Innovation of food productions for space exploration: Concepts, Agricultural aspects, Food production systems

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ABSTRACT

Long-duration human space missions require food systems that can operate independently of Earth-based resupply. This review examines the evolution of space food systems, evaluates potential biological resources for food production, and discusses recent advances in plant cultivation and emerging food production technologies. The study is organized into key themes: the historical development of space food, biological resources, plant cultivation under microgravity, Controlled Environment Agriculture (CEA), automation, three-dimensional (3D) food printing, and closed-loop life-support systems. Historically, space food systems have progressed from the packaged meals of the Mercury and Apollo missions to the more diverse food systems used on the Space Shuttle, the International Space Station, and commercial resupply missions. Despite those advances, current systems remain dependent on regular deliveries from Earth. A combination of plants, microorganisms, algae, fungi, insects, and cultivated meat could provide complementary nutritional and life-support functions, while CEA, automated food production, 3D food printing, and Engineered Closed Circular Environmental Life-Support Systems (ECCLES) offer promising approaches to self-sufficient food production. However, significant challenges remain, including reduced crop performance under microgravity, high energy demands, automation reliability, food safety, and system integration. Developing integrated food production systems will be essential for supporting astronaut health, enabling sustainable long-duration missions, and establishing permanent human habitats beyond Earth.

Keywords: Space food production, Controlled environment agriculture, Microgravity, 3D food printing, Closed-loop life-support systems

Introduction

Space exploration is increasingly focused on long-duration missions to the Moon and Mars, making sustainable food production a critical requirement rather than a logistical consideration. Unlike short-term

missions, future expeditions beyond low Earth orbit will require food systems capable of providing continuous nutritional support while reducing reliance on Earth-based resupply (Watkins et al., 2022). As a result, space food production has become an interdisciplinary field that combines agriculture, biotechnology, environmental engineering, and life-support technologies to support astronaut health and mission success.

Food systems for space missions must satisfy requirements that extend well beyond nutritional adequacy. In addition to preserving food safety and quality during prolonged storage, they must minimize payload mass and volume, use limited resources efficiently, and function reliably under microgravity. These constraints distinguish space agriculture from terrestrial food production and have driven the development of resource-efficient, automated, and closed-loop production systems (Nguyen et al., 2023).

The evolution of space food systems has closely followed advances in human spaceflight. Early Mercury and Apollo missions relied on pre-packaged foods, including sterile purees, thermostabilized products, and freeze-dried meals designed for short-duration flights (Klicka & Smith, 1982). During the Space Shuttle era, food technology advanced with the introduction of canned foods, rehydratable meals, and improved packaging following the removal of onboard refrigeration and freezer facilities (Perchonok & Bourland, 2002).

The International Space Station (ISS) marked an important step toward more diverse food systems. Refrigerated and frozen foods, rehydratable beverages, thermostabilized meals, and limited fresh produce improved dietary variety while maintaining nutritional quality (Kloeris, 2000). More recently, commercial cargo missions, particularly those operated by SpaceX Dragon, have expanded the supply of fresh foods to the ISS, further improving food availability in low Earth orbit (SpaceX, 2020). Nevertheless, these systems still depend on regular resupply missions from Earth and are therefore unsuitable for future deep-space exploration.

Developing autonomous food production remains one of the greatest challenges for long-duration missions. Pre-packaged foods gradually lose nutritional value during extended storage and are unlikely to meet the demands of multi-year missions (Watkins et al., 2022). At the same time, microgravity affects plant growth by altering water transport, root development, and physiological processes, making reliable crop production in space particularly challenging (Baba et al., 2022; Medina et al., 2021; Wang et al., 2022).

These challenges have accelerated the development of technologies that enable in situ food production while recycling essential resources. Controlled Environment Agriculture (CEA), automated food production, three-dimensional (3D) food printing, and Engineered Closed Circular Environmental Life-Support Systems (ECCLES) are being developed to integrate food production with environmental control, waste recycling, and resource recovery (Archambault et al., 2023; Nguyen et al., 2023). In parallel, expanding the range of biological resources beyond conventional crops including bacteria, algae, fungi, insects, and cultivated meat could improve nutritional diversity while increasing the resilience and sustainability of future space food systems.

This review examines the evolution of food production for space exploration, from early space food systems to emerging technologies for long-duration missions. It evaluates the potential of diverse biological resources, summarizes recent advances in plant cultivation under space conditions, and reviews key technologies, including Controlled Environment Agriculture (CEA), automated food production, 3D food printing, and Engineered Closed Circular Environmental Life-Support Systems (ECCLES). Together, these developments provide a foundation for sustainable and self-sufficient food systems that will support future human exploration beyond Earth.

Evolution of Space Food Systems

Early Missions (Mercury–Apollo)

Early human space missions relied exclusively on pre-packaged foods designed for short-duration flights. During the Mercury program, astronauts consumed sterile foods packaged in aluminum tubes, including the applesauce eaten by John Glenn during the first U.S. crewed orbital mission (Klicka & Smith, 1982). As missions progressed through the Gemini, Apollo, and Skylab programs, food systems became more sophisticated to improve nutritional quality, storage stability, and crew acceptance. Thermostabilized meals, freeze-dried foods, compressed vegetables, and improved packaging expanded menu options while reducing storage requirements. Apollo missions also introduced utensil-compatible packaging and systematic nutritional monitoring to ensure adequate energy and mineral intake (Klicka & Smith, 1982). Although these advances established the foundation of modern space nutrition, all foods continued to be prepared on Earth before launch.

Space Shuttle and International Space Station (ISS)

The transition to reusable spacecraft and long-term orbital missions created new demands for space food systems. During the Space Shuttle era, the removal of onboard refrigerators and freezers encouraged the development of canned and rehydratable foods that could maintain quality over extended storage periods (Perchonok & Bourland, 2002). The International Space Station (ISS) further diversified astronauts' diets by incorporating refrigerated and frozen foods, thermostabilized meals, powdered beverages, and limited fresh produce supplied by international partners (Kloeris, 2000). Advances in packaging, including foil laminate pouches and rehydratable containers with septum valves, improved food handling under microgravity while reducing contamination risks (Kloeris, 2000; NASA, 2020). Despite these improvements, the ISS food system remains dependent on regular cargo resupply from Earth, limiting its suitability for future deep-space missions (NASA, 2009).

Current Commercial Missions (SpaceX)

Commercial spaceflight has significantly improved food logistics in low Earth orbit. SpaceX Dragon spacecraft now serve as the primary cargo vehicles for ISS resupply, delivering ready-to-eat meals alongside fresh foods such as fruit and cheese to enhance dietary variety and nutritional quality (SpaceX, 2020). More frequent and reliable cargo missions have strengthened food security for orbital operations. However, this model still relies on continuous Earth-based resupply and is therefore impractical for future missions to the Moon and Mars. The need for greater autonomy has driven the development of in situ food production technologies, including Controlled Environment Agriculture (CEA), automated food production, three-dimensional (3D) food printing, and closed-loop life-support systems designed to support sustainable human habitation beyond Earth (Archambault et al., 2023; Nguyen et al., 2023).

Biological Resources for Space Food Production

Long-duration space missions require food sources that provide balanced nutrition while supporting life-support functions, efficient resource use, and environmental sustainability. Unlike terrestrial agriculture, food production in space must operate under strict constraints on space, water, energy, and resupply opportunities. For this reason, researchers have explored a range of biological resources—including plants, microorganisms, algae, fungi, insects, and cultivated meat—to improve the resilience and sustainability of future space food systems.

Plants

Plants remain the foundation of proposed space food systems because they provide food while simultaneously generating oxygen and removing carbon dioxide through photosynthesis. Seeds occupy relatively little payload space yet supply essential dietary fiber, vitamins, and minerals. Plant cultivation

can also be integrated into closed-loop life-support systems by using carbon dioxide generated by astronauts to sustain photosynthesis (Nguyen et al., 2023). However, microgravity alters water transport, root orientation, and plant development, making reliable crop production a major challenge for long-duration missions (Baba et al., 2022; Medina et al., 2021; Wang et al., 2022).

Bacteria

Beneficial bacteria offer an alternative approach to food production through microbial fermentation and single-cell protein technologies. Food-grade microorganisms, particularly lactic acid bacteria, are widely used to produce fermented foods with desirable nutritional and sensory properties while offering efficient and genetically stable production systems (Jarvis, 2020). Hydrogen-oxidizing bacteria have also attracted interest because they require little land and can produce biomass independently of conventional agriculture (Alvarado et al., 2021). However, large-scale application will depend on cultivation systems that ensure consistent productivity and food safety (Smith, 2019).

Algae

Algae are promising candidates for space food production because they combine several functions within a single biological system. In addition to providing protein-rich biomass, they generate oxygen, recycle carbon dioxide, and may serve as biofuel feedstocks. Their rapid growth and low demands for land and water make them particularly suitable for closed-loop life-support systems (Niederwieser et al., 2018). Microalgae can be cultivated in photobioreactors that optimize light exposure, gas exchange, and nutrient recycling (Detrell, 2024). Nevertheless, maintaining stable production under space conditions requires sophisticated environmental control, and further technological development is needed before routine deployment (Deuri et al., 2024).

Fungi

Fungi provide a complementary food source that requires less space than conventional crops and does not rely on photosynthesis. Instead, fungal biomass is produced through heterotrophic metabolism, allowing cultivation under limited light conditions (Cortesão et al., 2020). Their ability to convert organic waste into edible biomass also makes them well suited for resource recycling within closed habitats (Lucht & Broussard, 2025; Parshall, 2023). Although fungi can enhance the efficiency of integrated food systems, they are more likely to complement than replace other food sources.

Insects

Edible insects have gained attention as an efficient source of dietary protein because they require less land and water than conventional livestock while converting feed into biomass efficiently. Species such as mealworms, silkworms, and fly larvae also provide essential vitamins and minerals and can recycle inedible plant material and organic waste (Dufour, 1981; Kok & van Huis, 2021). Their inclusion in closed-loop food systems could improve both nutritional sustainability and waste management. However, cultural acceptance, food processing, and consumer perception remain important barriers, particularly for multinational astronaut crews (Jansson & Berggren, 2015).

Cultivated Meat

Cultivated meat offers a potential source of animal protein without the need for conventional livestock production. Animal cells grown in controlled bioreactors could provide high-quality protein while reducing the environmental costs associated with traditional meat production (European Space Agency [ESA], 2023). Early experiments aboard the International Space Station have demonstrated the feasibility of producing cultured meat under microgravity, highlighting its potential for future planetary habitats (Reiss et al., 2021). However, major technical challenges remain, particularly the development of energy-efficient bioreactors capable of supporting continuous large-scale production in space.

Taken together, these biological resources perform complementary rather than competing roles. Plants are central to food

production and atmospheric regeneration, while microorganisms and algae support nutrient recycling and oxygen production. Fungi and insects offer resource-efficient protein sources, and cultivated meat could further diversify astronaut diets. Integrating these biological systems within closed-loop life-support systems is likely to provide the most resilient and sustainable approach to food production for future long-duration space missions.

Plant Cultivation in Space

Plant cultivation is central to sustainable space food production because crops can provide food, generate oxygen, recycle carbon dioxide, and support closed-loop life-support systems. Unlike stored food supplies, crop production offers a renewable source of nutrients and contributes to environmental control within spacecraft and extraterrestrial habitats. However, reliable cultivation in space requires systems that can function under microgravity, limited resources, and tightly controlled environmental conditions.

Candidate Crops

Crop selection for space agriculture depends on nutritional value, growth efficiency, and adaptability to controlled environments. Wheat (Triticum aestivum) has been widely studied because of its high nutritional value and ability to complete a "seed-to-seed" life cycle under spaceflight conditions using the Svetoblock-M growth system aboard the Mir Space Station, although microgravity affects water distribution and root development (Mashinsky et al., 1994). Pea (Pisum sativum) is also promising because of its rapid growth and nutritional quality, but root orientation and growth rate remain affected by the absence of gravity even under controlled ISS conditions (Spencer et al., 2023). Tomato (Lycopersicon esculentum) has shown potential for space cultivation, particularly when supported by beneficial fungi such as Trichoderma harzianum, although careful management of water and nutrient supply is still required (Dasilva, 2024; Land et al., 2024). Overall, these findings suggest that several crops can be grown in space, but cultivation strategies must be adapted to species-specific physiological responses.

Hydroponics and Aeroponics

As soil-based agriculture is impractical in space, soilless systems have become the main approach for controlled crop production. Hydroponics delivers nutrients through aqueous solutions, allowing efficient cultivation while reducing water use and eliminating the need for soil. Crops such as lettuce, radish, and green onion have shown compatibility with hydroponic systems (U.S. Department of Agriculture, 2024). Aeroponics further improves resource efficiency by supplying nutrients as fine aerosols directly to plant roots, thereby minimizing water consumption while maintaining nutrient availability. Together, hydroponic and aeroponic systems offer controlled production environments suited to spacecraft and extraterrestrial habitats, where water conservation and environmental regulation are essential.

Aquaponics

Aquaponics combines plant cultivation with aquaculture in a symbiotic system: fish waste provides nutrients for plants, while plants help purify the water. This approach improves resource recycling and reduces the need for external nutrient inputs, making it relevant for long-duration missions under closed-loop conditions. Experimental applications suggest that aquaponic systems can support crops such as tomatoes, herbs, and cabbage in space-relevant environments (Bowman, 2023; Go Green Aquaponics, 2026). However, aquaponics is more operationally complex than hydroponics because both plant and aquatic components must remain biologically balanced.

Effects of Microgravity on Plant Growth

Microgravity remains a major biological constraint for space agriculture. Reduced gravity disrupts environmental cues that guide normal plant development, altering root orientation, water movement, and overall plant architecture. At the cellular level, microgravity can trigger physiological and

molecular responses, including changes in gene expression related to cell wall formation, oxidative stress, autophagy, and defense mechanisms (Baba et al., 2022; Medina et al., 2021). These changes may reduce plant productivity and affect long-term crop performance under extraterrestrial conditions. Even so, current evidence indicates that many crops retain adaptive capacity when grown under carefully controlled environments. Further optimization of environmental control systems and cultivation techniques will therefore be necessary to achieve reliable crop production for future lunar and Martian missions (Wang et al., 2022).

Overall, sustainable space agriculture will depend on matching suitable crop species with advanced soilless cultivation systems that can maintain stable production under microgravity. The integration of hydroponic, aeroponic, or aquaponic technologies with precise environmental control represents an important step toward self-sufficient food production for long-duration human space exploration.

Advanced Food Production Technologies

Future deep-space missions will require food production systems that can operate with minimal reliance on Earth while making efficient use of limited water, energy, and space. As a result, research has shifted beyond conventional food preservation toward integrated systems that combine controlled agriculture, automation, additive manufacturing, and closed-loop resource recycling. Together, these technologies have the potential to improve food security, reduce crew workload, and support sustainable long-duration space exploration.

Controlled Environment Agriculture (CEA)

Controlled Environment Agriculture (CEA) enables crop production by precisely regulating temperature, humidity, light intensity, and nutrient delivery (Archambault et al., 2023). By combining hydroponic cultivation with automated environmental control, CEA improves production efficiency while reducing water consumption. NASA's Controlled Ecological Life Support System (CELSS) program also laid the foundation for technologies such as LED lighting and vertical farming, which are now widely used in controlled agriculture (Wheeler, 2017). Despite these advantages, CEA remains energy intensive, particularly because of its dependence on artificial lighting and continuous environmental regulation, highlighting the need for more energy-efficient systems before deployment in long-duration missions.

Automated Food Production

Automation is expected to play a central role in future space food systems by reducing crew workload and improving operational reliability. Robotic platforms capable of planting, irrigating, harvesting, and monitoring crop health can maintain continuous food production with minimal astronaut intervention (Paape et al., 2024). In food processing, Microwave-Assisted Thermal Sterilization (MATS) enhances the safety and quality of ready-to-eat meals compared with conventional thermal processing, although prolonged storage can still affect texture and flavour (Ross et al., 2023). Highly autonomous production systems will be particularly important for Mars missions, where communication delays and limited human resources demand reliable, self-sustaining operations (Badajoz et al., 2023).

Three-Dimensional (3D) Food Printing

Three-dimensional (3D) food printing offers a flexible approach to producing customized meals from powdered or cartridge-based ingredients. Preparing food on demand reduces storage volume, extends ingredient shelf life, and allows nutritional composition to be tailored to astronauts' physiological needs (Gaskill, 2019). Additive manufacturing also supports broader space operations by enabling in situ fabrication of tools and replacement parts, reducing dependence on Earth-based resupply (Ellery, 2024). Although 3D printing shows considerable promise, routine application will require reliable ingredient storage systems and further technological refinement.

Engineered Closed Circular Environmental Life-Support Systems (ECCLES)

Engineered Closed Circular Environmental Life-Support Systems (ECCLES) provide a framework for integrating food production with air regeneration, water purification, and waste recycling into a single ecosystem. By linking human metabolism, plant cultivation, and biological waste treatment, ECCLES aims to minimize external resource requirements while maintaining long-term habitability (Gitelson & Lisovsky, 2008). Previous studies have demonstrated the feasibility of growing crops such as wheat, lettuce, soybeans, and potatoes within closed ecological systems, illustrating the potential of biological recycling for future extraterrestrial habitats (Macelroy, 1992). However, maintaining biological stability and balancing interconnected ecological processes remain major engineering challenges. Further improvements in system integration and operational reliability will be essential before fully autonomous life-support systems can support extended missions to the Moon and Mars.

Rather than functioning as independent technologies, these approaches are most effective when integrated into a single food production system. CEA provides the cultivation platform, automation improves operational efficiency, 3D food printing enables flexible meal preparation, and ECCLES closes resource loops through recycling and environmental management. Their integration offers a practical pathway toward self-sufficient food systems capable of supporting long-duration human exploration beyond Earth.

Comparative Analysis

No single biological resource or production technology can meet all the nutritional, environmental, and operational demands of long-duration space missions. Instead, sustainable food production will depend on integrating complementary biological resources with advanced production technologies, each contributing distinct advantages while addressing different aspects of food security and life-support.

Strengths

Among the biological resources reviewed, plants remain the cornerstone of space food systems because they provide food while simultaneously supporting oxygen production and carbon dioxide removal. Algae further improve system sustainability through rapid biomass production, oxygen generation, and nutrient recycling, whereas fungi, insects, and cultivated meat offer alternative protein sources with lower resource requirements than conventional livestock (Niederwieser et al., 2018; Cortesão et al., 2020; Kok & van Huis, 2021; Reiss et al., 2021). These biological resources are complemented by technological advances. Controlled Environment Agriculture (CEA) enables reliable crop production under tightly regulated conditions, automation improves operational efficiency and reduces crew workload, 3D food printing supports personalized nutrition with efficient ingredient storage, and Engineered Closed Circular Environmental Life-Support Systems (ECCLES) integrate food production with water, air, and nutrient recycling to enhance long-term sustainability (Archambault et al., 2023; Ross et al., 2023; Gaskill, 2019; Nguyen et al., 2023).

Limitations

Despite substantial progress, none of these approaches can independently support autonomous food production beyond Earth. Plant cultivation remains limited by the effects of microgravity on root development, water transport, and overall plant growth (Baba et al., 2022; Medina et al., 2021; Wang et al., 2022). CEA requires considerable energy to maintain artificial lighting and environmental control, while automated systems depend on reliable robotics and continuous monitoring (Archambault et al., 2023; Badajoz et al., 2023). Similarly, algae, fungi, insects, and cultivated meat still require improvements in cultivation efficiency, processing technologies, and resource utilization before large-scale application becomes feasible (Detrell, 2024; Lucht & Broussard, 2025; ESA, 2023). These limitations indicate that

current technologies should be viewed as complementary components rather than standalone solutions.

Relative Technology Readiness

The technologies reviewed differ considerably in their level of maturity. Conventional packaged foods, thermostabilized meals, and ISS food systems are well-established technologies that have supported human spaceflight for decades (Kloeris, 2000; NASA, 2009; NASA, 2020). Plant cultivation has progressed beyond laboratory research, with several crop species successfully grown under spaceflight conditions, demonstrating increasing potential for future food production (Mashinsky et al., 1994; Spencer et al., 2023; Dasilva, 2024). In contrast, automated food production, 3D food printing, cultivated meat, and fully integrated ECCLES remain at the experimental or prototype stage. Although early results are encouraging, these technologies require further validation under the conditions expected during long-duration missions before operational deployment (Ellery, 2024; Reiss et al., 2021; Nguyen et al., 2023).

Remaining Research Gaps

Several challenges must be addressed before self-sufficient food production can support deep-space exploration. Future research should improve crop productivity under microgravity, reduce the energy requirements of controlled cultivation systems, increase the reliability of automated production, and strengthen the integration of biological production with closed-loop resource recycling. Further work is also needed to optimize the cultivation of algae, fungi, insects, and cultivated meat while ensuring food safety, nutritional quality, and long-term system stability. Ultimately, sustainable space food production will depend on integrating complementary biological resources with advanced technologies into a resilient life-support system capable of supporting continuous human habitation beyond Earth (Nguyen et al., 2023).

Future Directions

Achieving autonomous food production remains essential for sustained human exploration of the Moon, Mars, and beyond. Future research should focus on integrating biological resources with advanced production technologies into unified life-support systems rather than optimizing individual components in isolation. Controlled Environment Agriculture (CEA), automated cultivation, additive manufacturing, and Engineered Closed Circular Environmental Life-Support Systems (ECCLES) should be developed as interoperable platforms capable of producing food, recycling resources, and maintaining environmental stability within a single system (Archambault et al., 2023; Nguyen et al., 2023).

Improving crop performance under microgravity remains a key research priority. Further studies are needed to better understand plant adaptation to reduced gravity, optimize environmental control strategies, and develop cultivation systems that maximize productivity while reducing water and energy consumption (Baba et al., 2022; Medina et al., 2021). Alternative biological resources, including algae, fungi, insects, and cultivated meat, also require further evaluation to improve production efficiency, nutritional quality, food safety, and compatibility with closed-loop ecosystems before routine application in space habitats.

Advances in automation and digital technologies are expected to further strengthen space food production. Autonomous monitoring, robotic crop management, and intelligent process control could reduce crew workload while improving system reliability during long-duration missions (Badajoz et al., 2023). Future space food systems should therefore be designed as integrated ecosystems that balance productivity, resource efficiency, and operational reliability while supporting both the physical and psychological well-being of astronauts.

Conclusion

Sustainable food production will be a cornerstone of future long-duration space exploration. The evolution of space food systems reflects a gradual shift from dependence on pre-packaged foods toward

integrated production systems capable of generating fresh food while recycling essential resources. This review highlights the complementary roles of biological resources including plants, microorganisms, algae, fungi, insects, and cultivated meat and emerging technologies such as Controlled Environment Agriculture, automated food production, three-dimensional food printing, and Engineered Closed Circular Environmental Life-Support Systems in supporting self-sufficient space habitats.

Although significant progress has been made, no single biological resource or technology can meet the nutritional, environmental, and operational demands of future lunar and Martian missions. Instead, sustainable food production will depend on integrating complementary biological systems with advanced technologies within resilient closed-loop life-support systems that maximize resource efficiency and long-term stability (Nguyen et al., 2023). Continued advances in controlled agriculture, automation, biological engineering, and resource recycling will be critical for enabling continuous human habitation beyond Earth. At the same time, many of these innovations have the potential to improve controlled-environment agriculture, circular resource management, and sustainable food production on Earth.

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