinese researchers, who send seeds in recoverable satellites that remain on Earth orbit for several days (Luo et al., 2007). This methodology is well established and has been termed Space Breeding. The technique of mutant induction, both in laboratory conditions and in space, has already been successfully used in China, resulting in the release of more than 600 cultivars of 44 crops. In space experiments, at least four tomato cultivars (for productivity, earliness, and fruit quality) and rice (for earliness, grain quality, productivity, and low plant stature) have been registered (Liu et al., 2004).

This strategic choice allows for the exploration of sustainable food production in a controlled environment, optimising the use of limited resources such as space, water, and nutrients.

2.2. Focus on Chickpeas and Sweet Potatoes

The model plants selected for the study are sweet potato as an energy source and chickpea as a protein source, following a strategic and systematic approach to assess the viability of sustainable production systems for these two crops. Sweet potato stands out as an energy source due to its high starch and carbohydrate content (Sapakhova et al., 2023). It is a hardy and easy-to-grow crop, capable of adapting to different environmental conditions. Additionally, sweet potato is rich in essential nutrients such as vitamin A, vitamin C, fiber, and bioactive compounds, making it a suitable choice to meet the energy needs of astronauts. Chickpea, on the other hand, is a highly nutritious legume known for being an excellent source of plant protein (Kaur & Prasad, 2021; Arriagada et al., 2022). Legumes play an important role in human nutrition, providing essential amino acids, iron, zinc, and fiber. Chickpea is hardy and easy to grow, making it a suitable choice as a protein source in a space environment. Furthermore, chickpea has a natural ability to fix atmospheric nitrogen, reducing the need for chemical fertilizers in space cultivation systems (Kaur & Prasad, 2021). Thus, choosing these crops is a key component of this proposal to achieve the goal of producing energy and protein sources for space missions.

Sweet potatoes and chickpeas possess characteristics that facilitate their integration into space agricultural systems. Both crops have relatively short growing cycles and can be cultivated vertically, maximizing the use of available space. Furthermore, legumes like chickpeas have the ability to fix atmospheric nitrogen, which can contribute to the availability of nutrients in the cultivation system (Ridvan, 2023). By starting with these two species, the project can conduct in-depth studies on the cultivation, nutrition, and productivity of these crops in a simulated space environment. This information is essential to improve cultivation techniques, optimize production, and assess the ability to provide a balanced and sustainable diet for future long-duration space missions. As studies and experiments with sweet potatoes and chickpeas yield positive results, the experience gained can be applied in the development of more complex productive systems, involving a greater diversity of crops and the integration of other components and waste recycling.

Part of these studies will be established with an analogous irradiation environment, which will allow emulation of the effects of ionizing radiation present in the lunar environment, To achieve this goal, an existing facility will be modified to create a controlled environment suitable for long-term irradiation experiments, with dose rates closely resembling those found in the lunar environment, enabling the study of chronic effects in long-term irradiations, with potential spin-offs for other areas. This new setup will also enable the emulation of high-LET particle effects by utilising neutrons with energies specifically calculated to emulate cosmic radiation effects in lunar conditions, a method previously adopted by other facilities (Takahashi et al., 2020). This experimental framework represents a significant step forward in strengthening the research agenda, facilitating preliminary experiments at reduced costs, and promoting more sustainable scientific output over the long term.

In conclusion, the choice of sweet potatoes as an energy source and chickpeas as a protein source will allow the investigation of nutrition, cultivation efficiency, and logistics involved in developing the productive system sustainably in space, while providing a foundation for the future development of more diverse and integrated agricultural systems. It is expected that by the end of the project, it will be possible to develop and select plants with adapted traits to closed environments cultivation, such as those to be developed on the Moon, with a greater tolerance to chronic radiation, more water and energy efficiency, greater nutritional value, and architecture compatible with cultivation in these conditions. It is also expected to develop a prototype growth environment for sweet potato and chickpea plants, thus enabling the correct cultivation guidance on the lunar surface. It is believed that plants more adapted to adverse conditions on Earth, such as those resulting from climate change, or to production in closed environments, such as vertical farms already observed in various parts of the world, including cities like São Paulo, or deserts like Dubai, will also be obtained. Additionally, unforeseen discoveries or even technological breakthroughs, similar to what occurred in the Apollo Project, which had varied impacts in several areas of knowledge, are also expected.

3. Methodology

The activities planned for the first phase of the program, over the next five years, are divided into four components:

Project Management – The Space Farming Brazil initiative is anchored in a robust project management framework designed to facilitate effective collaboration among nearly 45 researchers from 12 Brazilian institutions and a U.S. university. This interdisciplinary team will focus on clear objectives and milestones, ensuring accountability and progress tracking throughout the project. A proactive risk management strategy will identify and mitigate potential challenges, while efficient resource allocation will optimize financial and technological support. Adherence to international safety and quality standards is paramount, with rigorous testing and validation processes integrated into the research. Additionally, the initiative will prioritize outreach and dissemination of findings to engage the scientific community and the public, highlighting the significance of advancements in space agriculture for both extraterrestrial missions and terrestrial applications. This comprehensive approach aims to drive innovation and ensure the successful execution of the initiative.

Space Breeding – This is a critical component of the Space Farming Brazil initiative, focusing on developing new plant genotypes that can thrive in the unique challenges of space environments. The primary goal is to enhance genetic variability and select cultivars that exhibit resilience to extreme conditions such as ionizing radiation, limited water availability, and nutrient scarcity. By simulating mutagenic space conditions, the project aims to induce beneficial mutations that will lead to the development of robust, high-yielding varieties suitable for both lunar agriculture and terrestrial applications, ultimately contributing to sustainable food production in controlled environments.

Space Farming – Space farming is a critical component of the initiative, aimed at establishing sustainable agricultural systems tailored for extraterrestrial environments, particularly on the Moon. The project focuses on developing production systems that optimize resource use, including water, energy, and nutrients, in controlled environments. By employing advanced techniques such as aeroponics and real-time monitoring, the initiative seeks to enhance crop productivity and resilience. This research not only aims to support long-term human presence in space but also seeks to generate insights and technologies that can improve agricultural practices on Earth, addressing challenges posed by climate change and resource limitations.;

Experimental Development – Experimental development is a pilar of the Space Farming Brazil initiative, focusing on creating and validating innovative agricultural technologies for space environments. It involves conducting simulations and experiments to assess plant responses to conditions such as microgravity and ionizing radiation. By generating genetic variability and selecting resilient plant varieties, the project aims to enhance crop tolerance to the extreme abiotic stresses encountered in space. The use of controlled environments will facilitate the adaptation of plants to enclosed systems, employing techniques like aeroponics to maximize resource efficiency. The findings from these experiments will inform the design of sustainable agricultural systems for future lunar missions and provide valuable insights applicable to terrestrial agriculture, particularly in addressing food security and climate resilience.

3.1. Space Plant Breeding Techniques

The main goal of Space Breeding is the generation of new variability and/or selection of genotypes adapted to space stresses. The selected genotype to be used in space breeding is the cv. BRS-Anembé, a purple sweet potato cultivar, so it is a good source of anthocyanin, an important antioxidant for plant and astronaut health. The cv BRS-Aleppo was selected as the chickpea genotype, an important source of tryptophan, predecessor of the serotonin, very helpful to the astronauts in stressful conditions.

The Space Plant Breeding Techniques will be very similar between chickpea and sweet potato species. Both will use seeds but just for sweet potato will also use cuttings. The strategy of simulating the mutagenic space environment is to simulate energy deposition in seeds/axillary buds for space and testing radiation fields. The first step is the seed/cuttings varieties chemical characterization and the analysis of the internal structure of seeds/axillary buds using X-ray microtomography. Based on these data, it is possible for doing a computational simulation and selection of high LET radiation doses. The simulated space radiation dose will be compared with conventional mutagenic breeding techniques. A preliminary testing will be performed to determine the gamma-ray doses in seeds and cuttings.

The LD 50 and GR 50 will be selected for low LET ionizing radiation. After that seeds/cutting will be exposed to the pre-selected doses of high and low LET radiation to induce mutants. Another study that is foreseen is the effect of microgravity on seed and explant irradiation using the 3D clinostat.

3.2. Selection Criteria for Model Plants

Field planting of Seeds and cuttings treated with pre-selected doses of high LET and gamma rays will be planted in the field to advance generations and select mutants. Selected plants will be evaluated for multiple agronomic traits in field and indoor chamber conditions. Model plants will need to have high efficiency in the use of water and energy and ionizing radiation tolerance.

3.3. Experimental Design for Space Conditions

Outspace greenhouses will have all conditions to keep plants growing. So, a technological solution will be provided for chickpea and sweet potato selected genotypes. For that, many experiments need to be performed to adapt these plants' growth from the field to a closed and bioregenerative environment. These adaptations include: adjustment of the environmental setup of the plant growth chamber, the development of indoor structures and pumping systems for hydroponics and aeroponics under low-gravity conditions, the determination of factors related to artificial lighting for the controlled environment production, the development of nutrient solutions and mineral nutrition for hydroponic and aeroponic cultivation, evaluation of technological options, microbiological, chemical and physicochemical characterization for effluent treatment and water reuse in hydroponics and aeroponics in a controlled environment and the prototyping of a capsule for vegetable production in a controlled atmosphere. Besides the use of a growth chamber, plants will be evaluated also by its production in Active Living Wall, under total light restriction conditions. For the ionizing simulation, analogous irradiation systems will be developed, after making a detailed design, assembly, approval and validation of the analogous irradiation environment.

Also, many other characterizations will be performed with chickpea and sweet potato genotypes as the microbiological characterization fertigated with reused water, in plant growth promotion and sustainability of the production system, molecular (analysis of the polymorphisms – SNPs - and genomic alterations - InDels, inversions, translocations and duplications), metabolomic and cytogenetic characterization of plants under challenging conditions, physiological characterization focusing on water, light, and nutrient use efficiency, development of a real-time remote monitoring system for plant physiological status via bioelectrical signal capture, analysis, and classification System, post-harvest quality characterization and cooking process evaluation.

About conservation activities, the expert team intend to work in in vitro production of seedlings using SETIS temporary immersion bioreactors or use of the Compact Germplasm Bank (CGB) and production of double haploids.

To advance from 1st phase (simulations on Earth) to the 2nd phase of the project (orbit tests), many activities will need to be performed as analysis and construction of test setup, design and simulation of packaging structures, analysis of results and specification of environmental tests, reworks, improvements and adaptations, if necessary, of the developed projects.

4. Environmental Challenges

Many challenges are foreseen when the goal is to simulate a space environment. Main challenge is to simulate the microgravity force to evaluate its direct or indirect effect in plants physiology or water distribution. Ionizing radiation simulation is also a challenge since in real conditions can be observed solar storms can enhance the radiation dose that was not predicted. The artificial and pressurized atmosphere will need to be carefully studied since plants and microorganisms directly depend on what kind of elements are present in the environment.

4.1. Factors Affecting Plant Growth in Space

Plant growth in space is influenced by several unique factors that differ from Earth conditions. Microgravity alters gravitational forces, affecting nutrient uptake and water movement, which can lead to changes in root orientation. This necessitates the development of cultivars that can adapt to microgravity.

Radiation exposure, including cosmic rays and solar particles, poses risks such as DNA damage and mutations. To counter these effects, research into radiation-resistant plant varieties and protective growth environments is essential. Nutrient availability is also critical; the composition of hydroponic or aeroponic systems may differ from Earth, requiring effective nutrient recycling systems to sustain plant health.

Water management is a significant challenge in space, necessitating efficient systems to provide adequate hydration while minimizing waste. Additionally, artificial lighting must be optimized to support photosynthesis, as natural sunlight is unavailable.

Temperature stability and atmospheric composition are vital for plant health, as space environments can experience extreme fluctuations. Finally, plants may encounter abiotic stressors and potential pests, making research into resilient varieties and pest management strategies crucial.

By addressing these factors, it may become feasible the effective cultivation strategies for sustainable life support systems in future space missions.

4.2. Strategies for Overcoming Abiotic Stressors

To ensure successful plant growth in space, it is crucial to develop strategies that mitigate the effects of abiotic stressors such as microgravity, radiation, nutrient deficiencies, and water scarcity. One effective approach is the selection and genetic modification of plant varieties that exhibit enhanced resilience to these stressors. This includes breeding for traits such as drought tolerance, radiation resistance, and efficient nutrient uptake.

Implementing advanced growth systems, such as hydroponics and aeroponics, can optimize nutrient delivery and water use efficiency, reducing waste and ensuring that plants receive adequate resources. Additionally, the use of controlled environment agriculture (CEA) techniques allows for precise regulation of light, temperature, and atmospheric conditions, creating optimal growth environments.

Integrating biotechnological solutions, such as the application of beneficial microorganisms, can enhance plant health and stress tolerance by improving nutrient availability and disease resistance. Furthermore, real-time monitoring systems can track plant physiological responses, enabling timely interventions to address stress conditions.

By combining these strategies, it will become possible to enhance plant resilience, ensuring sustainable food production in the challenging conditions of space.

5. Expected Outcomes

5.1. Development of Resilient Crop Varieties

The development of resilient crop varieties is a primary expected outcome of the space farming initiative. By utilizing space breeding techniques, the researcher team aim to generate new plant genotypes that can withstand the unique challenges of extraterrestrial environments, such as microgravity, radiation, and limited resources.

Key objectives include enhancing traits such as drought tolerance, nutrient efficiency, and resistance to ionizing radiation. The selected cultivars, such as the BRS-Anembé sweet potato and BRS-Aleppo chickpea, are specifically chosen for their nutritional benefits and adaptability to controlled environments.

Through rigorous testing and selection processes, these resilient varieties will not only support sustainable food production in space but also provide valuable insights for improving crop resilience on Earth, addressing challenges related to climate change and resource scarcity.

5.2. Contributions to Sustainable Life Support Systems

The initiative aims to significantly enhance sustainable life support systems for future space missions. By developing efficient agricultural practices tailored to extraterrestrial environments, the project will contribute to closed-loop systems that recycle water, nutrients, and waste, minimizing resource consumption.

The integration of resilient crop varieties will ensure a reliable food supply, essential for long-duration missions. Additionally, advancements in controlled environment agriculture (CEA) will optimize growth conditions, improving energy and resource efficiency.

Research into the use of beneficial microorganisms and automated systems will further enhance crop productivity while reducing the workload on astronauts. These innovations will not only support human life in space but also provide valuable technologies and methodologies that can be applied to improve sustainability in terrestrial agriculture.

6. Implications for Future Space Missions

6.1. Enhancing Food Security in Extraterrestrial Environments

Enhancing food security in extraterrestrial environments is a critical objective of the space farming initiative. By developing resilient crop varieties and sustainable agricultural practices, the project aims to establish reliable food production systems that can operate independently of Earth supplies.

The cultivation of nutrient-rich crops, such as chickpeas and sweet potatoes, will help provide essential sustenance for astronauts during long-duration missions. Implementing closed-loop systems will ensure efficient use of resources, allowing for the recycling of water and nutrients, thereby minimizing waste.

Moreover, the integration of advanced technologies, such as automated growth monitoring and biotechnological enhancements, will optimize crop yields and resilience against space-specific stressors. These efforts will not only secure food availability for future missions to the Moon and Mars but also contribute to the overall health and well-being of crew members, making long-term space exploration feasible.

6.2. Potential Applications on Earth

The advancements in space farming technologies and resilient crop development have significant potential applications on Earth. The techniques and knowledge gained from cultivating crops in controlled extraterrestrial environments can be adapted to improve agricultural practices in resource-limited settings.

For instance, the development of drought-tolerant and nutrient-efficient crop varieties can enhance food security in regions facing climate change challenges. Additionally, the closed-loop systems designed for space can be implemented in urban agriculture and vertical farming, promoting sustainable practices that minimize waste and optimize resource use.

Furthermore, the integration of biotechnological innovations and automated systems can lead to increased productivity and resilience in terrestrial farming, addressing issues such as soil degradation and water scarcity. Overall, the insights gained from space agriculture can drive advancements in sustainable practices, benefiting both space exploration and global food systems.

7. CONCLUSION

7.1. Goals, challenges and potential contributions

The primary goal of the space farming initiative is to develop sustainable agricultural systems capable of supporting human life in extraterrestrial environments. This ambitious program seeks to cultivate resilient crop varieties that can thrive under the unique conditions of space, ensuring food security for long-duration missions to the Moon, Mars, and beyond.

However, the initiative faces several challenges, including simulating microgravity and radiation effects on plant physiology, as well as creating closed-loop systems that effectively recycle resources. Overcoming these obstacles requires rigorous testing, innovative research methodologies, and collaboration among multidisciplinary teams.

The potential contributions of this initiative extend beyond space exploration. The technologies and practices developed for space farming can significantly impact terrestrial agriculture by enhancing crop resilience, optimizing resource use, and promoting sustainable practices. By addressing both the challenges of space and the needs of Earth, this program aims to foster international partnerships and drive advancements in food security and sustainability for future generations.

7.2. Future Directions

The future directions of the space farming initiative are poised to expand significantly as research progresses. Building on the foundational work with chickpeas and sweet potatoes, the program will explore a broader range of plant species, enhancing genetic diversity and resilience to extreme conditions. This expansion will facilitate the development of crops tailored not only for lunar and Martian environments but also for addressing agricultural challenges on Earth.

Collaboration with international partners will be crucial in advancing research and technology transfer, fostering innovations in areas such as artificial intelligence, automation, and materials engineering. Additionally, the initiative will focus on integrating biogenerative life support systems that synergize food production with waste recycling, creating sustainable ecosystems in space. The insights gained from these systems will inform practices that can be applied to improve sustainability in urban and rural agriculture on Earth.

Ultimately, the space farming initiative aims to contribute to a resilient future for humanity, ensuring food security in both extraterrestrial missions and addressing pressing challenges in global agriculture. By leveraging the lessons learned from space, the program aspires to drive innovation and sustainability across multiple sectors.

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References

Arriagada, O., et al., (2022). A Comprehensive review on chickpea (Cicer arietinum L.) breeding for abiotic stress tolerance and climate change resilience. International Journal of Molecular Sciences, 23(12), 6794.

Butturini, M.; Marcelis, L. F. (2020) Vertical farming in Europe: Present status and outlook. Plant Fact. 1, 77–91.

Corrado, L. et al. (2023). The macroeconomic spillovers from space activity. Proceedings of the National Academy of Sciences, 120(43), e2221342120.

IPCC (2023) https://www.ipcc.ch/ar6-syr/ consultado em 16/11/23

Kaur, R., & Prasad, K. (2021). Nutritional characteristics and value-added products of Chickpea (Cicer arietinum)—A review. Journal of Postharvest Technology, 9(2), 1-13.

Liu, L. et al. (2004) Mutation Breeding Review. 14:1-62.

Liu, L. et al. (2008) Advances in crop improvement by space mutagenesis in China. https://www.intlcss.org/files/icss/congress-proceedings/2008-papers/cs3-s7/cs3-s7-o2-luxiang-liu.pdf.

Luo, Y. et al. (2007) Front. Biol. China 2:297–302.

Mei, M. et al. (1998) Adv. Space Res. 22 (12): 1691-1697.

NASA (2022) https://www.nasa.gov/wp-content/uploads/2022/11/Artemis-Accords-signed-13Oct2020.pdf, em 16/11/23

Rıdvan, U. Ç. A. R. (2023). Biological Nitrogen Fixation in Legumes: An Overview. MAS Journal of Applied Sciences, 8(2), 213-221.

Sapakhova, Z. et al. (2023). Sweet Potato as a Key Crop for Food Security under the Conditions of Global Climate Change: A Review. Plants, 12(13), 2516.

Takahashi, A.; Yamanouchi, S.; Takeuchi, K.; Takahashi, S.; Tashiro, M.; Hidema, J.; Higashitani, A.; Adachi, T.; Zhang, S.; Guirguis, F.N.L.; et al. (2020). Combined Environment Simulator for Low-Dose-Rate Radiation and Partial Gravity of Moon and Mars. Life, 10, 274. https://doi.org/10.3390/life10110274

International Organization for Standardization. (2016). Space systems — Risk management (ISO 14645:2016). ISO. Retrieved from https://www.iso.org/standard/67256.html

International Organization for Standardization. (2017). Space systems — Human-life safety in space systems — Part 1: Requirements (ISO 10776:2017). ISO. Retrieved from https://www.iso.org/standard/72258.html

NASA. (2006). NASA Standard for Mitigating In-Space Debris (NASA-STD-8719.14). NASA Office of Safety and Mission Assurance. Retrieved from https://standards.nasa.gov/standard/nasa/nasa-std-7002a

International Organization for Standardization. (2017). Space systems — Design, development, verification, and operation of space systems — Safety requirements (ISO 19683:2017). ISO. Retrieved from https://www.iso.org/standard/70385.html

NASA. (2004). NASA Standard for Models and Simulations (NASA-STD-7001B). NASA Office of Safety and Mission Assurance. Retrieved from https://standards.nasa.gov/standard/nasa/nasa-std-7001b

NASA Systems Engineering Handbook. (2020). NASA Systems Engineering Handbook (Rev. 2). NASA. Retrieved from https://ntrs.nasa.gov/citations/20205003691

NASA-STD-8739.8. (2013). NASA Software Assurance Standard. NASA Office of Safety and Mission Assurance. Retrieved from https://standards.nasa.gov/standard/nasa/nasa-std-87398