



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; 9(2): 515-521
Received: 20-12-2025
Accepted: 22-01-2026

Athira G
Department of Vegetable Science, College
of Agriculture, Vellanikkara, Kerala
Agricultural University, Thrissur, Kerala,
India

Kavya Suresh
Department of Vegetable Science, College
of Agriculture, Vellanikkara, Kerala
Agricultural University, Thrissur, Kerala,
India

Keerthana MV
Department of Vegetable Science, College
of Agriculture, Vellanikkara, Kerala
Agricultural University, Thrissur, Kerala,
India

Khushal B Muradi
Department of Vegetable Science, College
of Agriculture, Vellanikkara, Kerala
Agricultural University, Thrissur, Kerala,
India

Harshavardhan Mohan Totawa
Department of Vegetable Science, College
of Agriculture, Vellayani, Kerala
Agricultural University,
Thiruvananthapuram, Kerala, India

Dr. Chaithra BS
Assistant Professor, Kadiri Baburao
College of Agriculture, C. S. Puram,
Andhra Pradesh, India

Yogesh V Wayal
Department of Genetics and Plant
Breeding, College of Agriculture, Vellayani,
Kerala Agricultural University,
Thiruvananthapuram, Kerala, India

K Bhrundha
Department of Plant Physiology, College of
Agriculture, Vellanikkara, Kerala
Agricultural University, Thrissur, Kerala,
India

Jagmal P Khatana
Department of Agronomy, Chimanbhai
Patel College of Agriculture,
Sardarkrushinagar Dantiwada Agricultural
University, Dantiwada, Gujarat, India

Laxmi PS
Department of Postharvest Management,
College of Agriculture, Vellanikkara,
Kerala Agricultural University, Thrissur,
Kerala, India

Corresponding Author:
Athira G
Department of Vegetable Science, College
of Agriculture, Vellanikkara, Kerala
Agricultural University, Thrissur, Kerala,
India

Space farming of vegetables: Growing crops beyond earth

Athira G, Kavya Suresh, Keerthana MV, Khushal B Muradi, Harshavardhan Mohan Totawa, Chaithra BS, Yogesh V Wayal, K Bhrundha, Jagmal P Khatana and Laxmi PS

DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i2g.4994>

Abstract

As humanity looks beyond Earth to explore and potentially colonize other planets, one critical challenge stands out was how to sustain life in space. The long-term resupply from Earth raised the cost of space mission, and dried foods for months affected the health of crews. Considering these aspects of space mission, space culture and particularly vegetable cultivation in space, has great significance. Vegetables are more responsive to environmental parameters, have short growth duration, rich in minerals and nutrients, require less space to grow and are easy to cultivate. These features make them an inevitable component of space culture. Vegetables that are ready to eat after harvest are preferred for space culture. Plant growth chambers are typically utilized to study plant behaviour and development under reduced gravity and in closed environments. It includes Oasis, 'Veggie' (Vegetable Production System) 'Advanced Plant Habitat' (APH) and so on. An irrigation and nutrient delivery system (NDS) for space missions must support all stages of plant growth while ensuring proper water, nutrient supply, and root aeration within spacecraft safety constraints. Substrate-based systems using 1-2 mm arcillite mixed with Osmocote were preferred over aeroponic or hydroponic systems. Additionally, the porous tube plant nutrient delivery system (PTPNDS), was widely used in space agriculture due to its ability to retain water, supply nutrients through capillary action, and prevent oxygen deficiency in both simulated and real microgravity conditions. The major challenge in space farming is microgravity. Reduced gravity and microgravity affect water and nutrients delivery to plants. Moreover, under microgravity, thicker boundary layers formed around plant leaves that reduce transpiration, as well as gas exchange and caused deleterious changes in pH with serious effects on cell metabolism. In the near future, space exploration will increase, and the cultivation of plants may be necessary to supplement the dietary needs of the crew members in flights. This calls for more research intervention in space culture of vegetables. There is also ample scope for our country to initiate research and development in this rather challenging yet exciting field of space culture.

Keywords: Space culture, vegetables, plant growth chambers, microgravity

1. Introduction

As humans explore space, they want to bring plants for both aesthetic and practical reasons. We already know from our pioneering astronauts that fresh flowers and gardens on the International Space Station create a beautiful atmosphere and allow us to take a little piece of Earth with us on our journeys. They are good for our psychological well-being on Earth and in space. They will be critical for keeping astronauts healthy on long-duration missions.

A lack of vitamin C was all it took to give sailors scurvy, and vitamin deficiencies can cause several other health problems. Simply packing some multivitamins will not be enough to keep astronauts healthy as they explore deep space. They will require fresh produce. Right now, on the space station, astronauts receive regular shipments of a wide variety of freeze-dried and prepackaged meals to cover their dietary needs and resupply missions keep them freshly stocked. When crews venture further into space, traveling for months or years without resupply shipments, the vitamins in prepackaged form break down over time, which presents a problem for astronaut health.

Considering these aspects of space missions, space culture particularly vegetable cultivation in space, has great significance. Space culture is the cultivation of plants for food and other

resources in outer space or on extra-terrestrial celestial objects. It focuses on improving human habitability, by supplying fresh food and for relaxation and recreation of the crew. Space culture is suited for long-duration onboarding of the Space Station (SS). There are numerous parallels between farming on a space station or colony and farming on celestial bodies such as the Moon or Mars. Farming on celestial bodies may not be as complex as farming in microgravity, depending on the body size. The availability of inputs for the space agricultural process varies depending on the environment, including the relative availability of carbon dioxide, nitrogen, and oxygen, soil medium, and insolation.

2. Importance of growing plants in space

The weight allowed for food is limited to 1.72 kg per person per day, which includes the 0.45 kg of packaging weight. This is because it requires a special processing and packaging techniques for zero gravity in space. A major concern for ISS astronauts is that they cannot have a refrigerator on board to keep fresh food because there is no room for it ^[1, 2]. Moreover, due to the narrow spaces on the ISS, food can be stored in lockers close to electrical equipment, with temperatures even higher than the controlled temperatures of 21-23 °C ^[3]. Consequently, fruits and vegetables have a very short post-harvest shelf life and must be consumed within the first days or weeks of the flight. Such constraints may force astronauts on the ISS to eat dried food for months, with likely health and performance consequences during and after space flight, such as weight loss, cytotoxic oxidative stress, impaired eye health and alterations of the central nervous system, despite the availability of fruit juices, dried fruits, and multivitamin pharmaceutical products ^[8, 4, 5, 6]. Indeed, essential nutrients for humans are deficient in processed and prepackaged space foods (e.g., potassium, calcium, vitamin D and vitamin K) or are more unstable and rapidly degrade during long-term missions (e.g., vitamins A, C, B1, and B6) ^[2, 8, 7]. Therefore, to supplement the diet of astronauts, the ISS must receive supplies of fresh food by uncrewed cargo spaceflights such as US Dragon and Cygnus and Russian Progress supply ships, which raises the costs of space missions ^[9]. However, for very long journeys, packing or supplying enough food may not be a viable option. In fact, for a hypothetical human mission to Mars, where the average distance from Earth is approximately 225 million kilometres, such a trip may take almost eight months to complete. Adding the time spent on Mars and the return journey, the entire short stay mission could last at least 1.5 years, while long surface stays could last up to three years ^[10]. Hence, plant production in a fully functional space greenhouse is the only option able to provide fresh food to space travellers. This would guaranty them to be self-sufficient and having a proper dietary intake for months/years for short-duration missions, like low earth orbit (LEO), cis-lunar or lunar surface missions, as well as for long-duration and distance exploration missions, like missions to Mars ^[6, 10, 11, 12]. The plants in the space station metabolize carbon dioxide in the air to produce valuable oxygen. The existence of a space farm would aid the creation of a sustainable environment, as plants generate oxygen and continuously purify the air on the space station or spaceship and help control cabin humidity.

3. The role of vegetables in conquering space

Horticultural crops are more responsive to environmental parameters and light characteristics; the vegetables have mostly of short growth duration. Thus, make a good precursor of

vegetables with short growth durations to grow. Vegetables contains more minerals and nutrients. Vegetables require less space to grow. And also, vegetables are easy to cultivate. Their limited size and high harvest index, ensure that leafy greens are always at the top of any list for “space vegetables” for fresh food ^[13].

4. Choosing the crops for space culture

The paper develops a structured, repeatable methodology for selecting the most suitable crops to grow in confined space habitats, focusing on the EDEN-ISS growth rack on the International Space Station and the Future Exploration Greenhouse (FEG) in Antarctica as an analogue site. It begins from the need for bio-regenerative life-support systems that provide fresh, ready-to-eat food which supports both nutrition and psychological well-being of astronauts, under severe constraints of volume, energy, crew time, and microgravity. The authors define hard criteria (e.g., edible and ready-to-eat, plant height limits, suitability for artificial systems, harvest within mission time) that determine whether a crop is admissible at all, and soft criteria grouped into three main aspects: human quality (taste, texture, appearance, pungency), cultivation (handling time, spread harvest, shelf life, disease resistance), and yield (light/energy use efficiency, space-time production efficiency, harvest index). Using a combination of a decision tree for hard criteria, paired comparisons to weight criteria, and a 0-1 scoring scale, they rank candidate vegetables and herbs separately for the small ISS rack (where quality is prioritized over yield) and the larger FEG (where yield is prioritized). For the ISS rack, lettuce, radish, chives, strawberry, dwarf tomato, and red mustard score highest, with lettuce ranked first; for the FEG, lettuce again tops the list, followed by cucumber and dwarf tomato, with chives and tomato also highly ranked due to their production potential. The authors conclude that such an explicit, flexible framework reduces subjective bias, can be updated as new data or cultivars become available, and can be adapted for future missions where plants may provide a larger share of the crew's diet ^[11].

5. Plant growth chambers in space

To research plant behaviour and development under reduced gravity and in isolated environments, plant cultivation studies are commonly conducted in small chambers that are not an active part of the life support system ^[6]. Few of them are discussed below.

5.1. The Oasis Series

The Oasis 1 plant growth system was the first flight experiment conducted by the Soviet Union. The technology was first tested in space during the unmanned Cosmos 368 mission. Salyut 1 made the first flight on a human mission in 1971. The eight cultivation slots of Oasis 1 were used to grow flax, leek, onion, and Chinese cabbage during the expedition.

The required lighting was provided by fluorescent bulbs. The first of the popular Oasis series chambers was Oasis 1. Salyut 4 was home to Oasis 1M, an enhanced version of Oasis 1. A new nutrient delivery system was used after issues with the water metering system were resolved. One million peas and onions were cultivated in Oasis. The pea experiments did not work out. Only four of the thirty plants in the first mission matured, and the pea plants in the second mission perished in three weeks. The cosmonauts hypothesized that the plants may have been burned to death by excessive light, even if the reasons for the failure are unclear. In contrast, the onions fared much better and

reached a height of 20 cm. The first space-grown crops consumed by humans were onions, which were cultivated in July 1975 by cosmonauts Klimuk and Sevastianov. Salyut 6 carried Oasis 1AM, the Oasis family's next plant growth system. To make maintenance easier, the lighting system was divided into modular parts. The watering system was also altered. The final Oasis experiment, Oasis 1A, was placed in the Salyut 7 facility. Oasis 1A was able to give the root zone more aeration than its predecessors could. The grow chamber underwent additional improvements. The new system made it possible to relocate plants for improved gas exchange, ventilation, and lighting^[6].

5. 2. Biomass Production System (BPS)

During Expedition 4 in 2002, the Biomass Production System (BPS) was a plant growth chamber used on the International Space Station. Its purpose was to verify subsystems while in orbit. During this trip, two experiments were conducted: the Photosynthesis Experiment and System Testing and Operation (PESTO) experiment and the Technology Validation Test (TVT). When the secondary impacts of the spaceflight environment are taken into account, PESTO showed that plants growing in space are identical to earth controls. The spaceflight and ground control plants showed comparable rates of photosynthesis and transpiration, which were supported by identical biomass. Originally intended to be installed in the Space Hab Module and Shuttle Middeck, the system was later modified to be installed in an EXPRESS Rack in order to fly to the ISS. There were four separate plant growth chambers in the BPS. Temperature, humidity, illumination, and CO₂ were all independently controlled in each chamber. The experiment also included an active nutrient delivery system. The total BPS measured 52 cm in depth, 46 cm in width, and 55 cm in height. There were 54.4 kg of total mass. The four compartments, each measuring 260 cm², made up the entire grow area of 1040 cm². The Plant Research Unit (PRU) later made use of the

subsystems and technologies that the BPS had proven^[6].

5.3. VEGGIE: NASA's most recent accomplishment in creating BLSS is the VEGGIE Food Production System. Early in 2014, it was introduced. The first system created specifically for food production in microgravity, as opposed to plant experiments, is called VEGGIE. VEGGIE can be stored to 10% of its nominal deployed volume thanks to its deployable architecture. One middeck locker may hold six VEGGIE units when they are collapsed. Each unit offers a 0.17 m² grow area with a configurable height of 5 to 45 cm and is composed of three main subsystems: the lighting subsystem, the bellows enclosure, and the root mat. The lighting subsystem is a specially made LED panel containing red, blue, and green LEDs. The plants can receive over 300 $\mu\text{mol}/(\text{m}^2\cdot\text{s})$ of illumination from the panel. To keep the plants contained and the humidity high, the bellows enclosure divides the cabin from the plant environment. Because the enclosure is supported by a foldable framework, the distance between the root mat and the lighting subsystem can be changed while still keeping the area contained. The root mat functions as a passive nutrient delivery system, requiring little crew time to supply nutrient solution and water. After a number of growing media were examined, specially designed rooting cushions were ultimately chosen. The ISS crew will use crops grown by the VEGGIE system as additional meals. Reaching this goal is difficult and necessitates adherence to NASA's food microbiological requirements. To reduce the risk of consuming grown veggies, the project team created a HACCP plan based on the plans tested with Lada. During a test campaign at NASA's Desert Research and Technology Studies (DRATS), the chosen sanitizer proved to be useful and functional. More than 99% of the microbial load was eliminated when the harvested lettuce plants were sterilized following a 28-day growing cycle. The produce's microbial burden was well within NASA's acceptable range. For the first time ever, NASA astronauts were permitted to consume vegetables grown in space on August 10, 2015^[14].

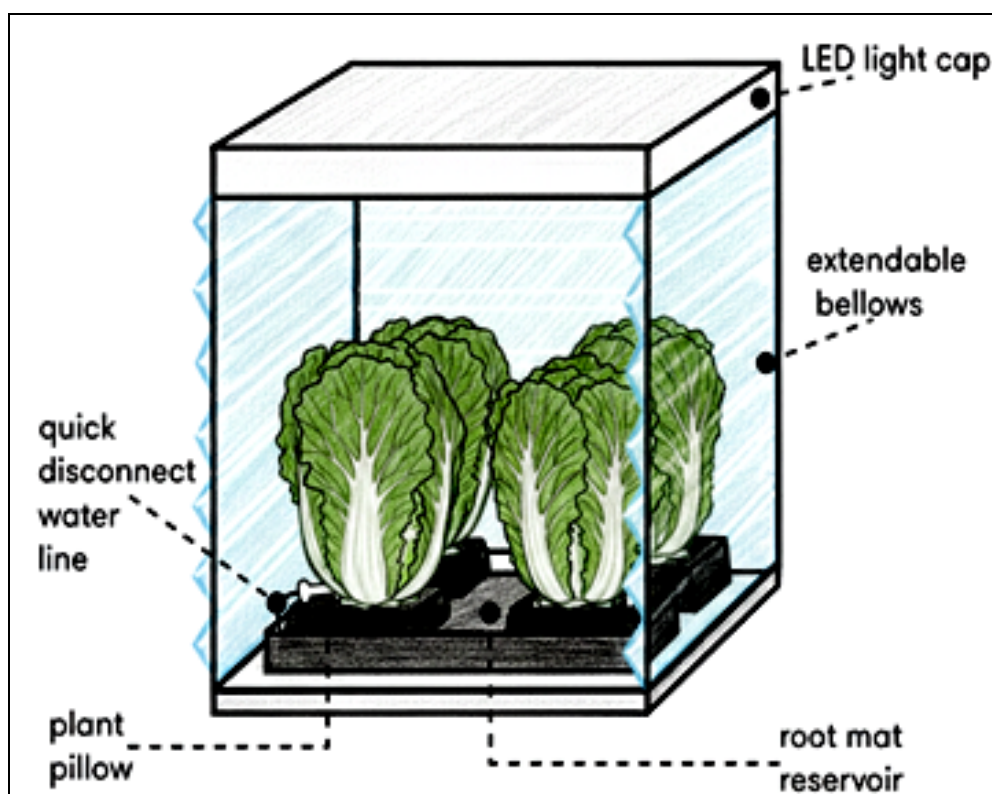


Fig 1: A diagrammatic view of veggie^[14]

5.3.1. Operation of veggie

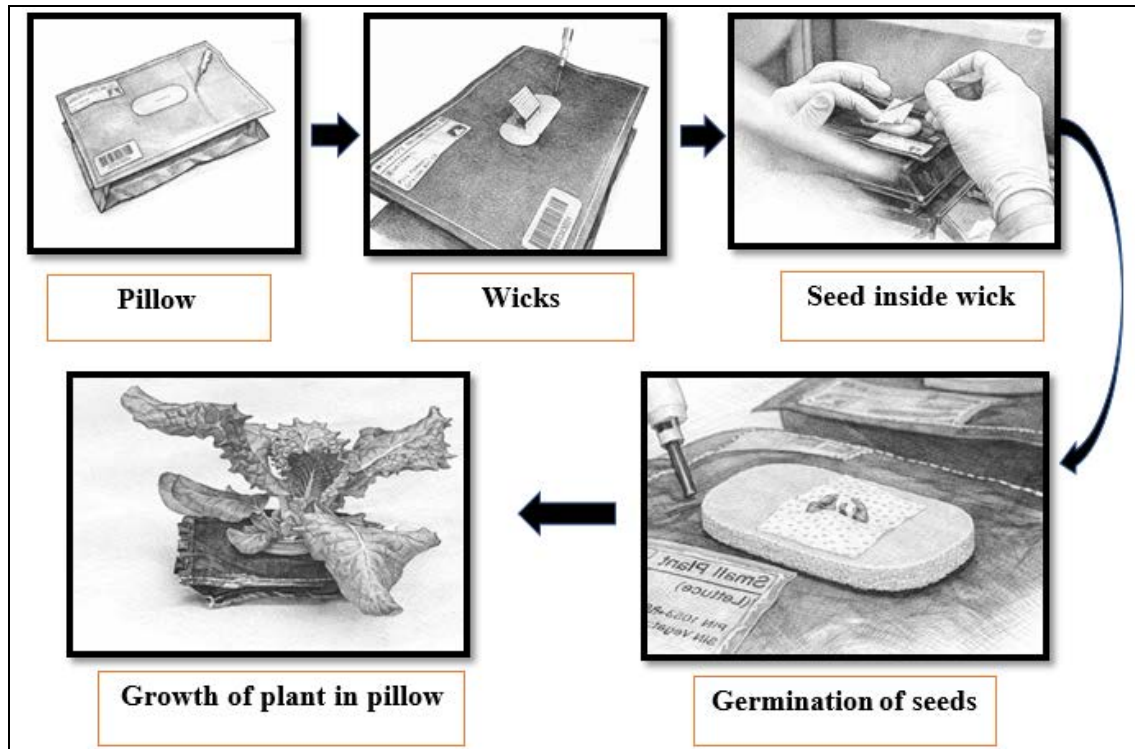


Fig 2: Operation of veggie ^[14]

5.4. Advanced Plant Habitat (APH)

Plant bioscience research on the International Space Station will be carried out in the Advanced Plant Habitat (APH), a fully automated plant growth facility. Crew participation in installing the science, adding water, and performing other maintenance tasks is low with this system. NASA and Madison, Wisconsin's ORBITEC collaborated to design the system. At the agency's Kennedy Space Center in Florida, the system's components are overseen and prepared for launch. The APH has an ecologically controlled growth chamber and is a completely contained, closed-loop device. Broad spectrum white LED lights as well as red, blue, and green LED lights are used in the plant environment. More than 180 sensors in the system provide the Kennedy team with real-time data on temperature, oxygen content, and moisture levels in the air, soil, close to plant roots, and at the stem and leaf level. The APH will be placed in a conventional EXPedite the PROcessing of Experiments to Space Station (EXPRESS) rack in the Japanese Experiment Module Kibo after being launched to the space station on a Commercial Resupply Services mission. The first plant experiment to be grown in the chamber will be Arabidopsis seeds, which are little flowering plants related to mustard and cabbage. PH-01, or Plant Habitat 1, is the name of the experiment. As part of the post-installation checkup aboard the space station, a brief grow-out of dwarf wheat and Arabidopsis will take place before to the start of PH-01. For up to a 135-day science study, the spacious, enclosed room can accommodate basic and commercial plant research or other bioscience research on board the space station. It is also built to last for at least a year without maintenance. The open architecture principle that underpins the design of the plant habitat enables the removal and replacement of crucial subsystems on board the space station. In order to reduce the amount of crew time required to cultivate the plants, the APH will be controlled by the team at Kennedy and triggered by astronauts on board the space station. The team at Kennedy will have access to real-time data telemetry, remote controlling, and

photo downlink via the Plant Habitat Avionics Real-Time Manager in EXPRESS Rack, also known as PHARMER. Sensors in the APH's active watering system will determine when the plants require water and maintain the flow of water as needed ^[15].

5.4.1. Advanced Plant Habitat Components

- Structural Mounting Assembly
- Air Filtration Assembly (provides filtered air to the system)
- Plant Habitat Facility Kits (includes hoses, water bags, syringes)
- Science Carrier (the tray that the plants will grow in)
- Growth Chamber (GC) (enclosed volume that the plants will grow in)
- Environmental Control System (GC temperature, humidity and air flow control)
- Fluid International Subrack Interface Standard Drawer (contains the carbon dioxide bottles, water reservoirs and gaseous nitrogen regulation)
- Orbital Replacement Unit Component Drawer (water distribution system, power system and main computer, or PHARMER)
- Growth Light Assembly (lighting system) ^[15]

6. Media for space farming

Within the operational and safety limitations of a spaceship, an irrigation and nutrient delivery system (NDS) must be able to sustain the many stages of plant growth and provide roots with sufficient amounts of water, nutrients, and air. Numerous experiments have examined various rooting materials, soils, and hydroponic systems as alternatives to conventional ones in order to achieve this goal. Monje *et al.* suggested using a substrate-based NDS system made up of a 1-2 mm arcillite/Osmocote mix in place of aeroponic or hydroponic systems because of the necessity of well-aerated and watered root zones to allow root

respiration and the need to moderately minimize the solution volume to prevent the solution temperature from rising. Scotts Company's Osmocote fertilizer is made up of round, resin-coated pellets that contain encapsulated nutrients. These pellets are released gradually when plants are watered, eliminating the need for astronauts to monitor the nutrient solution's recirculation or the efficient mixing of fresh nutrients. A small-grained soil (0.5 mm) allowed for good water distribution in the root zone but hindered air flow, whereas a grain soil larger than 2 mm (2-5 mm) allowed for proper aeration but may cause water to scatter or air to fill empty spaces between grains, resulting in reduced root hydration. This led to the decision to use 1-2 mm grain sizes^[16]. Arcillite with a diameter of 1.5-3 mm was utilized as an inorganic rooting matrix for embedding porous stainless-steel tubes in Morrow *et al.*'s Astroculture series of tests for the Space Shuttle and the MiR Svet chamber^[17, 18].

Dreschel and Sager first developed the PTPNDS hydroponic porous method, which was refined over the years^[19] and applied in a number of space agricultural studies, either with^[20, 21] or without^[22] simulated microgravity. For the application of clinorotation simulating microgravity, the system has been used because of its tubular shape, its capacity to retain water (avoid any free water leakage), its ability to transfer water to the roots or in the substrate by capillary forces, and its ability to prevent issues related to a lack of oxygen in the rhizosphere^[23]. The hydrophilic porous polyethylene tube was first constructed as a 2.5 cm solid polyvinyl chloride (PVC) pipe with a pore diameter of 20 μ m and a wall thickness of 0.3 cm. In this arrangement, the air space of the outer PVC external shell encircled the plant root zone, which grew directly on the surface of the inner porous tube that supplied nutrients^[24]. The system was implemented by creating hydraulic pressure control systems for laboratory-scale crop tests, researching its effects on pore size and root zone volume, creating mathematical and physical models to explain it, and using the system to cultivate crop plants in both simulated and actual microgravity, similar to the Russian Svet hardware^[19, 23].

7. Effect of space stress on plants

The study of how space factors including microgravity, increased radiation, and lack of magnetic fields affect a variety of phenomena, including germination, morphogenesis, gravitropism, vascular development, synthesis and distribution of storage compounds, accumulation of phenolic molecules, cell wall formation, cellulose assembly, lignification, reproduction, gametophytic selection, mutagenesis, mechanisms of DNA repair, and photosynthetic capacity, is known as plant space biology^[25].

The transport of water and nutrients to plants is impacted by reduced gravity and microgravity, which is especially important for root development and function. Microgravity's primary impact is a decrease in gravitational body forces, which lowers hydrostatic pressure, sedimentation rates, and buoyancy-driven flows. This results in a significant rise in surface tension that takes center stage. Negative pH changes that have a major impact on cell metabolism may also be brought on by the decreased diffusion of waste materials and CO₂ out of the cell due to the lack of convection.²⁶ Furthermore, the absence of natural convection in microgravity results in larger boundary layers surrounding plant leaves, which lower water vapor transpiration, gas exchanges, and heat transfer all of which further impair the uptake of nutrients and water by the roots^[29, 27, 28].

Managing water and nutrients is thought to be one of the most

difficult parts of growing plants in space. As far as we are aware, very little is known about how spatial considerations affect how water and nutrients are absorbed, transported, and distributed in plants. Unless there is some forced flow or movement, the mass transfer and exchange of gases, liquids, and tiny molecules like ions become diffusion limited due to the lower gravity level in space^[30]. As a result, transpiration one of the main factors influencing water transport in the xylem is reduced due to decreased heat convection. This has an impact on the transpiration stream's ability to absorb water and nutrients.³⁰

8. Plant adaptations to spaceflight environments

Light is one of the other environmental elements that plants need to orient and direct their growth. Deeper investigation revealed that spaceflight had an impact on the molecular operations of the photosystem, but not on the photosynthetic process as a whole. In contrast to plants cultivated on Earth, the team discovered that the plants grown in space had different photosynthetic machinery because many important proteins that regulate the photosystem had moved to different organs. The expression of the NusG-like protein, which regulates RNA synthesis, increased, indicating that the plants growing in space were attempting to adjust to the challenges of space by increasing the translational efficiency of their chloroplast ribosomes. The space-grown plants may have also been attempting to improve their water-oxidizing response and repair photosystem damage, as seen by the abundance of other proteins^[31, 32].

Furthermore, the transcripts of plants growing in space did not match the proteins that resulted from the roots and shoots, indicating that significant post-translational changes were place. However, there are a variety of reasons for this, including different methods for collecting and analysing RNA and protein, weakened translation processes, and increased alternative splicing as a result of space environmental stresses^[31].

Higher plants appear to adapt to space conditions in low Earth orbit, at least for one generation from seed to seed, if they are given a controlled atmosphere with forced ventilation and a functional water and nutrition delivery system. Additionally, it appears that gas exchange, metabolism, and photosynthesis function similarly in microgravity as they do on Earth; however, extra care must be taken to avoid root zone hypoxia. According to certain research, exposure to microgravity has an impact on nutritional intake. Therefore, more research is required to determine how a space environment affects the movement of water and solutes in plants. It may be simpler to provide nutrients and water to plants on the Moon and Mars than in microgravity, as models have indicated, because gravitational forces are at work on their surfaces^[33].

8.1. Artificial Gravity Generator

They have installed an artificial gravity generator to lessen the impact of microgravity. Although plants may grow and generate seeds in microgravity, the impact of the absence of gravity on crop output is still unknown. Because of centrifugal forces, plants cultivated in this revolving apparatus experience artificial gravity when they are sent into space. As a result, this apparatus makes it possible to conduct comparative plant studies and ascertain the most effective way to cultivate food in space^[34].

9. Limitations of space culture

Space vegetable culture is fundamentally limited by volume, mass, energy, and hostile environmental conditions. These constraints make current systems useful for supplements, not full food supply.

9.1. Physical & Engineering Limits

- **Limited area & volume:** Growth hardware on ISS (e.g., Veggie, ~0.16 m²) cannot produce enough fresh food to meaningfully replace packaged diets [35, 36].
- **Power and energy demand:** High LED lighting needs and cooling severely constrain scaling up production [17, 35].
- **Water and nutrient management in microgravity:** Capillarity replaces gravity; irrigation is error-prone (under- or over-watering in VEG-01) and requires complex substrates or hydroponics hardware [36, 37, 38].

9.2. Environmental Stressors

- **Altered gravity:** Affects gas exchange, fluid movement, root growth and hormone signaling, impacting photosynthesis and morphology [17, 39, 40, 41].
- **Super-elevated CO₂:** Continuous ISS-like CO₂ (~2800 ppm) can severely reduce growth and leaf area in some crops (e.g., Chinese cabbage ‘Tokyo Bekana’) [42].
- **Radiation & confinement:** Ionizing radiation and confined atmospheres may alter plant development and quality; long-term, multi-generation effects are still poorly understood [43, 40].

9.3. Food Safety & Quality

- **Microbial control:** Leafy greens grown on ISS are generally safe, but show variable bacterial and fungal loads; there are still no specific microbial standards for space-grown fresh produce [7, 44].
- **Nutrient trade-offs:** Light and CO₂ regimes that improve yield can worsen nitrate or iron accumulation, posing health concerns in combination with processed foods. [45, 46]
- **Quality at high light:** Higher light boosts yield but can degrade leaf quality (tip burn, toughness) in several vegetables [42].

9.4. Operational & Biological Limitations

- **Crop choice restrictions:** Short cycle leafy greens dominate because fruit and root crops need more time, area, and management [13, 45].
- **Labor and complexity:** Even “simple” systems like Veggie demand crew time for watering, pruning, cleaning, and troubleshooting [36].
- **Incomplete life support integration:** Current systems contribute minimally to O₂ production, CO₂ removal, and waste recycling; full bioregenerative life support remains a future goal.

10. Conclusion

Vegetable space farming is technically feasible, microbiologically safe, and nutritionally valuable as a supplemental food source, while also supporting crew psychological health. However, limitations in available volume, mass, power, and crew time, together with crop-specific sensitivities to light, CO₂, and microgravity, mean that present systems cannot yet provide full dietary self-sufficiency. Future work must optimize crop selection, lighting and environmental “recipes,” automation, and integration into closed ecological life-support so that vegetable production can scale from small “salad machines” to robust, efficient food systems for long-duration lunar and Martian missions.

11. Future prospects

In the near future, space exploration will increase, and the

cultivation of plants may be necessary to supplement the dietary needs of the astronauts. Further plant experiment trails may be extended to other group of vegetables. Although in India, several organizations are working on space agriculture, and horticulture, crops were cultivated under controlled environmental conditions like greenhouses. No work has been reported under crop cultivation with no gravity, low gravity, or micro-gravity given spacecraft for feeding food for space travellers so far, nonetheless lots of avenues are opened for Indian researchers to take up the task of space culture.

References

1. Smith SM, Zwart SR. Chapter 3 Nutritional *Biochemistry* of Spaceflight. In: *Advances in Clinical Chemistry*. Elsevier: Amsterdam, The Netherlands. 2008;46:87-130.
2. Cooper M, Perchonok M, Douglas GL. Initial assessment of the nutritional quality of the space food system over three years of ambient storage. *Npj Microgravity*. 2017;3:17.
3. Thirsk R, Kuipers A, Mukai C, Williams D. The space-flight environment: The International Space Station and beyond. *CMAJ*. 2009;180:1216-1220.
4. Stein TP. Space flight and oxidative stress. *Nutrition*. 2002;18:867-871.
5. Palinkas LA. Psychosocial issues in long-term space flight: overview. *Gravitational and Space Biology Bulletin*. 2001;14(2):25-33.
6. Zabel P, Bamsey M, Schubert D, Tajmar M. Review and analysis of over 40 years of space plant growth systems. *Life Sci. Space Res*. 2016;10:1-16.
7. Khodadad C, Hummerick M, Spencer L, Dixit A, Richards J, Romeyn M, *et al*. Microbiological and nutritional analysis of lettuce crops grown on the International Space Station. *Front Plant Sci*. 2020;11:1-12.
8. Cooper MR. Initial Nutritional Quality of ISS Space Food Provisions. NASA HRP Investigator’s Workshop: Galveston, TX, USA. 2013.
9. ESA/ESOC. Launch list. *Space Res. Today*. 2019;206:53-64.
10. Genta G, Maffione PF. A graphical tool to design two-ways human Mars missions. *Acta Astronaut*. 2019;154:301-310.
11. Dueck T, Kempkes F, Esther M, Cecilia S. Choosing crops for cultivation in space. 46th International Conference on Environmental Systems. 2016;206:1-9.
12. Guo SS, Mao RX, Zhang LL, Tang YK, Li YH. Progress and prospect of research on controlled ecological life support technique. *REACH*. 2017;6:1-10.
13. Janhavi, Manjunathagowda DC. Plants culture in space environment for feeding food to the space travellers. *Int J Chem Stud*. 2020;8:2936-2938.
14. NASA. Vegetable Production System (Veggie). Available from: <https://techport.nasa.gov/view/10498>; https://www.nasa.gov/mission_pages/station/research/experiments/explorer/Investigation.html?#id=374
15. John S, Abou-Issa F, Hasenstein KH. Space flight cultivation for radish (*Raphanus sativus*) in the advanced plant habitat. *Gravitational and Space Res*. 2021;9(1):121-132.
16. Casado J. Cultivating the future—growing food in space. *Spaceflight*. 2006;48:180-189.
17. Monje O, Stutte G, Goins G, Porterfield D, Bingham G. Farming in space: environmental and biophysical concerns. *Adv Space Res*. 2003;31(1):151-167.
18. Morrow R, Bula RJ, Tibbitts T, Dinauer WA. Matrix-based porous tube water and nutrient delivery system. *SAE Tech*

- Pap. 1992;920611:1-7.
19. Dreschel TW, Brown CS, Piastuch WC, Hinkle CR, Knott WM. Porous tube plant nutrient delivery system development: A device for nutrient delivery in microgravity. *Adv Space Res.* 1994;14:47-51.
 20. Colla G, Roupael Y, Cardarelli M, Mazzucato A, Olimpieri I. Growth, yield and reproduction of dwarf tomato grown under simulated microgravity conditions. *Plant Biosyst.* 2007;141:75-81.
 21. Hoehn A, Scovazzo P, Stodieck L, Clawson J, Kalinowski W, Rakow A, *et al.* Microgravity root zone hydration systems. *SAE Tech Pap.* 2000;001:1-10.
 22. Avercheva O, Berkovich YA, Smolyanina S, Bassarskaya E, Pogosyan S, Ptushenko V, *et al.* Biochemical, photosynthetic and productive parameters of Chinese cabbage grown under blue-red LED assembly designed for space agriculture. *Adv Space Res.* 2014;53:1574-1581.
 23. Dreschel T, Hall C, Foster T. Demonstration of a porous tube hydroponic system to control plant moisture and growth. NASA: Washington, DC, USA. 2003. Available from: <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20050215299.pdf>
 24. Dreschel T, Sager J. Control of water and nutrients using a porous tube: A method for growing plants in space. *Hort Sci.* 1989;24:944-947.
 25. De Micco V, Aronne G, Colla G, Fortezza R, De Pascale S. Agro-biology for bioregenerative life support systems in long-term space missions: general constraints and the Italian efforts. *J Plant Interact.* 2009;4(4):241-252.
 26. Osborn MA. Strategy for research in space biology and medicine in the new century. National Academy Press: Washington, DC, USA. 2023.
 27. Kuang A, Xiao Y, McClure G, Musgrave ME. Influence of microgravity on ultrastructure and storage reserves in seeds of *Brassica rapa* L. *Ann Bot.* 2000;85:851-859.
 28. Poulet L, Fontaine JP, Dussap CG. Plant's response to space environment: a comprehensive review including mechanistic modelling for future space gardeners. *Bot Lett.* 2016;163:337-347.
 29. Monje O, Nugent M, Hummerick M, Dreschel T, Spencer L, Romeyn M. New frontiers in food production beyond LEO. ICES: Toronto, ON, Canada. 2019;260:1-6.
 30. Porterfield DM. The biophysical limitations in physiological transport and exchange in plants grown in microgravity. *J Plant Growth Regul.* 2002;21(2):177-190.
 31. Olanrewaju GO, Haveman NJ, Naldrett MJ, Paul AL, Ferl RJ, Wyatt SE. Integrative transcriptomics and proteomics profiling of *Arabidopsis thaliana* elucidates novel mechanisms underlying spaceflight adaptation. *Front Plant Sci.* 2023;14:1260429.
 32. Bowlby B. Extraterrestrial agriculture: plant cultivation in space. *BioTechniques.* 2024;76(5):169-173.
 33. Maggi F, Pallud C. Martian base agriculture: the effect of low gravity on water flow, nutrient cycles, and microbial biomass dynamics. *Adv Space Res.* 2010;46(10):1257-1265.
 34. Vermeulena AC. The space farming project: space colonization, techno-agriculture and the future of extraterrestrial biopolitics. 2019.
 35. Carillo P, Morrone B, Fusco G, De Pascale S, Roupael Y. Challenges for a sustainable food production system on board of the International Space Station: a technical review. *Agronomy.* 2020;10:687.
 36. Massa G, Dufour N, Carver J, Hummerick M, Wheeler R, Morrow R, *et al.* VEG-01: Veggie hardware validation testing on the International Space Station. *Open Agric.* 2017;2:33-41.
 37. Srivastava S, Halder S, Ranad A, Gairola S, Yadave S, Lipidharanf K. Hydroponic: a study of space farming. *Int J For Multidiscip Res.* 2024;36:1-15.
 38. Ryu J, Baek J, Subah Z. A low-cost autonomous and scalable hydroponics system for space farming. *HardwareX.* 2025;21:101402.
 39. De Pascale S, Arena C, Aronne G, De Micco V, Pannico A, Paradiso R, *et al.* Biology and crop production in space environments: challenges and opportunities. *Life Sci Space Res.* 2021;29:30-37.
 40. Nie H, Zhou W, Zheng Z, Deng Y, Zhang W, Zhang M, *et al.* Exploring plant responses to altered gravity for advancing space agriculture. *Plant Commun.* 2025;6:100460.
 41. Ambiya R, Beena R, Nivedhitha MS. Exploring microgravity's effect on seed germination and growth of plants. *Int J Plant Soil Sci.* 2024;36(12):75-90.
 42. Burgner S, Nemali K, Massa G, Wheeler R, Morrow R, Mitchell C. Growth and photosynthetic responses of Chinese cabbage (*Brassica rapa* L. cv. Tokyo Bekana) to continuously elevated carbon dioxide in a simulated Space Station "Veggie" crop-production environment. *Life Sci Space Res.* 2020;27:83-88.
 43. De Micco V, Aronne G, Caplin N, Carnero-Díaz E, Herranz R, Horemans N, *et al.* Perspectives for plant biology in space and analogue environments. *NPJ Microgravity.* 2023;9:1-15.
 44. Buncheck J, Hummerick M, Spencer L, Romeyn M, Young M, Morrow R, *et al.* Pick-and-eat space crop production flight testing on the International Space Station. *J Plant Interact.* 2024;19:1-12.
 45. Meinen E, Dueck T, Kempkes F, Stanghellini C. Growing fresh food on future space missions: environmental conditions and crop management. *Scientia Hort.* 2018;235:270-278.
 46. Hitt M, Cai S, Nix G, Patel S, Tsay L. Balancing nutrient content and nitrate levels in space agriculture: investigating LED light and CO₂ effects on space-grown leafy green vegetables. *Gravitational and Space Res.* 2025;13:103-120.