Astrobotany and Space Agriculture: Growing the Future Beyond Earth

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ABSTRACT

The expansion of human activities beyond low Earth orbit will require sustainable approaches to food production and life-support, particularly for long-duration missions to the Moon and Mars. Astrobotany and space agriculture provide a foundation for developing plant-based systems capable of producing fresh food while contributing to atmospheric regeneration, water recycling, and crew well-being. This article reviews the biological and technological challenges associated with cultivating plants beyond Earth, with particular emphasis on microgravity, partial gravity, ionising radiation, altered atmospheric conditions, restricted root-zone environments, and plant–microbe interactions. It further examines the progression of plant research from early orbital experiments to advanced cultivation platforms such as NASA's Veggie system and Advanced Plant Habitat aboard the International Space Station. Key approaches for extraterrestrial crop production, including hydroponics, aeroponics, substrate-based cultivation, precision LED lighting, and closed-loop resource recycling, are discussed. The selection of suitable crops is also considered in relation to growth duration, nutritional value, biomass productivity, resource-use efficiency, and space constraints. Beyond food production, plants have potential roles within bioregenerative life-support systems through carbon dioxide fixation, oxygen generation, and water recycling, although current systems remain insufficient to replace conventional life-support technologies completely. The article also highlights how technologies developed for space cultivation, including controlled-environment agriculture, sensor-based monitoring, resource-efficient hydroponics, and precision lighting, can contribute to sustainable agriculture on Earth. Future lunar and Martian cultivation will depend on advances in automation, radiation protection, microbial management, resource recycling, and reliable multi-crop production. Thus, space agriculture represents not only a pathway toward sustainable human exploration beyond Earth but also an important research frontier for developing resilient, resource-efficient agricultural systems on our home planet.

INTRODUCTION:

Human spaceflight has traditionally depended on pre-packaged, shelf-stable food transported from Earth to sustain astronauts during short-duration orbital missions. However, this approach becomes increasingly impractical for long-duration exploration missions, such as a crewed journey to Mars, which may require six to nine months of transit, or the establishment of a permanent research station on the Moon. The cost and logistical constraints associated with transporting large quantities of food make complete dependence on Earth-based supplies unsustainable. Launch costs to low Earth orbit remain approximately US $1,500-$2,700 per kilogram, depending on the launch vehicle and trajectory, while food payloads compete for valuable mass with life-support systems, scientific equipment, and other mission-critical hardware. A three-person crew travelling to Mars, for instance, could require approximately 900-1,000 kg of food for the outbound journey alone, even before accounting for food requirements during surface operations (Cooper *et al.,* 2011). Under such circumstances, producing fresh food during space missions is no longer simply a matter of improving dietary variety or astronaut well-being; it represents an important component of sustainable long-duration space exploration.

Agriculture on Earth has evolved within a relatively stable environment characterized by gravity, a protective atmosphere, abundant water, and predictable light–dark cycles. These conditions cannot be readily replicated in extraterrestrial environments. Microgravity and reduced-gravity conditions can profoundly alter fundamental plant processes, including root orientation, water distribution, nutrient transport, and gas exchange. At the same time, exposure to elevated radiation, confined atmospheric conditions, and limited environmental resources introduces additional stresses that terrestrial crops have rarely encountered during their evolutionary history. Addressing these challenges has given rise to **astrobotany**, an interdisciplinary field concerned with understanding plant growth, development, physiology, and adaptation under spaceflight conditions. Astrobotany brings together concepts from plant physiology, agronomy, controlled-environment agriculture (CEA), space biology, and environmental engineering to develop reliable methods for cultivating plants beyond Earth.

The significance of space agriculture, however, extends well beyond the needs of future astronauts. Research conducted in spacecraft and space analogues is contributing to advances in controlled-environment cultivation, including precision LED lighting, hydroponic and soilless production systems, optimized root-zone management, environmental sensing, and automated climate

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control. Many of these technologies are increasingly being adapted for terrestrial applications such as vertical farming, protected cultivation, urban agriculture, and food production in resource-constrained environments. Furthermore, investigating plant responses to stresses such as altered gravity, restricted root-zone oxygen, radiation, and limited water availability can provide valuable insights into plant adaptation and stress physiology. Consequently, space agriculture is evolving from a strategy for sustaining human life beyond Earth into a broader research platform for developing efficient, resilient, and resource-conscious agricultural systems on Earth. In this sense, the pursuit of **"growing the future beyond Earth"** may ultimately contribute to securing the future of agriculture on our own planet.

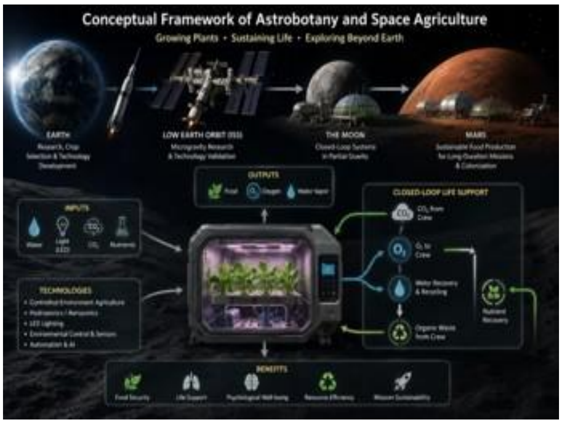

Figure 1. Conceptual framework of astrobotany and space agriculture

Astrobotany: Understanding Plants Beyond Earth

Astrobotany is an interdisciplinary field that investigates how plants grow, develop, reproduce, and respond to environmental conditions beyond those characteristics of Earth. Its scope encompasses plant responses to microgravity and partial gravity, elevated levels of ionising radiation, altered atmospheric composition, restricted root-zone volumes, and the confined, humidity-controlled environments of spacecraft and space habitats. By integrating concepts from gravitational biology, radiation biology, plant ecophysiology, and molecular plant science, astrobotany seeks to understand how the absence or modification of familiar environmental cues influences fundamental processes of plant growth and development.

Gravity is a major environmental signal governing plant architecture and development, particularly through **gravitropism**. Under terrestrial conditions, roots generally exhibit positive gravitropism by growing downward, whereas shoots display negative gravitropism by growing upward. This directional growth is mediated largely by the sedimentation of specialised starch-filled organelles known as statoliths within gravity-sensing cells called statocytes, which are present primarily in the root cap and shoot apex. Under microgravity, statolith sedimentation is greatly reduced or absent, weakening the directional signal required for normal gravitropic responses. Consequently, plants may exhibit altered root orientation, modified shoot architecture, and changes in the distribution and transport of growth-regulating hormones, particularly auxin along the shoot–root axis (Morita, 2010). Reduced gravity also influences water and solute transport within plant growth systems. In the absence of normal gravitational drainage, water can accumulate around roots as films or form irregular bubbles, potentially altering root-zone aeration, nutrient availability, and overall water distribution.

Radiation represents another major challenge for plant cultivation beyond Earth's protective atmosphere and magnetosphere. During deep-space missions, plants may be exposed to galactic cosmic rays and solar particle events at radiation levels substantially greater than those encountered in terrestrial environments and potentially higher than those experienced during routine operations aboard the International Space Station (ISS). Ionising radiation can cause DNA damage, including double-strand breaks, interfere with cell division in actively growing meristematic tissues, and contribute to oxidative stress and premature leaf senescence. The sensitivity of reproductive tissues, including pollen, ovules, and developing seeds, is particularly important because successful completion of the reproductive cycle will be essential for missions that depend on seed production and crop regeneration over multiple generations (Verseux *et al*., 2016).

Plant–microbe interactions introduce an additional layer of complexity to space-based cultivation. Plants grown in closed habitats develop within microbial communities that can differ considerably from those found in conventional terrestrial soils. The behaviour and functioning of beneficial microorganisms, including mycorrhizal fungi and plant-growth-promoting rhizobacteria, may be altered by microgravity, restricted root-zone conditions, and modified atmospheric environments. These microorganisms normally contribute to nutrient acquisition, root development, stress tolerance, and plant health, making their stability important for sustainable crop production in space. At the same time, microorganisms that are normally kept in check by competitive interactions in natural soil environments may proliferate under the relatively stable temperature, humidity, and nutrient conditions of controlled plant-growth chambers. Fungal growth and microbial proliferation observed in the ISS Veggie plant-growth system highlight the importance of understanding and managing plant-associated microbial communities in closed space habitats (Massa *et al.,* 2017).

Together, altered gravity, space radiation, and changes in plant microbe interactions demonstrate that growing plants beyond Earth involves far more than simply providing light, water, and nutrients. Astrobotany therefore serves as a foundation for identifying the biological constraints of extraterrestrial agriculture and for developing cultivation strategies capable of supporting reliable plant growth throughout long-duration space missions.

Figure 2. Effects of altered gravity on plant growth and development.

From Space Experiments to Space Agriculture

Systematic plant experimentation in space began in the 1960s with Soviet Biosatellite missions carrying seeds of various species for exposure to microgravity and radiation. Early experiments established that plant germination could occur in orbit and that basic developmental processes were not immediately abolished by the absence of gravity, though morphological abnormalities were frequently observed. During the 1970s and 1980s, Soviet cosmonauts aboard Salyut stations cultivated onions and other short-cycle crops in rudimentary hydroponic trays, generating the first evidence that vegetative growth cycles could be completed in space habitats (Sychev *et al.,* 2007).

Figure 3. Evolution of plant cultivation in space: from early orbital experiments to advanced plant-growth systems.

The construction and continuous occupation of the ISS from 2000 onward created a stable orbital platform for longer-duration plant research. NASA's Veggie plant growth system, developed and deployed to the ISS in 2014, represented the first operational food-production experiment under the agency's Advanced Food Technology programme. Veggie uses a flexible, expandable enclosure illuminated by an array of red, blue, and green LEDs delivering a photosynthetically active radiation (PAR) flux suitable for leafy vegetable cultivation. Crops including *Lactuca sativa* (romaine and red lettuce varieties), *Brassica rapa* (mizuna mustard), and zinnia flowers have been successfully grown to harvest. Astronauts consumed the first ISS-grown lettuce in 2015 following microbiological safety verification, marking a milestone in crew-consumed space-grown food (Massa *et al.,* 2017).

The Advanced Plant Habitat (APH), deployed to the ISS in 2018, considerably expanded research capability. APH is a fully enclosed, automated growth chamber integrating more than 180 sensors monitoring air temperature, relative humidity, carbon dioxide concentration, root-zone moisture content, and PAR irradiance. Unlike Veggie, which requires regular crew interaction for watering and observation, APH operates largely autonomously, transmitting continuous telemetry to a ground-support team at Kennedy Space Center. APH has supported growth experiments with *Arabidopsis thaliana*, dwarf wheat (*Triticum aestivum*), and other model and crop species, providing high-resolution physiological data not obtainable from simpler systems (Monje *et al.,* 2020).

The Plant Habitat-03 experiment, completed aboard the ISS in 2022, grew Chile Peppers (*Capsicum annuum*) through a complete fruiting cycle over 137 days one of the longest continuous plant growth experiments conducted in orbit. The experiment demonstrated that reproductive development, including pollination and fruit set, can proceed in microgravity and provided data on the sensory qualities and nutritional composition of space-grown produce (NASA, 2022).

Figure 4. (a) NASA astronaut Shane Kimbrough inserts a science carrier device into the Advanced Plant Habitat (APH), which contains 48 Hatch Chile Pepper seeds. (b) A harvest of Hatch Chile peppers @NASA

How Plants Can Be Grown Beyond Earth

Cultivating crops beyond Earth requires decoupling plant production from the soil, gravity, and weather systems on which terrestrial agriculture depends. Hydroponics that is the cultivation of plants in nutrient solutions without soil satisfies this requirement by delivering water and dissolved mineral nutrients directly to the root zone through controlled delivery systems. In a spacecraft or habitat context, the absence of gravity prevents nutrient solution from draining predictably, so conventional flood-and-drain or deep-water culture systems must be adapted. Nutrient film technique (NFT) systems, in which a thin continuous film of solution flows along a root channel, can be configured to function using pump-driven circulation rather than gravitational flow. Aeroponic systems, which deliver nutrient solution as a fine mist directly to suspended root systems, offer the additional advantage of continuous root-zone aeration, eliminating the risk of anaerobic conditions that can develop in flooded hydroponic media under microgravity.

Substrate-based cultivation using porous inorganic growing media including clay aggregates, perlite, and porous ceramic tiles that provides physical root anchorage and capillary water distribution, partly compensating for the absence of gravitational drainage. NASA's Veggie system employs a porous clay-based substrate containing controlled-release fertiliser, which distributes moisture and nutrients to plant roots through capillary action. While this approach is operationally simple and reliable for short-cycle leafy crops, its precision for water and nutrient management is more limited than recirculating hydroponic systems.

Artificial illumination is essential for all space cultivation, as solar radiation is not reliably accessible within spacecraft interiors. Light-emitting diode (LED) technology has become standard for space plant lighting because of its high photon efficacy, spectral flexibility, and low heat output. Plants use primarily red light (approximately 660 nm) for photosynthesis and blue light (approximately 450 nm) for photomorphogenic responses including compact growth habit and root development. Far-red light (approximately 730 nm) modulates shade-avoidance responses and can accelerate flowering in long-day species. By adjusting the proportions of these wavebands, LED systems can be optimised for specific crops and growth stages a capability not available with broad-spectrum lamps (Massa *et al.,* 2017).

Closed-loop resource recycling is a fundamental design principle for sustainable space agriculture. Transpiration water lost from plant surfaces is recovered through atmospheric condensation systems and returned as irrigation water after filtration, contributing to the spacecraft's overall water recycling balance. Carbon dioxide produced by crew respiration can be supplied as a carbon source for plant photosynthesis, closing the atmospheric loop and reducing the volume of chemical carbon dioxide scrubbing required. Integrating plant growth with waste processing using treated grey water or composted organic waste as nutrient sources further reduces resupply requirements on extended missions, though the microbial and chemical safety implications require careful management (Wheeler, 2017).

Crops for Space

Not all crops are equally suited to cultivation in resource-limited, confined space environments. Selection criteria for space crops prioritise a compact growth habit that minimises volume requirements, a high ratio of edible to total plant biomass (harvest index), a short growth cycle permitting multiple harvests within a mission segment, and efficient use of water, nutrients, and light energy. Nutritional completeness - particularly the capacity to deliver vitamins, minerals, and essential fatty acids lacking from shelf-stable rations - is a further important criterion.

Leafy vegetables satisfy most of these criteria and have consequently dominated early ISS food-production experiments. Cultivars of *Lactuca sativa* (lettuce), *Brassica rapa* (mustard greens, pak choi), and spinach (*Spinacia oleracea*) produce harvestable biomass within three to five weeks, provide vitamins C, K, and folate, and maintain compact rosette growth habits that require minimal canopy management. Radish (*Raphanus sativus*) was the focus of the Plant Habitat-02 experiment on the ISS, completing a 27-day growth cycle and yielding edible roots and leaves (Heiney, 2020).

Cereals and legumes are of interest for longer missions requiring calorie-dense staple crops. Dwarf wheat cultivars have been studied in orbital experiments since the 1990s; however, achieving consistently viable grain yields in microgravity remains challenging due to irregular pollination and altered ear development. Soybeans (*Glycine max*) are of particular nutritional interest because they provide both protein and lipids. Tomatoes (*Solanum lycopersicum*) and peppers (*Capsicum annuum*) represent fruit-bearing crops with demonstrated growth feasibility in orbital environments, though their longer growth cycles and higher canopy volumes impose greater resource demands compared to leafy vegetables.

Plants as Part of Life-Support Systems

Within the engineering framework of bioregenerative life-support systems (BLSS), plants are valued not solely as food sources but as biological processors that simultaneously regenerate atmosphere, recycle water, and manage organic waste. The photosynthetic conversion of carbon dioxide and water into carbohydrate and oxygen is the biochemical basis of this life-support function. Calculations based on net photosynthetic rates measured for candidate space crops indicate that approximately 11-13 m^2 of actively growing leafy vegetable canopy is required to meet the oxygen demand of one adult astronaut (Wheeler, 2017). At the cultivation scales realistically achievable within near-term spacecraft, plant systems can therefore supplement but not replace chemical oxygen generation and carbon dioxide removal systems.

Transpirational water vapour released from plant canopies contributes meaningfully to spacecraft humidity management and water recovery. On the ISS, the Water Recovery System processes humidity condensate - partially derived from plant transpiration - as part of the overall water recycling loop, achieving recovery rates exceeding 90% (Carter *et al.,* 2020). Scaling plant cultivation would increase the transpirational contribution to recovered water, reducing the demand for resupply water. This integration of plant systems into water management infrastructure represents a demonstrated operational capability.

The psychological contribution of plant cultivation to astronaut well-being, while more difficult to quantify than atmospheric or nutritional parameters, has been consistently noted in crew evaluations and post-mission reports. The presence of living plants in an otherwise mechanical environment provides visual interest, engagement with a biological growth process, and the sensory experience of fresh food factors associated with improved mood, reduced stress, and maintenance of a sense of normalcy during prolonged confinement (Stuster, 2010). These benefits are increasingly regarded as legitimate mission-planning considerations for long-duration missions beyond low Earth orbit.

Major Challenges in Space Agriculture

Microgravity and partial gravity remain the most fundamental and pervasive challenges for space-based plant cultivation. Beyond the gravitropic disruptions described earlier, microgravity impairs gas exchange at the leaf surface by inhibiting the convective boundary-layer airflow that normally facilitates carbon dioxide uptake and oxygen removal from the leaf microenvironment. Forced ventilation provided by fans within plant growth chambers can partially compensate, but optimising airflow without inducing mechanical stress or creating heterogeneous conditions across the canopy requires careful engineering. Root-zone aeration is similarly problematic: in the absence of gravity, water does not drain freely from substrates, creating a risk of anaerobic root zones that impair nutrient uptake and can promote pathogenic waterborne organisms.

Radiation exposure is a challenge of a different character. Within the ISS, the Earth’s magnetosphere and the station’s structural shielding reduce radiation doses to levels that appear manageable for plants over growth-cycle timescales; however, transit missions and surface habitats on the Moon or Mars will expose crops to substantially higher cumulative doses of galactic cosmic rays and solar particle events. The long-term genetic and physiological consequences of chronic radiation exposure particularly effects on reproductive biology and seed viability across multiple generations are not yet fully characterised (Verseux *et al.,* 2016).

Microbial contamination of plant growth systems represents an operationally significant risk. The enclosed, warm, humid environments optimal for plant growth are equally favourable for the proliferation of opportunistic fungal and bacterial pathogens. Incidents of fungal overgrowth have been documented in ISS plant growth chambers, and the closed nature of these systems means that a pathogen, once established, is difficult to eradicate without abandoning the crop. Detection currently depends on visual inspection and periodic microbiological culturing reactive approaches unsuited to autonomous systems operating during long-duration missions where real-time ground support communication is unavailable.

Energy and volume constraints impose practical limits on cultivation scale. LED lighting systems for plant growth typically require 200–300 W m^{-2} of growing area; providing this energy on a spacecraft or surface habitat with limited photovoltaic generation capacity restricts the proportion of crew nutritional requirements that plant production can realistically supply in the near term. Achieving full caloric provisioning from on-site agriculture would require cultivation areas of hundreds of square metres per crew member incompatible with the volume budgets of foreseeable spacecraft designs.

Space Agriculture and the Future of Terrestrial Agriculture

Technologies developed to meet the demanding constraints of space cultivation have practical applications in terrestrial agriculture, particularly in the rapidly expanding field of controlled-environment agriculture. LED grow-light systems optimised through space-plant research are now widely deployed in commercial vertical farms and greenhouse operations, with manufacturers reporting photon efficacies exceeding 3.0 μmol J^{-1} substantially above the efficiency of earlier high-pressure sodium lamps. The spectral tuning data generated by space-plant experiments underpin the design of crop-specific lighting recipes used in commercial production of leafy vegetables, herbs, and other high-value crops in indoor farms worldwide (Kozai *et al*., 2019).

Closed-loop nutrient and water management systems derived from space agriculture research contribute to reducing the resource footprint of food production in regions facing water scarcity or soil degradation. Recirculating hydroponic systems that recover and reuse nutrient solution with minimal discharge can reduce water consumption by 70–90% relative to conventional irrigation, while simultaneously eliminating nutrient runoff that contributes to eutrophication of water bodies. These efficiencies are of particular relevance to arid regions and urban food-production systems where freshwater access is constrained.

Research into plant stress physiology conducted under space conditions is expanding understanding of how plants perceive and respond to multiple simultaneous environmental stressors - knowledge increasingly relevant as agricultural systems on Earth face compounding pressures from climate change, including elevated temperatures, erratic precipitation, and elevated atmospheric CO_2. Sensor-dense monitoring systems used in space plant chambers providing continuous, high-resolution data on plant microclimate, gas exchange, and root-zone conditions are informing the development of precision agriculture systems for field and greenhouse applications that reduce input costs and improve resource-use efficiency (Wheeler, 2017).

Future Prospects: Moon, Mars, and Beyond

The Artemis programme's planned return of astronauts to the lunar surface, and NASA's stated goal of human Mars transit missions in the coming decades, provide the near-term context within which space agriculture must develop from a research discipline into an operational capability. For lunar surface habitats, initial cultivation is likely to focus on leafy vegetables and radishes in compact, semi-automated chambers supplementing pre-packaged rations. Lunar regolith, while containing mineral elements that plants require, is characterised by fine abrasive particles, the absence of organic matter, and, on the near-surface, perchlorate compounds potentially phytotoxic at elevated concentrations. Direct regolith-based cultivation would require substantial amendment and biological conditioning before supporting productive crops (Verseux *et al.*, 2016).

Mars presents a gravitational environment (0.38 g) intermediate between the Moon and Earth, which may prove more favourable for plant development than true microgravity, though the gravitropic, hydrodynamic, and structural consequences of partial Martian gravity for agricultural crops are not yet experimentally established. The Martian atmosphere, composed predominantly of carbon dioxide at approximately 0.6% of terrestrial atmospheric pressure, could in principle provide carbon for photosynthesis within pressurised plant growth modules though achieving adequate atmospheric pressure within those modules for normal plant photosynthetic function requires engineering solutions beyond current demonstrated capability. Future bioregenerative life-support systems envisioned for Mars habitats would integrate crops, microorganisms, waste-processing systems, and atmospheric management into interconnected closed loops, but such integrated systems remain at the conceptual and modelling stage at present.

Multi-crop production systems capable of providing a nutritionally adequate diet from space agriculture alone are a long-term research objective. Achieving full dietary provisioning from on-site cultivation requires not only resolving the technical challenges described above but also developing reliable automated systems that can manage crop cycles, detect and respond to disease or equipment failures, and adapt cultivation protocols without continuous human oversight essential requirements for habitats where crew time is limited and communication delays with Earth may reach twenty minutes in each direction.

CONCLUSION

Plants are not peripheral to the future of human space exploration; they are integral to it. The capacity to grow food, regenerate oxygen, recycle water, and support crew psychological well-being within a single, biologically driven system confers on plant cultivation a strategic importance that no currently available technology can replicate. Astrobotany as the discipline underpinning this capability has moved from curiosity-driven experiments in the 1960s to operational food production on the ISS and the engineering foundations of bioregenerative life-support design for future lunar and Martian habitats.

Substantial scientific and engineering challenges remain, particularly in managing plant physiology under partial gravity and radiation conditions, controlling microbial risks in closed cultivation systems, and scaling production to meaningful dietary contributions within realistic spacecraft volume and power budgets. These are tractable research problems, not insurmountable barriers, and the trajectory of progress over the past two decades suggests that operational space agriculture on the lunar surface and in Mars transit vehicles is a realistic near-future prospect.

The knowledge generated in pursuit of these goals will not remain confined to spacecraft. Resource-efficient cultivation technologies, precision environmental control, and a deeper mechanistic understanding of plant adaptation to stress will inform terrestrial agriculture at a time when food systems face mounting pressures from population growth, land degradation, and climate change. In this respect, growing food beyond Earth is not a departure from the challenges of feeding humanity at home it is an extension of them.

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