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# Perspectives for plant biology in space and analogue environments

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Advancements in plant space biology are required for the realization of human space exploration missions, where the re-supply of resources from Earth is not feasible. Until a few decades ago, space life science was focused on the impact of the space environment on the human body. More recently, the interest in plant space biology has increased because plants are key organisms in Bioregenerative Life Support Systems (BLSS) for the regeneration of resources and fresh food production. Moreover, plants play an important role in psychological support for astronauts. The definition of cultivation requirements for the design, realization, and successful operation of BLSS must consider the effects of space factors on plants. Altered gravitational fields and radiation exposure are the main space factors inducing changes in gene expression, cell proliferation and differentiation, signalling and physiological processes with possible consequences on tissue organization and organogenesis, thus on the whole plant functioning. Interestingly, the changes at the cellular and molecular levels do not always result in organismic or developmental changes. This apparent paradox is a current research challenge. In this paper, the main findings of gravity- and radiation-related research on higher plants are summarized, highlighting the knowledge gaps that are still necessary to fill. Existing experimental facilities to simulate the effect of space factors, as well as requirements for future facilities for possible experiments to achieve fundamental biology goals are considered. Finally, the need for making synergies among disciplines and for establishing global standard operating procedures for analyses and data collection in space experiments is highlighted.

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## INTRODUCTION

At the beginning of space exploration, research in space life science was focused on the human body to gain a fundamental understanding on the responses to the stressful space environment, to ultimately prevent health risks and protect astronauts by managing space-induced pathological issues<sup>1,2</sup>. In the last decades, increasing interest has been raised towards plant space biology due to the awareness that cultivation of higher plants in space is a requirement for long-duration human missions, where the regeneration of resources and plant-based food production onboard must be increased at the expense of re-supply from Earth<sup>3</sup>.

Plants play a crucial role in Bioregenerative Life Support Systems (BLSS). Artificial ecosystems such as the BLSS are high-technology systems, based on the integration of physico-chemical and biological processes, to support long interplanetary missions<sup>4,5</sup>. The BLSS concept includes several interconnected compartments in which different organisms are used to sequentially recycle resources<sup>6,7</sup>. Within a BLSS, the photoautotrophic compartment enables the production of edible biomass, oxygen, and water as resources for the astronaut, starting from carbon dioxide, wastewater and other wastes. An example of BLSS is the MELISSA (Micro-Ecological Life Support System Alternative) loop by the European Space Agency (ESA) that aims to sustain astronaut life in space missions to reduce the initial payload and

dependency from Earth<sup>8</sup>. The MELISSA loop is made of interconnected compartments among which the requirements of the higher plant compartment need to be fulfilled at least in part by the outputs of other compartments<sup>9</sup>. As well, the species/ cultivar choice and environmental control are dictated by the need to meet the requirements of the other compartments (e.g., oxygen requirements of the animal crew) in addition to the generally accepted requirements including short cultivation cycles, reduced plant size, high harvest index, and resistance to diseases. Increasing effort is posed on plants to produce healthy food specifically designed to sustain crew in long term missions<sup>4,7,10,11</sup>.

Additionally, research in space-plant biology and space-agriculture is required alongside the strong efforts to increase the knowledge on human biology in space with the aim to predict risk factors, prevent disease(s), and implement effective countermeasures to manage health emergencies during missions. Among countermeasures for assuring astronauts' well-being against degenerative diseases and psychological issues, there is the introduction, in their nutrition, of plant-derived fresh food produced directly on board or within a habitat. Further, there may also be benefits for crew mental health by allowing crews to participate in plant cultivation in the living and/or working pressurized modules in space<sup>12,13</sup>.

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## **Table of Contents Perspectives In Biology**

1. Understanding the eBook Perspectives In Biology
  - The Rise of Digital Reading Perspectives In Biology
  - Advantages of eBooks Over Traditional Books
2. Identifying Perspectives In Biology
  - Exploring Different Genres
  - Considering Fiction vs. Non-Fiction
  - Determining Your Reading Goals
3. Choosing the Right eBook Platform
  - Popular eBook Platforms
  - Features to Look for in an Perspectives In Biology
  - User-Friendly Interface
4. Exploring eBook Recommendations from Perspectives In Biology
  - Personalized Recommendations

- Perspectives In Biology User Reviews and Ratings
- Perspectives In Biology and Bestseller Lists
- 5. Accessing Perspectives In Biology Free and Paid eBooks
  - Perspectives In Biology Public Domain eBooks
  - Perspectives In Biology eBook Subscription Services
  - Perspectives In Biology Budget-Friendly Options
- 6. Navigating Perspectives In Biology eBook Formats
  - ePub, PDF, MOBI, and More
  - Perspectives In Biology Compatibility with Devices
  - Perspectives In Biology Enhanced eBook Features
- 7. Enhancing Your Reading Experience
  - Adjustable Fonts and Text Sizes of Perspectives In Biology
  - Highlighting and Note-Taking Perspectives In Biology
  - Interactive Elements Perspectives In Biology
- 8. Staying Engaged with Perspectives In Biology
  - Joining Online Reading Communities
  - Participating in Virtual Book Clubs
  - Following Authors and Publishers Perspectives In Biology
- 9. Balancing eBooks and Physical Books Perspectives In Biology
  - Benefits of a Digital Library
  - Creating a Diverse Reading Collection Perspectives In Biology
- 10. Overcoming Reading Challenges
  - Dealing with Digital Eye Strain
  - Minimizing Distractions
  - Managing Screen Time
- 11. Cultivating a Reading Routine Perspectives In Biology
  - Setting Reading Goals Perspectives In Biology
  - Carving Out Dedicated Reading Time
- 12. Sourcing Reliable Information of Perspectives In Biology
  - Fact-Checking eBook Content of Perspectives In Biology

- Distinguishing Credible Sources
- 13. Promoting Lifelong Learning
  - Utilizing eBooks for Skill Development
  - Exploring Educational eBooks
- 14. Embracing eBook Trends
  - Integration of Multimedia Elements
  - Interactive and Gamified eBooks

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