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THE ORBITAL REVOLUTION: THE NEW AGE SPACE FARMING

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ABSTRACT

Six decades of biological research conducted in low Earth orbit have transformed space farming from a speculative concept into one of the most applied sciences of this century. Plants aboard spacecraft or space stations do more than just supplement crew nutrition, they generate oxygen, process wastewater, and filter cabin air, making them indispensable to the closed life-support loops that any long-duration deep-space mission will require. Of the many obstacles involved, microgravity and cosmic radiation remain the most serious biological threats. Microgravity disrupts gravitropic signalling and root anchorage, while also altering how water and gases distribute through plant tissues. Radiation induces double-strand DNA breaks, elevates mutation rates, and generates oxidative stress that cascades through multiple cellular compartments. Out of these challenges, space breeding has emerged as a novel, productive approach, deliberately harnessing the genetic variability that spaceflight induces to develop improved crop varieties. Cosmic radiation and microgravity together drive chromosomal aberrations, altered DNA methylation, and genetic polymorphism rates 10 to 30 per cent higher than those seen in ground-based controls. Advances in hydroponics, aeroponics, LED-tuned vertical farming, CRISPR crop engineering and AI-guided environmental management are progressively narrowing the gap between current capability and what sustainable extraterrestrial agriculture will demand. Trials on ISS modules, in Antarctic analogue facilities, and within simulated lunar habitats have confirmed that space agriculture is not theoretical, it is possible and produces measurable results. The innovations emerging from space agriculture research carry real implications for farming on Earth, like being more resource-efficient, more resilient, and less dependent on ideal growing conditions.

Key words : Space farming, Microgravity, Seed Germination, DNA methylation, Cosmic radiation, Space flight, Bio regenerative life support.

Introduction

Space farming is about growing food somewhere other than Earth, whether that's inside a spacecraft, aboard the International Space Station, or eventually on the surface of the Moon or Mars. What started as a far-fetched idea has matured into a genuine research priority, driven by the straightforward reality that resupplying food from Earth over years long missions would be financially and logistically unworkable. Beyond producing food, plants in space show a remarkable range of environmental tasks, recycling wastewater, generating oxygen, scrubbing the air, and turning human waste into usable biomass, making them the self-contained life-support loops that crews would need to survive independently, and converting

human waste into biomass, thereby contributing to a closed-loop life-support system essential for autonomous crew survival (Yadav *et al.*, 2022).

The central goal of this research is to build plant cultivation systems that are reliable, efficient, and genuinely self-sustaining, capable of delivering fresh, nutritious food to astronauts on long missions and to future residents of lunar or Martian settlements. These systems have to squeeze every bit of value out of available resources, operate within tight physical and energy constraints and make crews progressively less reliant on deliveries from home. There is an equally compelling secondary goal of taking what works in space and applying those insights to make farming on Earth more sustainable.

Most active experimentation takes place aboard the ISS, using dedicated plant growth chambers designed for the orbital environment. The most sophisticated of these is NASA's Advanced Plant Habitat, which is a fully enclosed, highly automated facility packed with more than 180 sensors, high-resolution cameras, and a climate-control system that researchers can operate from the ground control system. The APH delivers precisely calibrated light across multiple wavelengths through LED arrays, supports plants in a porous clay medium, and uses controlled-release fertilisers to make sure roots receive exactly the right balance of water, nutrients, and oxygen. Temperature, humidity, carbon dioxide levels, and light cycles are all tightly controlled to keep growth conditions as consistent as possible. Plant samples, once mature, are harvested and preserved, then returned to Earth for detailed physiological and genetic analysis (NASA, 2025).

Space farming is far from straightforward. Plants must cope with cosmic radiation, reduced atmospheric pressure, irregular or attenuated light and the ways that microgravity scrambles how resources are distributed within tissues. Under weightlessness, water and gases stop behaving the way they do on Earth instead of moving directionally, they spread uniformly around the roots, making it harder for plants to take up what they need. The limited space inside any orbital or planetary habitat means crop varieties have to be compact, produce as little inedible material as possible and convert nutrients into useful biomass with exceptional efficiency. Energy efficiency above all in the lighting systems that keep plants growing is absolutely critical. Designing greenhouses for extraterrestrial use also demands structural and material innovations that can shield against radiation without compromising the light that plants depend on.

Timeline of Space Farming

The story of space farming is interesting, sometimes surprising, progressing each decade, bringing new technology and a sharper scientific understanding of what it actually takes to keep plants alive and humans fed, beyond Earth. The timeline of space agriculture from early 1946 to 2025 is illustrated in Fig. 1.

Space Breeding

Space breeding works by deliberately exploiting what outer space does to living things. The combination of microgravity, extreme vacuum, cosmic radiation, and the absence of a geomagnetic field produces genetic variability in seeds, plant tissues, and whole organisms that breeders can then screen and select for useful traits. The space environment triggers cascading changes at the level of a plant's form, its physiological processes, and its underlying genetics. Not every change is beneficial; some mutations impair fertility or stunt growth, but a meaningful fraction produce genuinely useful traits like higher yields, adjusted maturation timing, and greater tolerance of stress. Those improvements benefit both space farming and the tougher corners of agriculture back on Earth (Mohanta *et al.*, 2021).

Historical Roots and Modern experiments

The lineage of space plant breeding runs back to the very first crewed spaceflights, with early work carried out on Soviet Salyut and Mir stations and NASA's Space Shuttle, and later expanded through China's seed-return satellite programme platforms like Shijian-8, before reaching the ISS and, most recently, deep-space probes. China has done more than any other country to push this field forward. Analysis of the resulting seeds has uncovered altered DNA methylation and transcription

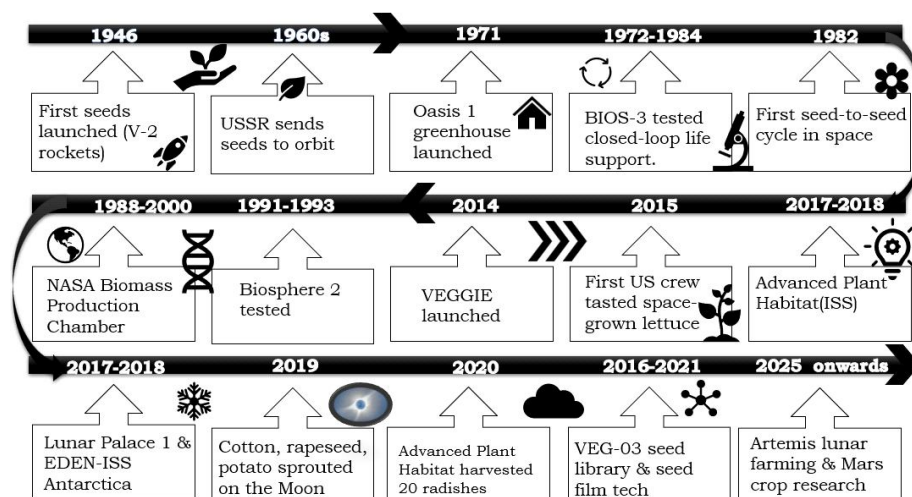


Fig. 1 : This Figure represents the evolution of space agriculture from early 1946 radiation experiments to the sophisticated lunar and Mars crop research planned for 2025. It connects historical milestones, such as the first lunar sprouts and ISS harvests, with the ground-based research that made them possible.

patterns that affect how plants respond to stress and metabolism, offering novel breeding opportunities.

Morphogenetic and Cellular responses

At the cellular level, space exposure reshapes plant biology in ways that are hard to miss. Cells tend to become rounder in microgravity and chloroplasts show measurable differences in their starch granule size. Root architecture shifts too, with more lateral branching and distinctive root hair patterns emerging under space conditions. Some species respond with outright developmental stress. Orchids may suppress flowering entirely, and peas can develop unusually elongated internodes (Zabel *et al.*, 2016). Cell division is also seriously affected. Mitosis slows down, and chromosomal aberrations dicentric fragments, acentric fragments, ring chromosomes, multicentric chromosomes become noticeably more frequent, because the cell's normal DNA repair machinery cannot keep pace with the damage inflicted by high-energy ionising radiation. Some of these rearrangements are stable enough to be passed on to future generations, while the unstable ones tend to be eliminated as the cell divides which is why space-induced mutations can be either long-lasting or fleeting depending on the specific lesion (Manzano *et al.*, 2016).

Looking even more closely, space-grown plants show thinner cell walls with reduced cellulose and lignin content, chloroplasts that lose their normal internal organisation, mitochondria that appear swollen, and disrupted endoplasmic reticulum and Golgi apparatus (Mohanta *et al.*, 2021). Enzyme activity shifts as well. Peroxidase, which signals that cells are mounting a response to oxidative stress, tends to be upregulated in plants that have been in space. When the elemental composition of plant tissues changes, phosphorus and potassium levels in shoots tend to rise, while calcium and various micronutrients decline deficits that appear to compromise ATPase activity and drag down photosynthetic efficiency (Nedukha, 1997).

Genetic diversity and Mutation characterisation

At the genetic level, the degree of variability that space breeding generates is substantial. Studies using SSR, RAPD, AFLP, and other molecular marker systems have tracked a wide range of changes single nucleotide polymorphisms, insertions, and microsatellite shifts across space-flown plant lines. Mutant lines consistently show 10 to 30 per cent more genetic variability than ground controls and the stable chromosomal rearrangements that arise can persist across successive generations. Spaceflight trials like Shi Jian-8 yield both improved germination and survival rates and distinct shifts in

morphology and enzyme activity for species such as cotton, maize, sunflower, soybean and tomato (Mohanta *et al.*, 2021).

Zeng *et al.* (2025) provide comprehensive multi-omic evidence that spaceflight-induced oxidative stress generates a heritable memory in rice, transmitted across five generations. The underlying mechanisms integrate persistent genomic instability, dynamic epigenetic reprogramming and flexible transcriptomic and splicing landscapes. Notably, transposable element methylation and stable changes in stress hormone signalling and metabolic pathways form the backbone of this adaptive response. The findings enrich our understanding of plant adaptation under extreme environments, have potential implications for crop improvement in terrestrial agriculture, and pave the way for cultivating resilient food sources in space. The integrated multi-omics approach deployed here is exemplary for unravelling complex transgenerational stress adaptive mechanisms in plants. The study “Multiomics in rice” by Zeng *et al.* (2025) is illustrated in Fig. 2.

Large-scale breeding programs, especially in China, have resulted in the release of mutant varieties, including rice, wheat, tomato, pepper, sesame, rapeseed and lucerne, displaying improved yields, disease resistance, or salt tolerance. China has developed over 240 approved varieties of staple crops alone, and more than 1,000 new varieties total across all crops. These space-bred crops have achieved significant agricultural value and food security gains, contributing over 2 billion kilograms annually to China's grain output and yielding 100 billion yuan in economic benefits.

Seed germination

The comparative analysis of plant growth and reproductive success in microgravity is shown in Table 1.

Spaceflight investigations of seed germination and plant growth have yielded significant insights into the physiological and genetic traits that govern plant development under the unique conditions of microgravity, cosmic radiation and confined-space habitats. Key physiological parameters of germination studied in space environments include germination rate, germination vigour, seedling establishment time, testa and endosperm rupture dynamics, seedling morphology, and stress responses such as oxidative damage and ageing sensitivity. These parameters have been extensively analysed using species such as *Eruca sativa* (rocket), *Arabidopsis thaliana*, and rice (*Oryza sativa*), selected both for their genetic tractability and their agricultural relevance (Paul *et al.*,

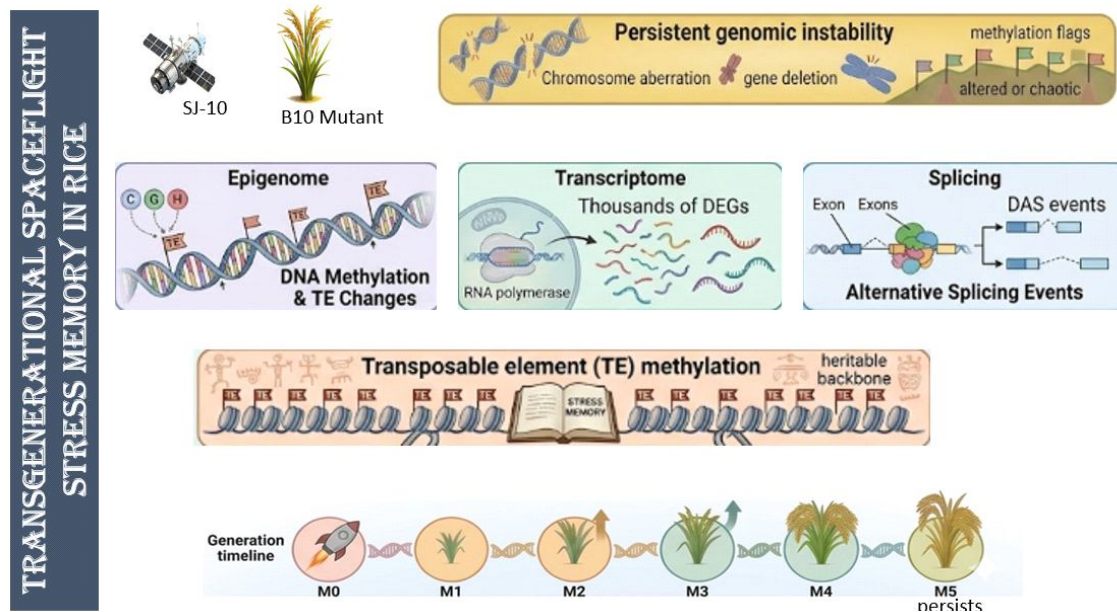


Fig. 2 : Transgenerational Spaceflight Stress Memory in Rice. Spaceflight stressors trigger ROS-driven oxidative stress, establishing heritable TE methylation and genomic instability that carry stress memory from M0 through M5. This memory integrates via epigenomic, transcriptomic, and splicing layers to drive the metabolic reprogramming and hormone signalling essential for adaptation.

2013; Chandler *et al.*, 2020).

One pivotal study, the “Rocket Science” project, demonstrated that six-month storage of *Eruca sativa* seeds aboard the ISS resulted in delayed seedling establishment and reduced germination vigour compared to Earth controls, despite no loss in seed viability. This delay was connected to molecular changes in dry seeds, primarily transcriptomic alterations indicative of partial ageing during spaceflight. Genes encoding heat shock proteins (hsp), DNA repair proteins (such as ATM kinase and DNA ligase 1), and oxidative stress response factors showed increased expression, suggesting that space environmental factors like low-dose cosmic radiation and microgravity accelerate seed ageing and sensitise seeds to stress. Physiologically, germination is marked by two distinct ruptures like testa rupture (exposing the endosperm) followed by endosperm rupture (allowing radicle emergence), which were both observed to occur more slowly post-spaceflight, indicating impaired or slowed metabolic activation (Chandler *et al.*, 2020). “Rocket Science” project, which tested how storing seeds aboard the International Space Station (ISS) for 6 months affects their ability to germinate back on Earth is depicted in Fig. 3.

At the genetic level, genomic and epigenetic studies have documented that space conditions induce mutations, gene expression modulation and epigenetic changes affecting germination and early growth traits. For example, Arabidopsis plants grown in microgravity

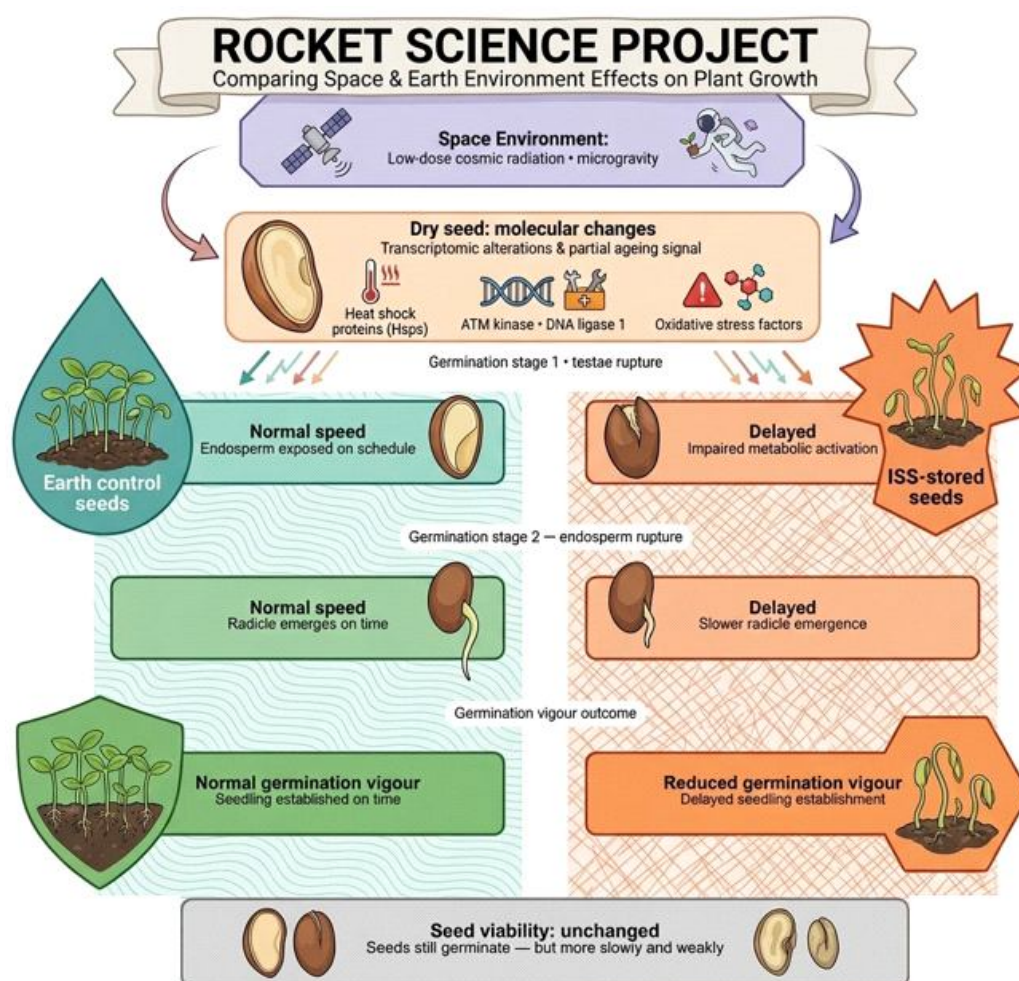
developed partially sterile reproductive organs and a subset of seeds showed reduced germination efficiency and vigour, while their progeny exhibited some recovery in later generations but also an increase in recessive mutations. RAPD and SNP analyses in rice seeds exposed to space radiation found substantial genetic polymorphisms (~30%) compared to Earth-grown controls. These polymorphisms manifested in altered growth patterns, including shorter plant height and shifted maturation timing, evidencing that spaceflight can induce heritable genomic changes that may affect agronomic traits like germination and development (Zhao *et al.*, 2007).

Transcriptomic profiling of seedlings in microgravity revealed broad differential gene expression related to hormone metabolism, particularly of auxin, gibberellins, cytokinins, and ethylene pathways, all crucial regulators of seed germination and seedling growth. Genes coding for auxin transporters (e.g., ABC transporter family), calcium signalling components, and cell wall remodelling enzymes were significantly altered, explaining observed changes in gravitropic responses and cell expansion during germination. Moreover, stress-related pathways such as heat shock proteins and ROS scavenging enzymes were activated to mitigate oxidative damage from the space environment (Paul *et al.*, 2013; Chandler *et al.*, 2020).

The physiological parameters monitored across space studies consistently include germination percentage,

Table 1 : Comparative analysis of Plant growth and Reproductive Success in Microgravity.

Experiment/Location	Primary Findings & Growth Metrics	Morphological & Physiological Changes	Reproductive Viability	Reference
Salyut 7 Space Station	Studied the effects of 0.01g, 0.1g and weightlessness on lettuce	Hypocotyls (shoots) were 8–16% longer than 1g controls; roots were reduced by ~17%.	Disrupted gravitropic response; geotropic sensitivity threshold found at 2.9×10^{-3} g.	Zabel <i>et al.</i> (2016)
Fiton-3	First full life cycle of <i>Arabidopsis thaliana</i> in microgravity.	Successful germination and growth through flowering within a micro-greenhouse.	Produced viable seeds with ~42% biological viability.	Salisbury <i>et al.</i> (1997)
ISS Multi-gen studies	Seed-to-seed cultivation over successive generations.	Secondary branches and siliques (seed pods) grew perpendicular to the main stem.	92% germination rate for space-grown seeds; protein bodies were 55% smaller.	Paul <i>et al.</i> (2013)
Space Seed Project (Kibo/ISS)	Cultivation of <i>Arabidopsis</i> from dry seed in a Plant Experiment Unit.	Observed delayed senescence (ageing) of rosette leaves.	Successful fully closed seed-to-seed cycle; maturity reached in ~3 days post-watering.	Takatsu <i>et al.</i> (2012)

**Fig. 3 :** Rocket Science Project, Spaceflight Effects on Seed Germination. The “Rocket Science” project tested how storing seeds aboard the International Space Station (ISS) for 6 months affects their ability to germinate back on Earth. The plant used was *Eruca sativa*, common rocket/arugula.

germination speed, seedling dry weight, hypocotyl and radicle length, and biomass accumulation, all of which are commonly reduced or delayed under real or simulated space environments compared to ground controls (Chandler *et al.*, 2020). Water uptake dynamics and oxygen consumption during imbibition are also studied as critical factors, since microgravity affects fluid distribution around seeds, potentially influencing germination kinetics (Maffei, 2024). Light quality and intensity modulate germination and early growth, with red and blue wavelengths interacting with gravity signals to regulate gene networks governing seedling development (Chandler *et al.*, 2020).

Key germination parameters tested in spaceflight studies reflect an integrated view of physiological vigour, stress resilience, gene expression modulation, genetic polymorphisms, and epigenetic adaptation. Space induces partial ageing and oxidative stress in seeds, alters hormone-related gene networks, fosters both transient

and heritable genetic changes. These factors collectively influence seed germination timing, uniformity, and seedling establishment, presenting important challenges and opportunities for growing plants as a sustainable resource in long-duration space exploration (Chandler *et al.*, 2020; Zhao *et al.*, 2007). A detailed picture of how space constraints affect seed germination physiology, molecular stress responses, genetic stability, and epigenetic regulation is provided in Table 2.

Space Stressors Impacting seeds

Space exploration poses a unique set of environmental stressors that impact seed viability, germination and subsequent plant growth. Key space stressors include microgravity, cosmic radiation, temperature extremes, vacuum conditions, and nutrient limitations, each exerting multifaceted physiological and molecular effects on seeds and seedlings. Understanding how these factors impair or modify seed biology is crucial for developing sustainable space agriculture capable of supporting long-

Table 2 : Space constraints affect seed germination physiology, molecular stress responses, genetic stability and epigenetic regulation.

Parameter/Category	Specific Traits / Genes Studied	Findings in Spaceflight Experiments	Reference
Germination Physiology	Germination percentage, germination speed (t50), seedling establishment time, testa, and endosperm rupture	Spaceflight often results in delayed germination and reduced vigour; slower testa/endosperm rupture observed	Chandler <i>et al.</i> (2020)
	Seedling morphology: hypocotyl length, radicle length, biomass	Generally, reduced seedling growth and biomass accumulation in microgravity	Chandler <i>et al.</i> (2020)
	Water uptake and oxygen consumption during imbibition	Altered fluid dynamics reduce imbibition efficiency and oxygen availability	Maffei (2024)
Genetic and Molecular	Expression of genes related to DNA repair (ATM kinase, DNA ligase 1), heat shock proteins (hsps) and oxidative stress response	Upregulated stress response and repair genes indicate increased molecular damage from radiation and microgravity.	Chandler <i>et al.</i> (2020)
	Hormone metabolism and signalling genes (auxin transporters, gibberellins, cytokinins, ethylene pathways)	Altered expression affects gravitropism, cell expansion, and seedling growth.	Chandler <i>et al.</i> (2020)
	Ribosomal biogenesis and translation-related genes	Downregulation impacts protein synthesis and metabolic vigour post-spaceflight	Chandler <i>et al.</i> (2020)
Genetic Variation & Mutation	RAPD and SNP polymorphisms in DNA sequences, mutation frequency	Significant genetic variations (~30%) and increased recessive mutations were observed in space-flown seeds	Zhao <i>et al.</i> (2007)
	Epigenetic modifications (DNA methylation changes)	Changes modulate gene expression across generations, influencing germination plasticity	Zhao <i>et al.</i> (2007)
Stress and Ageing Responses	Sensitivity to artificial ageing treatments, reactive oxygen species (ROS), and detox enzymes	Increased ageing sensitivity and oxidative stress response suggest accelerated molecular damage.	Chandler <i>et al.</i> (2020)

Table 3 : Experiments on angiosperm flowering and fruiting in spaceflight.

Species	Platform/hardware	Findings	Reference
<i>Arabidopsis thaliana</i> (L.) Heynh.			
<i>Arabidopsis thaliana</i>	Salyut 7/ Svetoblok growth chamber	Seed-to-seed development confirmed; first demonstration of complete plant life cycle in orbit.	Salisbury (1991)
<i>Arabidopsis thaliana</i>	ISS/Advanced Astroculture (ADVASC) growth facility	Seed-to-seed development achieved; second back-to-back generation completed. Protein bodies in cotyledons markedly smaller than ground controls.	Link <i>et al.</i> (2014)
<i>Arabidopsis thaliana</i>	ISS/ Kibo Plant Experiment Unit (PEU), Japanese Experiment Module	Seed-to-seed development in a fully sealed, automated unit; delayed rosette leaf senescence observed; germination initiated ~3 days post-watering.	Takatsu <i>et al.</i> (2012)
<i>Brassica rapa</i> L. cv. <i>Astroplants</i>			
<i>Brassica rapa</i> cv. <i>Astroplants</i>	Mir/ Svet growth facility	Seed-to-seed development and second back-to-back generation; delay in seed development noted; starch grains present in cotyledons of mature seeds.	Musgrave and Kuang (2001)
<i>Brassica rapa</i> cv. <i>Astroplants</i>	ISS/ Biomass Production System (BPS)	Seed-to-seed development with immature seeds; asynchronous embryo development and altered embryo morphology; elevated soluble carbohydrates and starch; suppressed protein accumulation in embryos.	Kuang <i>et al.</i> (2000)
<i>Brassica rapa</i> cv. <i>Astroplants</i>	STS-87/ Space Shuttle Columbia, Plant Growth Facility	Seed-to-seed development with immature seeds; reduced protein body size in cotyledons; increased starch grain density.	Kuang <i>et al.</i> , 2000
<i>Triticum aestivum</i> L. cv. <i>Super Dwarf</i>			
<i>Triticum aestivum</i> cv. <i>Super Dwarf</i>	Mir/ Svet growth facility	Formation of sterile spikes; seed-to-seed development and second back-to-back generation; reduced size and mass of caryopses compared to ground controls.	Ekaterina <i>et al.</i> (2019)
<i>Triticum aestivum</i> cv. <i>Super Dwarf</i>	ISS/ Lada growth facility	Seed-to-seed development confirmed; detailed data on grain reserve substances not reported.	Ekaterina <i>et al.</i> (2019)
<i>Pisum sativum</i> L.			
<i>Pisum sativum</i>	ISS/ Lada growth facility	Four successive generations were completed in microgravity; detailed data on grain reserve substances were not reported.	Zabel <i>et al.</i> (2016)

term human missions. Space Environmental Impacts on Seed Physiology and Germination are given in Table 3.

Microgravity, the near-weightless condition experienced aboard spacecraft, profoundly alters seed germination dynamics and plant physiology. Although studies, including those on *Arabidopsis thaliana* grown from seed to seed in microgravity aboard the ISS, demonstrated high germination rates (~92%) and successful seed-to-seed cycles (Paul *et al.*, 2013), the absence of gravity disrupts cellular mechanosensing and

cytoskeletal organisation, affecting hormone signalling, cell elongation, and directional growth. Research indicates that microgravity impairs cytoplasmic streaming and cell wall rigidity, modifies phytochrome-mediated light perception, and disturbs root and shoot orientation, which can delay seedling establishment and alter morphology (Van Loon, 2024). Moreover, fluid distribution within seeds during imbibition is affected, potentially changing water uptake kinetics and oxygen availability critical for metabolism activation at germination (Maffei, 2024).

Experimental clinostat and centrifuge studies simulating altered gravities have shown microgravity lengthens germination time by slowing testa and endosperm rupture processes (Saito *et al.*, 1995).

Cosmic radiation presents a major hazard in space that markedly influences seed DNA integrity and viability. Seeds exposed to unshielded cosmic rays and ultraviolet radiation outside the ISS display significantly reduced germination rates and seedling vigour (Shao *et al.*, 2017). For instance, *Arabidopsis* and tobacco seeds subjected to low Earth orbit space radiation had ~90% viability when shielded from short-wavelength UV but showed severe viability loss when exposed unprotected (Chandler *et al.*, 2020). Cosmic rays induce DNA strand breaks, nucleotide modifications, and generate reactive oxygen species that damage membranes and macromolecules, triggering stress response genes, including heat shock proteins and DNA repair enzymes. Such molecular damage can result in delayed germination, diminished seedling photosynthetic efficiency, abnormal morphology, and heritable mutations affecting stress tolerance (Zhao *et al.*, 2007).

Temperature fluctuations and extremes, ranging from near vacuum-induced cold to possible transient heating, further impact seed longevity and germination kinetics. While dry seeds generally tolerate wide temperature ranges (from cryogenic -196°C to wildfire-like >1000°C) on Earth, microgravity experiments confirm that moderate ambient ISS temperature (~18-25°C) preserves seed viability during storage (Chandler *et al.*, 2020). However, elevated temperatures above optimal germination ranges can reduce germination percentage and delay onset, as reported for several species. Vacuum and anoxic packaging have been shown to sustain seed quality and extend longevity by limiting oxygen-driven oxidative deterioration during storage (Groot *et al.*, 2015).

The vacuum of space adds additional stress by desiccating seeds and exposing them to oxidative damage. Vacuum-sealed packaging reduces oxygen that fuels free radicals, thereby protecting seeds from oxidative degradation and insect pests during storage. On the other hand, seeds directly exposed to vacuum and UV radiation without protection suffer molecular damage and near-total viability loss (Chandler *et al.*, 2020). Thus, vacuum influences seed survival principally through oxygen depletion and increased radiation exposure effects rather than pressure *per se*.

Nutrient availability in space presents indirect challenges to germination and early seedling establishment. Hydroponic or substrate cultivation environments aboard spacecraft require precise delivery

of mineral nutrients and water, both physically influenced by microgravity, where fluids behave differently, complicating uniform root zone distribution (NASA, 2025). Nutrient limitation delays seedling growth and affects metabolic recovery post-germination, necessitating optimised delivery systems and crop species well adapted to space cultivation conditions. Experimental systems such as “plant pillows” and closed greenhouses explore these solutions.

Effects of Microgravity

During a 122 day mission aboard the Mir space station, *Brassica rapa* L. plants completed full life cycles in microgravity, but analyses of the mature seeds revealed marked differences from Earth grown controls, space produced seeds had less than 20% of the cotyledon cell number found in ground controls, retained large amounts of starch instead of switching predominantly to protein and lipid reserves, and contained protein bodies 44% smaller than those in Earth seeds. Supporting Shuttle STS 87 embryo studies showed that 15 days after pollination, space-grown embryos had abundant starch grains and no protein bodies, whereas Earth embryos at the same stage had already formed protein bodies and reduced starch stores. These results indicate that while gravity is not essential for any stage of the *Brassica* life cycle, microgravity alters late seed development and maturation, delaying or disrupting normal reserve deposition and cellular development, which in turn compromises seed quality despite successful reproduction (Kuang *et al.*, 2000). The experiments on angiosperm flowering and fruiting in spaceflight are represented in Table 3.

In experiments aboard the ISS using the Biomass Production System, *Brassica rapa* (cv. Astroplants) grown from seed to immature seed stage under microgravity showed overall vegetative growth, leaf chlorophyll, starch and soluble carbohydrate levels comparable to ground controls, but with notable metabolic and developmental differences like stems from flight plants had, on average, 75% higher 3 butenylglucosinolate content (a secondary metabolite affecting flavor and potential health properties), and immature seeds produced in orbit contained more chlorophyll, starch, and soluble carbohydrates but significantly less protein than Earth-grown counterparts, microscopy revealed embryo development in the flight seeds was more variable and generally less advanced, with storage reserve deposition lagging behind the uniform premature stage seen in controls. These findings indicate that while current hardware can support healthy plant growth in microgravity, the spaceflight environment alters secondary metabolism

and seed-filling processes in ways that could affect both the nutritional composition and sensory qualities of space-grown produce, with implications for life-support crop selection and nutritional planning in long-duration missions (Musgrave *et al.*, 2001).

The Carman *et al.* (2015) study on the Mir “Greenhouse 2” *Super Dwarf* wheat crops underscores how environmental stressors in weightlessness can prevent seed formation entirely, thereby blocking any subsequent germination. In the first Mir crop (123 d), floral spikes formed, but no viable seeds developed. Ethylene in the Mir cabin atmosphere was measured at 1.1–1.7 $\mu\text{mol}/\text{mol}^{-1}$, well above the physiological thresholds for sensitive cereals, which, along with high NH_4 availability from the Balkanine zeolite substrate, likely disrupted reproductive development and caused kernel abortion, as confirmed by ground analogues. The second Mir crop (41 d) was harvested vegetatively for analysis; while no seeds were produced, physiological measurements revealed stress patterns that, had the plants continued to anthesis and seed fill, would have severely compromised seed quality and germination potential. These included hyperhydricity (excess tissue water content in culms, crowns, and live leaves from poor canopy ventilation in microgravity), nutrient imbalances (low magnesium and phosphorus, potentially toxic boron accumulation), hormone imbalances (low ABA and high cytokinins likely driven by ethylene suppression of ABA synthesis), and markers of oxidative stress and ROS triggered autophagy in mature and senescent leaves.

From a germination perspective, ABA is critical in seed maturation for inducing tolerance to desiccation and regulating dormancy; low ABA in parent tissues suggests seeds, if produced, may have been “green” or immature physiologically, with reduced storability and erratic germination. Hyperhydric stresses could limit oxygen diffusion into developing seeds, impacting embryo respiration and storage reserve synthesis. Deficiencies in magnesium (vital for ATP and chlorophyll biosynthesis) and phosphorus (key in energy metabolism) could further limit the biochemical readiness of seeds to germinate vigorously. Additionally, oxidative stress late in seed fill can damage cellular structures and macromolecules, impairing both viability and uniform emergence.

The germination of cotton seeds on the Moon during China’s Chang’e-4 mission in January 2019 marked the first successful biological growth outside Earth’s orbit. Seeds were housed within a sealed mini biosphere maintaining controlled temperature, humidity, air, and nutrient supply. Despite this, the lunar environment posed

severe constraints, intense cosmic radiation, microgravity equivalent to one-sixth of Earth’s gravity, and extreme temperature fluctuations. Cotton seeds sprouted successfully, but seedling vigour was markedly reduced compared to Earth controls, attributable to radiation damage and suboptimal canister conditions. Other seeds, including potato and *Arabidopsis*, failed to germinate. The experiment ended when the onset of lunar night drove temperatures to approximately -52°C , incompatible with seedling survival. These findings confirm the technical feasibility of lunar surface germination while underscoring the substantial environmental engineering required for sustainable cultivation beyond low Earth orbit (Xie *et al.*, 2024).

In genetic studies related to spaceflight, *Arabidopsis thaliana* has served as the primary model organism for elucidating molecular responses to space stressors. Transcriptomic analyses aboard the ISS revealed broad alterations in hormone signalling pathways, particularly auxin transport, gibberellin biosynthesis, cytokinin signalling, and ethylene synthesis with downstream consequences for root growth directionality, cell elongation, and germination-related stress adaptation (Kruse *et al.*, 2020).

The table documents nine spaceflight experiments conducted across four angiosperm species, tracking how plants performed when grown through complete life cycles in microgravity. Four plants were selected, each representing a different agricultural category: *Arabidopsis thaliana* as a genetic model organism, *Brassica rapa* as a leafy crop, *Triticum aestivum* as a cereal grain and *Pisum sativum* as a legume. This spread ensured findings were not species-specific. Experiments were distributed across Salyut 7, Mir, the ISS, and the Space Shuttle, spanning roughly four decades of spaceflight. The progression from simple Soviet growth chambers to the fully automated ISS facilities reflects how rapidly the technology has evolved. Platform/hardware identifies where and on what equipment each experiment was conducted, the spacecraft or space station (e.g. Mir, ISS, Space Shuttle Columbia) paired with the specific plant growth unit used onboard (e.g. Svet facility, ADVASC chamber, Lada growth facility), since different hardware provides different levels of environmental control and directly influences the experimental outcomes. Three patterns emerge consistently across all species. First, seed-to-seed development is achievable in microgravity, which is the critical proof of concept for self-sustaining space agriculture. Second, seed quality is reliably compromised when protein bodies are smaller, starch grains accumulate

abnormally and embryo development becomes asynchronous, meaning space-grown seeds are nutritionally and structurally different from Earth controls. Third, developmental timing is disrupted, delays in seed maturation, sterile spikes in wheat, and altered senescence patterns suggest that microgravity interferes with the hormonal and gravitropic signals that normally coordinate plant development.

Future Prospects

Microgravity is probably the single most pervasive obstacle facing space agriculture. It interferes with nearly every physical process that plants depend on: roots lose reliable anchorage, water and nutrients distribute unpredictably, and gas exchange becomes irregular. In weightlessness, water clings to surfaces instead of draining, which can deprive roots of oxygen and nutrients poorly distributed in the growing medium. Hydroponic and aeroponic systems, often combined with precision environmental chambers, are being refined to address these limitations, but only if supported by sophisticated automation and robust engineering, neither of which is trivial to maintain in an orbital or planetary habitat.

Space radiation is a separate serious problem. Beyond its well-documented effects on DNA, elevated mutation rates and reduced germination success, radiation can suppress crop yields and degrade nutritional content. Researchers are pursuing structural shielding using regolith or water, alongside genetic approaches including

conventional breeding and CRISPR editing to develop radiation-tolerant crop varieties. It is worth stating clearly, however, that no current crop variety has been demonstrated to be fully radiation tolerant under realistic deep-space exposure levels. This remains an open and unsolved problem.

The scarcity of resources in any spacecraft or planetary outpost compounds these difficulties. Water is precious, nutrient supplies are finite and closed-loop recycling systems operate under tight constraints. Bioregenerative life-support designs that recover and reuse air, water, nutrients, and organic matter continuously are a top research priority. Engineered microbial communities and AI-driven precision agriculture tools are being integrated into these designs, though the performance of such systems under multi-year operational stress has not yet been validated at scale. A conceptual illustration of an orbital growth module is given in Fig. 4.

Practical and economic realities shape the field's trajectory as much as the biology does. Growing space is inherently limited in any habitat, which means farms must be compact, modular, and vertically layered to extract the maximum edible biomass from every cubic metre. The cost of launching equipment and biological payloads into space remains high, resupply windows are infrequent, and the regulatory landscape for extraterrestrial biological systems is still evolving. The growing commercial space economy may help change this calculus. Public-private

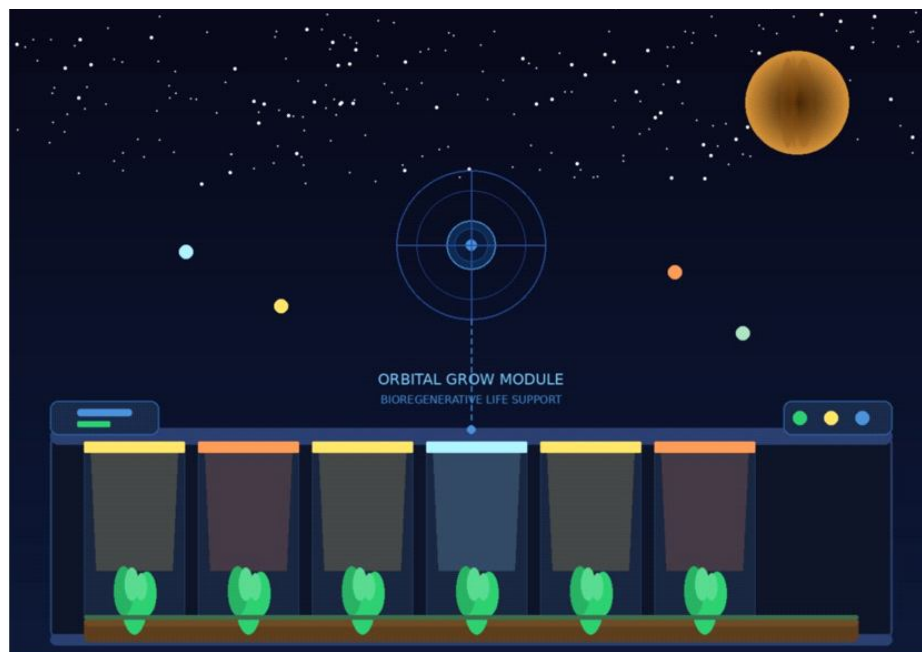


Fig. 4 : A conceptual illustration of an Orbital Grow Module depicting six hydroponic grow bays illuminated by multi-spectrum LED arrays within a pressurised space habitat, with an AI-driven satellite monitoring unit overhead and a Mars-like planet in the background, representing the integration of bioregenerative life support systems for sustainable space farming.

Partnerships and international collaborations are already accelerating both innovation and investment.

The technological picture is encouraging in places. Miniaturised growth systems on cubesats and the ISS have generated valuable data on plant responses to low gravity and radiation, giving breeders and engineers better targets for selecting stress-tolerant, metabolically efficient crops. CRISPR and related genome editing tools now make it possible to engineer crops specifically for particular mission profiles, though deployment of genetically modified organisms in closed space ecosystems raises regulatory and ecological questions that have not been resolved. Dense sensor arrays, automated phenotyping platforms, and AI-managed resource systems can help keep environmental conditions optimised while reducing demands on crew time (NASA, 2025).

The decisive experiments for the next decade will likely be the first long-duration Artemis lunar missions, where the actual performance of plant cultivation systems under real lunar radiation levels and gravity (1/6 g) will provide data that no Earth-based simulation can substitute. Whether current cultivation hardware and crop varieties are adequate for that environment or whether fundamental redesign is required remains an open question.

Conclusion

Space farming has come a long way from its origins as a speculative idea on the margins of aerospace science. From the first tentative germination tests on Soviet spacecraft to the fully automated Advanced Plant Habitat on the ISS with its 180-plus sensors and precise control over light, humidity, and gas exchange, decades of careful experimentation have demonstrated unambiguously that plant growth, reproduction and multigenerational development are achievable beyond Earth's gravity.

That achievement should not obscure how much remains to be solved. Microgravity undermines physiological processes that plants have refined over hundreds of millions of years. Gravitropic signalling breaks down, auxin redistribution goes awry, root-zone hypoxia emerges from aberrant fluid dynamics, and cell wall architecture becomes thinner and less organised. Cosmic radiation inflicts double-strand DNA breaks, raises reactive oxygen species to damaging levels, and sets off epigenetic reprogramming that, as multi-omics work on rice has now shown, can be transmitted as heritable stress memory through successive generations. These are not minor engineering inconveniences, they represent deep incompatibilities between plant biology as it evolved on

Earth and the conditions that prevail in space.

Perhaps the most significant single finding of recent years is the Zeng *et al.* (2025) demonstration that spaceflight-induced stress memory is transmissible across five rice generations through integrated epigenomic, transcriptomic, and metabolic mechanisms. This finding changes the way we should think about space-bred crop development, not as a one-generation intervention, but as a multigenerational process with complex and not fully predictable outcomes.

The most promising approaches are emerging at the intersection of genomics, controlled environment agriculture, and closed-loop systems biology. CRISPR-engineered cultivars built for radiation and microgravity tolerance, AI-integrated phenotyping platforms, and bioregenerative life-support architectures that weave crop production into atmospheric management and nutrient recycling are all advancing, though none have yet been validated under operational deep space conditions. The knowledge generated by this research does not flow in only one direction. Advances in precision resource management, compact vertical growing systems and the physiology of stress-resilient crops are already producing measurable benefits for food production on Earth.

Whether space agriculture ultimately succeeds in sustaining a permanent human presence beyond Earth will depend on sustained investment, genuine interdisciplinary collaboration and critically, a willingness to treat the unresolved problems honestly rather than to oversell current capabilities.

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