



From production to food systems: A systems-level review of drivers, requirements, and integration for Lunar and Martian food systems

Tor Blomqvist^{a,b,c,*} , Ralph Fritsche^{d,1} 

^a Department of System Analysis Space Segment, Institute of Space Systems, German Aerospace Center (DLR), Robert-Hooke-Straße 7, 28359, Bremen, Germany

^b Division of Glycoscience, Department of Chemistry, School of Engineering Sciences in Chemistry, Biotechnology and Health, KTH Royal Institute of Technology, AlbaNova University Centre, SE-106 91, Stockholm, Sweden

^c KTH FOOD, KTH Royal Institute of Technology, Brinellvägen 8, 114 28, Stockholm, Sweden

^d Deep Space Food Consortium, Methuselah Foundation, 8021 Flint Street, Springfield, VA, 22153, USA

ARTICLE INFO

Keywords:

Space food system
System integration
Ground test demonstrator
Closed-loop food production
Food system requirements

ABSTRACT

Long-duration missions to the Moon and Mars, which involve a constant human presence on the surface require food systems that extend beyond current strategies based on pre-packaged provisions. These missions demand sustainable, robust, and autonomous food production systems that integrate production, processing, storage, consumption, and resource recovery within tightly constrained and closed-loop environments. This paper adopts a systems perspective to address the development of such food systems, identifying key drivers, including nutritional, psychological, environmental, economic, and regulatory factors, and proposes evaluation metrics and requirements to guide design and integration. Recognizing food systems as socio-ecological constructs, the paper emphasizes the importance of interactions across multiple food system elements (e.g., production, waste management, preparation, socio-cultural factors) and temporal, spatial and governance scales. The study outlines critical attributes such as adaptability, resilience, and self-organization, then highlights the need for system-level validation through iterative ground testing. By grounding space food system development in a systems-level approach, this paper aims to start the discussion to create a strategic foundation for achieving operational food security on future deep space missions.

Glossary of key terms

- **System:** Encompasses the complex networks of all inputs and outputs involved in producing, distributing, and consuming food. This includes not only production processes and technologies but also the social, economic, and temporal dimensions that shape how food is produced, handled, stored, prepared, and ultimately consumed. These networks integrate technological, biological, and human components across multiple scales, linked by nonlinear feedback loops to manage resources, support crew well-being, and maintain overall system reliability.
- **Elements:** A distinct functional block within a larger food system, encompassing a specific capability such as production, post-harvest management, waste management, or socio-cultural factors (consumption). While elements can operate semi-independently, they are interconnected through resource flows and feedback loops, influencing the system's overall performance and robustness.
- **Subsystem:** A distinct module, component, or specialized function within the larger system (e.g., hydroponic growth unit, microbial cultivation unit, waste-processing unit). Subsystems can have nested structures, e.g., as the nutrient delivery system is a subsystem of the plant production system.
- **Levels:** Hierarchical layers of organization within the food production system, ranging from individual components or subsystems to the entire habitat. Each level has its own emergent properties and interacts with others through feedback loops and resource flows.
- **Agency:** The capacity of individuals or groups to make choices and influence outcomes related to their food, granting a degree of control, autonomy, and self-determination in production, preparation, and consumption.

* Corresponding author. Department of System Analysis Space Segment, Institute of Space Systems, German Aerospace Center (DLR), Robert-Hooke-Straße 7, 28359, Bremen, Germany.

E-mail address: tor.blomqvist@dlr.de (T. Blomqvist).

¹ Ralph Fritsche is a retired NASA Exploration Food Systems Project Manager and current Subject Matter Expert supporting NASA's Deep Space Food Challenge.

<https://doi.org/10.1016/j.actaastro.2026.02.021>

Received 18 December 2025; Received in revised form 5 February 2026; Accepted 11 February 2026

Available online 12 February 2026

0094-5765/© 2026 The Authors. Published by Elsevier Ltd on behalf of IAA. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

- **Governance:** The structures, institutions, and decision-making processes, ranging from mission-level management to international coordination, that shape how food systems are organized, regulated, and operated.
- **Sustainability:** In the context of this paper, sustainability refers to the long-term viability of the technological, economic, and social bases of the food system. It emphasizes the continuous functioning and health of the relationships between the system's subsystems, ensuring operational continuity across varying mission phases.

1. Introduction

1.1.

Exploration missions beyond Low Earth Orbit (LEO) pose unique challenges, especially in providing a sustainable food system for extended-duration missions. While the current ISS food system is established and reliable, it cannot ensure shelf stability for longer-duration exploration missions to Mars, which would require maintaining food quality and stability for a minimum of 3 years, potentially up to five years in some mission scenarios [1,2]. Moreover, Crew Specific Menu (CSM) foods (e.g., fresh fruit, preference foods, cheese, and other individual requirements) have become increasingly important for crew morale, despite an increased variety of the standard menu [3]. Food and mealtime activities play a vital role in psychological wellness with increases in mission duration, isolation, and confinement [4]. If the food lacks either variety or organoleptic appeal, it will have a negative impact on crew caloric intake, mood and morale, meaning that, regardless of nutritional content, the food will provide no benefit if not consumed [5–8]. However, providing palatable variety and freshness for missions beyond LEO—particularly Mars missions with food potentially pre-positioned years in advance—presents major challenges.

Producing food in space could help address key aspects of these challenges: first, by complementing existing provisions through increased micronutrient intake and variety; then, as mission durations lengthen and distances from Earth increase, by gradually replacing supplied provisions step by step, ultimately leading to self-sufficient, bioregenerative food production systems.

Off-planet food production systems can easily escalate into a wide variety of technologies and possibilities, with or without a frame of reference for their application during a relevant mission scenario [9]. Moreover, technology development initiatives often focus on a single narrow subset of incremental advancements, most commonly food production technologies, while overlooking other critical elements such as post-harvest management, side stream and waste management, preparation, and the socio-cultural importance of food. Each food system element has its own emergent properties, and different levels and subsystems with varying degrees of redundancy and complexity that interact in a network of feedback loops (e.g., resource use, reclamation, waste-to-resource recycling, and psychological impacts on crew morale) [10]. For instance, a production technology may be useless without the proper post-harvest management capabilities, if crew workload makes the system impractical to operate, or if the output is not palatable. Consequently, regardless of output, no single component can be evaluated in isolation without considering its dependencies on other elements and scales within the overarching system.

To avoid scattered or overly speculative thinking, a systems perspective is crucial. In particular, one that recognizes the food-system complexity and accounts for the multiple elements, scales, feedback loops, and nonlinear interactions that shape food production and consumption within a decentralized setting. In such systems, no single process operates in isolation; rather, production, waste management, and crew behavior continuously influence one another, creating emergent patterns that determine overall system performance. But to effectively address any component of the space food production system for both near-term and long-term, a few areas must be defined first.

- **Food system drivers:** While producing food on the Lunar or Martian surface is an intriguing challenge, the drivers behind that technological development are more complex than simply addressing the nutritional, logistical, and environmental challenges of deep space. Identifying these additional drivers will help guide research and development towards a more strategic approach and comprehension of the dynamics of the food system.
- **Long-term objective:** The long-term objectives for a potential Lunar or Martian food production system and what a bioregenerative food production system would entail, need to be better defined. Understanding the magnitude of this goal will require an overview of the system's structure, the relationship between its components, elements, drivers, and the rationale behind its development. A systems perspective will allow us to understand how a food system can be designed and operated across multiple scales. Food production technologies will likely be different for early exploration missions versus more established settlements, the long-term objective should guide today's designs and provide a path for evolution rather than obsolescence [11].
- **Evaluation metrics:** Developing components for the space food production system will require new readiness levels and evaluation metrics to incorporate system-level requirements and constraints. This means that even though individual technologies or components must be validated and assessed for their specific functions and reliability, they also need to be assessed in an integrated system context. Research and development will have to move beyond a narrow disciplinary focus to consider the entire bioregenerative food production chain, from primary production to final consumption. Doing so will highlight critical parameters and illustrate the interplay between subsystems, as it becomes essential for future system integration.
- **System-level requirements and constraints:** As a food system has a primary function, it needs to fulfill systems-level requirements and be vetted in relation to food security dimensions: availability, access, utilization, agency, sustainability, and stability – further described in the System-Level Requirements and Constraints section below. Similarly, each technology or component in the food system needs to adhere to certain requirements. Building on existing criteria from Douglas et al. (2020) [1], these requirements are expanded to define additional considerations pertinent to the space food production system.

These insights will guide iterative improvements and help refine system integration strategies. By grounding research efforts in practical testing rather than speculative designs, future flight-ready solutions will be more robust and operationally sound. Moreover, these lessons can feed back into new ground-based test demonstrators, moving from simple plant modules to fully integrated systems encompassing production, processing, waste management, and resource recovery.

2. Methodology

This paper uses a framework-based narrative review and conceptual synthesis to translate terrestrial food systems and complex-system theory concepts into a deep space context and to derive (i) system drivers and (ii) an evaluative matrix of key factors for deep space food systems.

Sources were identified through targeted, non-systematic searches and backward/forward citation chaining, prioritizing publications relevant to (i) spaceflight food-system constraints and (ii) terrestrial food-systems and complex-systems theory concepts used for translation and synthesis.

The system boundary is defined as the end-to-end food system required to deliver crew nutrition and food-related wellbeing under exploration constraints. The boundary spans primary production, post-harvest handling and storage, processing/preparation, consumption, and waste/resource recovery, analyzed as a socio-ecological system

embedded in the broader mission architecture. Complex-system concepts (scales, levels, feedback, nonlinearity, emergence, robustness/resilience, path dependence) are used as an organizing lens to describe interactions and motivate integration-oriented requirements.

System drivers were derived using an abductive synthesis integrating (a) established terrestrial food system driver classes, and (b) deep-space mission constraints and human performance considerations. Candidate drivers were retained when they (i) recurred across independent sources and/or (ii) plausibly influenced feasibility, risk, or performance across multiple food system elements.

The requirements and constraints in Section 5.1 were constructed via a literature synthesis that adapts existing frameworks, specifically FAO/HLPE dimensions of food security and NASA's existing food system criteria (Douglas et al., 2020), which were expanded through practice-based elicitation and technical discussions to account for system-level dependencies.

3. Food system drivers

Drivers are major factors, or forces that shape how the food system

operates, evolves, and responds to change. Drivers may be influenced and shaped across temporal, spatial, and governance scales, all of which affect every element of the food system [12]. Improving the comprehension of the dynamics of the food system and its development will depend on the understanding and identification of its main drivers [13].

Although space food production systems present their own unique design challenges, the drivers that shape these systems (Fig. 1) are not unlike those on Earth, just recontextualized under vastly different conditions and constraints.

Food is an essential line of defense for crew health and performance, with adequate nutrition providing a key countermeasure against the physiological and physical challenges astronauts face as a result of increased exposure to radiation and reduced gravity [1]. With pharmacokinetic (how the body processes a drug) and pharmacodynamic (how a drug affects the body) properties of medications being altered in space, along with reduced drug stability and immune response alterations, it is difficult to assess the clinical impact of pharmacotherapy [14,15]. Conversely, the environmental conditions in space affect metabolic processes within the body and its ability to utilize nutrients, highlighting the need for a better understanding of nutritional

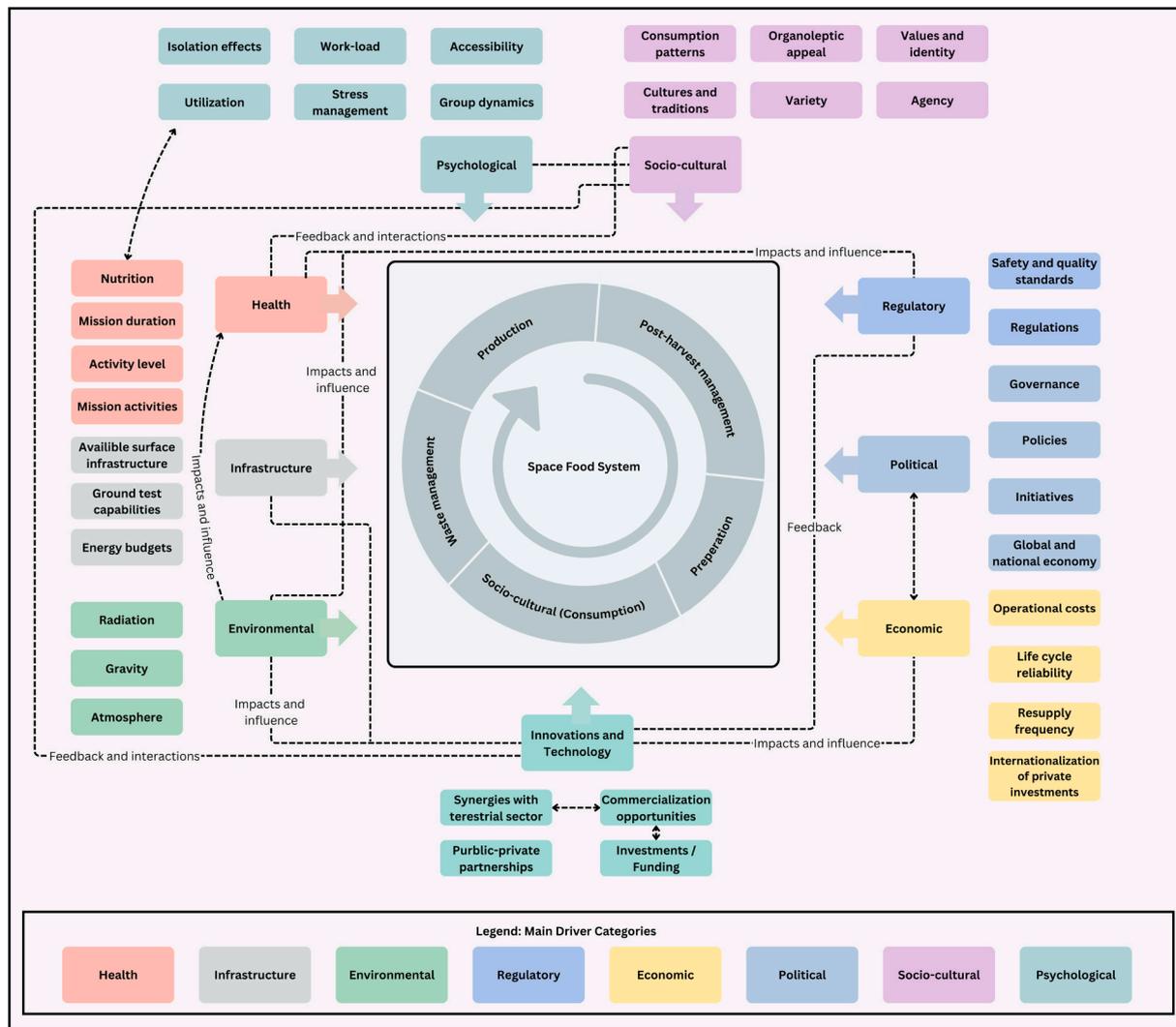


Fig. 1. The main drivers influencing the development of a space food production system and their interconnections. Drivers include nutritional and health needs, psychological and socio-cultural well-being, environmental and resource constraints, technological innovation, regulatory frameworks, and economic considerations. These drivers interact across temporal, spatial, and governance scales, shaping system design and integration pathways. Understanding their interactions highlights that the success of a Lunar or Martian food system cannot be explained by a single factor alone, but emerges from the interplay of multiple, often competing, forces within a system. The central ring represents core food-system functions, and the circular depiction is used to emphasize interdependence and feedback; it does not imply a fully closed-loop system. Material and non-material flows may cross the system boundary depending on the mission phase and architecture.

physiology [16–18]. This emphasizes the importance of a functioning food system based on foods that can supply sustained nutritional adequacy, which is the foundational driver.

Heavy emphasis is typically placed on resource constraints and technological innovation. While those aspects are indeed critical, concentrating solely on resource and technology drivers risks that overlook a host of critical forces that can determine the success or failure of a space food system. For instance, social, psychological, and demographic drivers, including crew size, cultural food preferences, taste preferences, and work-load limitations plays a large role in ensuring the psychological well-being of astronauts [5–8]. One of the primary reasons why space food has developed from toothpaste-like tubes to more palatable items is the emphasis on organoleptic appeal and variety to ensure personal and emotional well-being [19,20]. This means that regardless of a subsystem's output, nutritional quality, or reliability, if it is not palatable, it will not be consumed and therefore cannot fulfill its intended function.

Moreover, environmental drivers, such as radiation and variations in gravity, will influence the feasibility and implementation of certain technologies as well as encourage the development of novel technological approaches to solve problems that become relevant to specific environmental conditions across a spectrum of destinations. For instance, reduced gravity affects heat and mass transfer, fluid behavior, and physicochemical properties of food, which necessitates the development of processing methods and equipment that have been adapted to the space environment [21–26]. Additionally, elevated radiation levels can increase the pathogenicity of certain bacteria as well as improve microbial tolerance to intrinsic and extrinsic stressors. Such environmental drivers are known to impact food shelf-life stability and processing mechanisms, ultimately influencing safety and quality standards [27–29].

Regulatory drivers, including food safety and quality standards, have yet to be developed for a space-based integrated bioregenerative food production system. Such standards need to be tested first within integrated ground demonstrators, then in LEO, and finally on planetary surfaces, to be fully understood and refined. Meanwhile, economic drivers such as maintenance and operational costs heavily affect mission planning and overall system integration. Over time, however, these costs may shift as technology advances and resupply missions become less expensive and more reliable. This means that mass and resupply restrictions may have varied significance depending on spatial and temporal scales.

One of the major drivers of technological development lies within the sustainability challenges on Earth, and the ability to spin off technology into useful commercial products. This guides funding opportunities and research priorities, which directly affect the pace of development of space food systems. While space travel has specific requirements, it can act as an innovative platform to accelerate incremental research and innovation for the terrestrial sector.

By recognizing these overarching drivers and their interconnections, challenges and opportunities involved in a space food production system can be better anticipated. However, since such a system does not exist, the system drivers have yet to be identified and understood in how they interact across scales and contexts. To do so, a systems perspective becomes essential so that these drivers are considered in tandem rather than in isolation.

4. The systems perspective

In order to describe a food system, the food system perspective needs to be clarified to address complex relationships, deal with competing priorities, or improve the outcomes and sustainability of the system as a whole. The word system appears in many contexts and can be anything from a small set of components to a whole global value chain. It is therefore important to consider scales, elements, and levels when dealing with complex systems, as space food production systems will be

designed and operate across multiple scales, elements, and levels within them [11].

4.1. Scales

The word scale broadly refers to the level of organization in time, space, and governance. Understanding the levels within each scale and how they overlap and interact is essential when setting a strategic objective for any space food production system. Similarly, recognizing how temporal, spatial, and governance scales intersect and influence each other may help balance immediate operational needs with long-term sustainability, individual well-being with habitat-wide resource allocation, and national-level regulations with global research and development trends.

- **Temporal:** Food systems must function reliably and evolve over short-term missions and extended or indefinite stays. This includes everything from immediate resource needs and ensuring stable conditions over days or weeks, to managing propagation materials, resources, recycling processes, and growth cycles over months. Additionally, there are temporal trends, such as shifts in crew composition, crew dynamics, and the pricing of resupply missions, as well as decadal changes tied to technology development and adoption. These longer timeframes influence research priorities and phased scale-up strategies for the space food system.
- **Spatial:** At the individual level, consumption patterns and workload directly affect how resources, knowledge, and labor are organized at the base or settlement level. This, in turn, impacts how elements of the food system are configured and how different elements and subsystems interact. Requirements from the individual scale can also feed back to the international scale, which governs regulations, standards, and broader policy decisions that span multiple temporal scales. Finally, research and development for space food production is affected by the global scale, where international priorities, collaboration, and funding opportunities can accelerate or constrain progress, especially as Earth-bound needs drive technology innovation.
- **Governance:** National space agencies set priorities and requirements for mission planners, determining protocols and objectives for exploration, research, and operations. These decisions may be coordinated internationally and across public–private partnerships, involving agreements on resource sharing and data sharing that shape overall food production strategies. In this context, local, national, and global governance bodies can influence everything from technology standards to funding mechanisms, thereby guiding how food systems develop and operate in space.

4.2. Elements

An autonomous food production system in space would consist of five primary elements visualized in Fig. 2, production technologies, post-harvest management (storage and processing), waste management, preparation, and the socio-cultural element (consumption). Yet these elements can also be viewed as scales along the spatial dimension, depending on the granularity or scope of analysis. For example, when studying “production technologies,” you might zoom in on a single plant production module (micro-scale) or zoom out to the entire habitat or settlement (meso-scale) and even further to the Earth–Moon system (macro-scale). A food system consists of multiple elements and multi-layered nested systems within these elements. This nested structure allows each element to be analyzed on multiple levels: one can examine an individual subsystem (e.g., a LED light) or the entire habitat's integrated life support system. Recognizing that these elements function across different spatial scales, can more effectively account for how each level and element interacts with others to form the overall food production system.

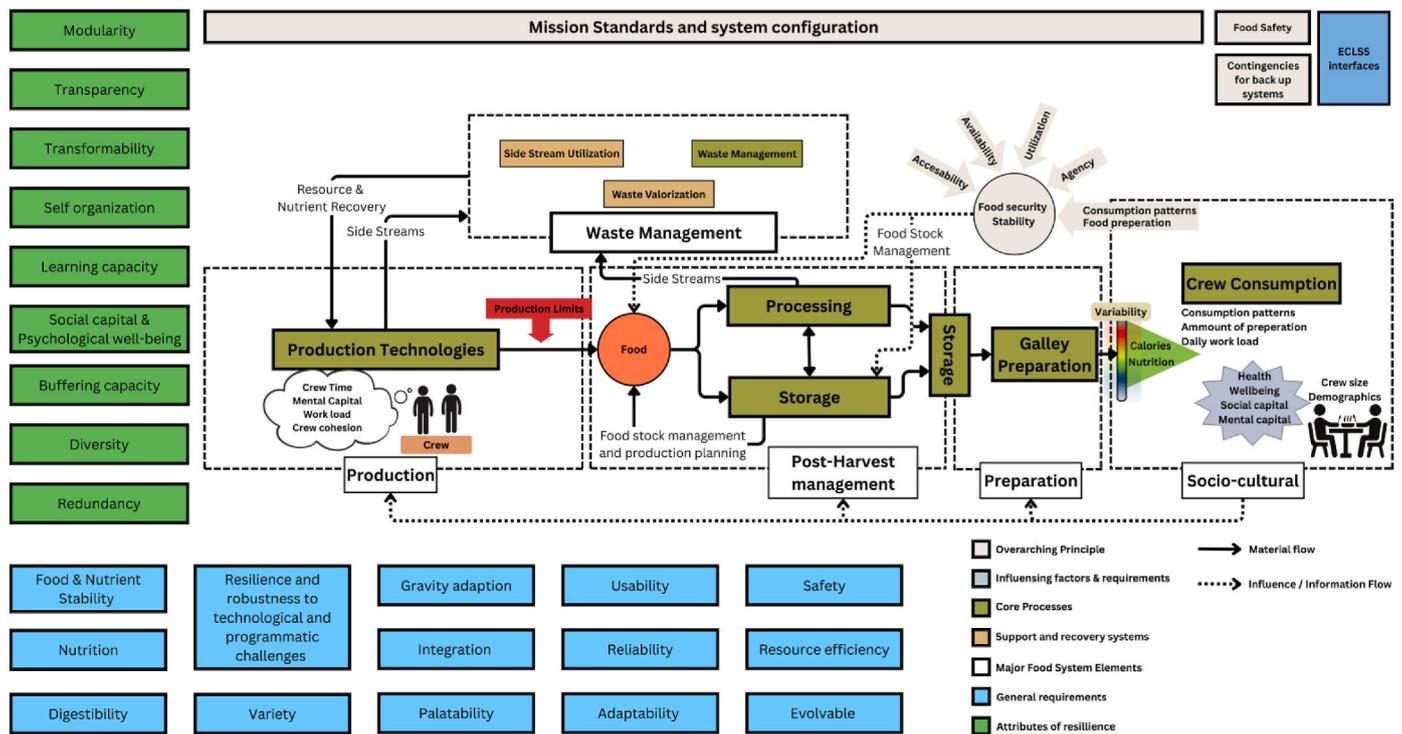


Fig. 2. An overview of the various elements of the space food production system and its most general pathways and feedback loops between elements. The requirements (blue) for space food system components are further explained in section 3. The resilience attributes (green) are attributes of the system that enhance the system's ability to adapt under evolving conditions. Over time, as infrastructure and crew sizes expand, each of these elements will become more evolved as the need for technologies and processes within these elements will emerge. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Each level has its own emergent properties, and different levels are often coupled through feedback mechanisms [10]. Similarly, interactions across elements and across scale are important for both system design and resilience. A production technology or product may, for instance, lose its value without having the proper storage or processing capabilities. This means that regardless of output, the technology or product cannot be evaluated as an individual element without taking cross-element dependencies into account. Cross-scale and element interactions also affect production planning. A shift in the power budget may limit the crop production subsystems and the ability to grow more nutrient-dense crops. Growing feedstock with less input requirements, for e.g., insects, or mushrooms, may instead mitigate the change in oxygen production and CO₂ sequestration, while converting inedible biomass into edible biomass. This type of redundancy allows for graceful degradation, ensuring that localized issues do not disrupt broader mission objectives [30]. However, efforts are often focused solely on production technologies, while neglecting other elements of the system. Yet food systems are intrinsically complex. Adapting a system approach that accounts for the whole system, and its internal interactions between components, elements, and scales is therefore critical, particularly in the context of space exploration, as systems must operate within closed loops where every resource is finite and interconnected. These constraints amplify the need for an integrated design.

4.3. The socio-ecological system

Food systems are socio-ecological systems, formed and intertwined by cultural, economic, political, social, technical, and biophysical factors linked through feedback loops [31,32]. While these systems are significantly more complex on Earth due to the multitude of interacting factors, their principles can still be translated to a space context, which is a smaller and more contained system. Even more so, smaller systems are particularly sensitive where direct feedback loops can exert

disproportionately large impacts on the overall system dynamics. These feedback mechanisms illustrate the dynamic nature of food systems, where changes in one component can ripple across others. This type of non-linearity in a system means that cause and effect are not always proportional or straightforward [32]. For instance, advances in production technology can improve yields but might introduce unintended consequences. A technology producing nutrient-dense food may, at the same time, offer a product of limited sensory appeal, which could lower crew morale and dietary satisfaction. If food lacks organoleptic appeal, variety, or is difficult to prepare, consumption may be reduced, which has consequences on the crew's caloric intake, mood, and morale [5–8]. By virtue of that, the nutritional content of the food has no significance if the food is not consumed. These factors, in turn, affect the sense of agency and food security, highlighting the necessity of integrating technical efficiency with cultural and psychological needs. Similarly, the choice of crops impacts both ecological systems and crew morale. Growing culturally significant foods may enhance psychological well-being but require greater resources than other crops of less cultural significance. Balancing these factors creates a feedback loop between production efficiency and social satisfaction. Moreover, automation may reduce workload but can diminish crew engagement with the food system. Incorporating, for instance, plant caring activities into mission routines can close this feedback loop, fostering a sense of agency and psychological resilience [33]. Agency becomes increasingly important as crew members operate within meticulously planned and tightly constrained schedules, such as on the ISS, where activities are organized in 5-min increments [34]. Such structured environments can inadvertently reduce perceived autonomy, as crew members may feel they are merely executing predefined routines rather than exercising agency. Similar to crop choice, allowing participation in food selection or preparation can therefore serve as a vital psychological countermeasure, restoring a sense of agency and personal involvement [3,35,36]. However, increased crew autonomy in these activities also introduces

operational trade-offs, as it competes directly with the limited crew time allocated to other mission-critical tasks. In addition, greater crew involvement can increase process variability and food safety risks (e.g., contamination pathways, inconsistent preparation, and higher waste generation), which in turn can impose additional monitoring, training, and sanitation burdens.

The interplay between human factors and operational constraints makes predicting outcomes difficult, as inputs and outputs do not always scale in a straightforward manner, making it difficult to model with high predictive confidence or anticipate the outcomes of specific actions [37]. Nevertheless, analogous quantitative scenario modeling approaches are widely used in terrestrial food-systems foresight to explore alternative assumptions and trajectories and to compare option spaces under uncertainty [38]. However, non-linear dynamics demand robust feedback loops and adaptive management to prevent small perturbations from spiraling into system-wide disruptions. This inherent uncertainty arises due to either gaps in knowledge or limitations in data, randomness or variability in system behavior, or the influence of external factors that are difficult to predict and control, or unpredictable human or organizational behavior [39].

4.4. Robustness and resilience

Complex systems tend to self-organize into emergent patterns or structures that arise from local interactions between components without direct top-down orchestration at every step. Instead, feedback loops and adaptive responses to critical points of instability will guide the system toward new equilibria or operational modes. In the context of food systems, this can be defined as the spontaneous emergence of new structures and solutions, driven by collective action and shared resources to build resilience against crises. On Earth, this manifests in community-based initiatives like food-sharing networks or adaptable distribution models that respond quickly to local needs without waiting for central directives [40]. Translated to a space food system, this principle implies that the crew must have the autonomy to adapt their strategies. Instead of relying solely on rigid schedules from mission control, the system should allow for adaptable resource usage and social routines. Paradoxically, fostering self-organization requires thoughtful system design and governance strategies that allow autonomous local adjustments without creating uncontrollable chain reactions. By designing modular technologies, subsystems, and transparent feedback networks, small-scale innovations can surface and spread. For instance, modularity facilitates resilience across multiple scales by enabling the crew to physically reconfigure standardized hardware components to bypass local malfunctions while simultaneously allowing for strategic redistribution of input toward alternative low-energy production lines in the event of a broader system failure. This capacity for both crew and systems to adapt dynamically will improve the system's ability to manage disruptions without risking overall mission stability, meaning that self-organization capacity is an important attribute of system resilience.

Engineering for resilience is difficult because it requires addressing unforeseen disturbances that lie beyond the defined uncertainty range typically covered by the fail-safe requirements of robustness. Resilience would emphasize safe-fail systems across scales and levels that would have the capacity to provide sufficient and appropriate food in the face of various unforeseen disturbances, and the ability to adapt to any unforeseen changes [30]. To some extent, using multiple redundant systems would allow for adaptation to changing conditions by either increasing or diversifying subsystems within elements to ensure against total system collapse or incorporating redundancy within subsystems and elements. However, since the same functionality would be sustained, there would be no real adaptation to change [41]. Attributes such as redundancy and diversity, along with modularity, buffering capacity, social capital, psychological well-being, transformability, transparency, self-organization, exposure to disturbances and learning

capacity are all attributes of resilience that enhance a system's ability to adapt and thrive under evolving conditions [42–45]. Crucially, resilience in a food system extends beyond technical components. Since food systems are socio-ecological constructs rather than engineered mechanisms, resilience thinking serves as a paradigm rather than a prescriptive, testable body of theory or a definitive list of requirements [46–48]. Moreover, in this context, resilience is not a fixed state but an ongoing process of evolution and adaptation. For instance, transparency in system design and data collection can enable quicker detection and resolution of vulnerabilities. Similarly, exposure to manageable disturbances, such as simulated failures during testing, can build a system's capacity for adaptation. Learning from these experiences, both technically and socially, enhances the system's ability to anticipate and respond to future challenges.

This will happen over time, both in concept operations in ground test demonstrators, in system integration facilities, and on the planetary surfaces. The latter will not have a full bioregenerative food production system in any near-term exploration missions, but will most likely occur in implementation phases, to allow for both research, development, and integration. This will allow components of the food system to be systematically evaluated and integrated depending on need and prior earth-based testing.

5. System design & integration

Developing components for the Lunar or Martian food production system requires revisiting evaluation metrics such as NASA's Technology Readiness Level (TRL) to incorporate system-level requirements and constraints. These metrics must be adapted to account for the unique complexities of space food systems, including their multi-element, multi-scale, nested structures and emergent properties. While components or individual subsystems can be viewed as discrete elements with their own properties, simply summing their individual performances is insufficient. Instead, their arrangement and interaction across different elements and scales give rise to emergent properties and patterns of organization that enable the system to function as a cohesive, coherent whole.

This means that even though individual technologies and components must be validated and assessed for their specific functions and reliability, or TRL, they also need to be assessed in an integrated system context. This approach ensures that multi-level and cross-element dependencies and interactions are fully understood and managed. For instance, a crop production system must not only operate efficiently at a production module level but also integrate seamlessly with other food production technologies, post-harvest management, habitat-wide life support systems, and other mission-level architectures.

Before physical integration occurs, virtual modeling and simulation through digital twins or other system emulators can be a first step in testing interactions, identifying bottlenecks, and refining design parameters. These tools enable the exploration of complex dependencies, perform sensitivity analyses, and simulate mission-scale dynamics under varying environmental and operational conditions. This virtual phase minimizes risks, informs component design, and supports decision-making before costly ground or flight implementation [49–56]. Similarly, analogous digital-twin approaches are widely applied in terrestrial agri-food processing and supply chains [57,58]. Following virtual analysis, ground test demonstrators or other physical integration platforms configured to emulate reference mission scenarios could provide validation for these technology selections in an operational context. Such facilities would interlink all major functions, enabling simultaneous interplay of technologies, subsystems, and elements across scales, including production systems, post-harvest systems, preparation capabilities, waste management, resource recovery, and architectural subsystems. This integrated approach would prevent siloed research activities and promote an inter/multidisciplinary and cohesive vision for future exploration architectures.

This will also allow for the quantification of inputs, outputs, and the transformation of materials and resources throughout the system to ensure that the food production system functions effectively. These material flow analyses provide key insights into the efficiency, effectiveness, and sustainability of the system and its components. By capturing data on resource utilization and material flows, the system's production costs and life cycle can be assessed, identifying the most cost-effective methods, whether through resupply schemes from Earth or in-situ production. Such analyses also support trade-off evaluations, systematically prioritizing components and methods based on their relative performance across multiple criteria. This perspective ensures that the system architecture is optimized for various mission scenarios, balancing localized efficiencies with broader mission-level goals.

However, achieving realistic feasibility assessments requires moving beyond technical considerations to include the human factor. The integration of components must account for how technologies and the whole system interface with crew operations, addressing usability, workload, and psychological well-being. For instance, the workload may not match the acceptability of the produced output, rendering certain labor-intensive technologies inferior.

These feedback loops also foster self-organization, which is enhanced through active participation by the crew, their decision-making, and adaptability. For instance, astronauts interacting with the food system, adjusting strategies, experimenting with food preparation techniques, or optimizing resource usage, introduce variability and feedback that help guide the system toward more efficient and sustainable configurations. This capacity for local adjustments allows both the crew and the system to adapt and learn more dynamically. Since this self-organization is inherently path-dependent and difficult to predict, as the system's evolution is shaped by both past configurations and present dynamics, it may be an important evaluation metric to ensure that the food production system not only meets technical objectives but also supports the holistic needs of the crew across all scales and elements of the mission architecture.

5.1. System-level requirements and constraints

5.1.1. Food security dimensions

A food system's primary purpose is to deliver food security, which is achieved when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life [59]. This definition shows the four dimensions of food security: availability, access, utilization, and stability, outlined in Table 1. The High-Level Panel of Experts (HLPE) of the Committee on World Food Security (CFS) proposed that sustainability and agency should be incorporated into the definition, and will be incorporated in this paper as two critical dimensions to food security [60–62]. To achieve food security, all of these dimensions need to be fulfilled simultaneously.

5.1.2. Technical and operational requirements for system components

The primary requirement of a food system is to ensure a safe, secure, sufficient, and sustainable food supply, as any system failure could have detrimental consequences, including the risk of food scarcity. This is especially critical for any space food system configuration when attempting to reduce dependency on Earth. To ensure that the aforementioned system-level requirements are met and that a system component may be successfully integrated, each component of the food system needs to fulfill certain criteria. Some of these criteria have already been defined by Douglas et al. [1]. Building upon these established criteria, the following sections will integrate and expand them to address additional considerations pertinent to any space food production system.

- **Safety** is crucial since foodborne illness in the spaceflight environment may not just jeopardize mission success but may pose an even

Table 1

The six dimensions of food security [59,61,62].

Dimension	Definition
Availability	The availability addresses the quantity of food of appropriate quality available. This can be from either the food produced locally, or supplied from Earth.
Access	The availability doesn't ensure access on an individual level. Even though food is supplied or produced, it needs to be nutritionally and culturally significant to the individual. Access may also involve the logistical capacity, ensuring that the astronauts can obtain and consume the food that is present.
Utilization	Utilization is the ability of an individual to reach the state of nutritional well-being, where all physiological needs are met. This also involves clean water, sanitation, food safety, food preparation and diversity of the food [59]. This dimension is combined with the biological utilization of the nutrients; if the previous dimensions are fulfilled, nutritional physiology is important to consider, and the body's ability to utilize the nutrients that are consumed, including digestion, absorption and bioavailability, which may be altered in spaceflight, determines the nutritional status of individuals [18].
Agency	Agency refers to the capacity of individuals and groups to exercise voice, and make decisions about their food, which grants a degree of control over their own circumstances. This increases the individual's autonomy and self-determination, to ensure that they have access to foods that are culturally acceptable, uphold human dignity, and reduce their fear of going hungry [60,63].
Sustainability	Sustainability in this context refers to the viability of the technological and social bases of food systems. It emphasizes the connections between the space food system, its long-term health, viability and the functioning of the relationships between the subsections of the food system [60].
Stability	The stability of all other dimensions over time, which emphasizes robustness, resilience and reliability. Stability is critical to ensuring the reliability of food supplies amidst potential disruptions. Space is fraught with risks, such as equipment failures or environmental anomalies. Redundant systems, storage buffers, and contingency protocols are essential to maintaining uninterrupted food availability.

greater threat to crew health since medical supplies are limited and may not function optimally [15,17,64]. Furthermore, the conditions of reduced gravity can exacerbate both the spread and pathogenicity of microorganisms [65,66]. The food must be free from microbiological, physical, or chemical risks for astronauts. Also, any operational procedure must ensure a simple enough process for a tired crew member to avoid them. Moreover, as space missions transition from relying on pre-packed food to developing and producing food directly in space, new regulatory challenges emerge. Current safety and handling regulations for equipment and systems in space are robust and well established, addressing a broad spectrum of concerns related to space operations. However, these regulations have yet to fully adapt to the requirements of in situ food production. Updating and refining regulatory frameworks becomes essential in this transition, as lunar habitats and space crafts will need standard operating procedures for the hygienic food handling, processing, storage, and traceability, as well as updating hardware requirements and finding gaps necessary to implement certain food production or post-harvest technologies. In addition to the aforementioned challenges, one significant barrier to food safety in production systems is the inability to monitor microbes and other critical control points in a timely, reliable, and operationally feasible manner. On the ISS, microbial safety is verified almost exclusively through sample return: frozen leaves or water samples are shipped back to Earth for culture or sequencing, often weeks or months after consumption [67,68]. For missions beyond LEO, such a model becomes unworkable; without real-time detection, crews may consume foods whose safety profiles remain unknown until long after ingestion. This monitoring gap transforms even modest microbial risks into mission-threatening uncertainties. Similarly, current sanitation practices for fresh produce are limited to the use of citric acid-based sanitizing wipes (e.g., ProSan®), while traditional cleaning methods generate large

volumes of greywater containing harsh detergents that are incompatible with spacecraft water recycling systems [3]. Consequently, food system components must be designed with sanitation and monitoring in mind, favoring materials, geometries, and system layouts that minimize microbial harborage and simplify cleaning processes while dedicated in situ detection and sanitation methods continue to mature.

- **Food & Nutrient Stability** is a major challenge for pre-packed food supply for Mars since the food requires stability for at least 5 years [1]. However, stability is an equally important topic for production systems, since producing food will have no meaning if its shelf life only last for a few days. This means that the reliability of any production component of the food production system cannot be properly assessed until proper storage infrastructure is in place.
- **Nutrition** – As with other exploration journeys throughout history, adequate crew nutrition can make the difference between mission success and failure. With increased mission durations, in particular those beyond LEO, nutrition must not only meet the requirements for health and energy, but also serve as an enabling factor in the physiological adaptation to the spaceflight environment [69,70]. Understanding the mechanisms by which the space environment affects human physiology and the extent to which nutrition can serve as a countermeasure to these effects [71,72] is necessary to maintain astronaut health and to properly evaluate the nutritional efficacy of certain foods. Another variable that must be considered is portion size: even though some crops, such as arugula, are highly nutritious and nutrient-dense, their low edible mass per serving limits their overall contribution to daily nutrient intake. Thus, a food's nutritional value must be assessed not only by its composition but also by the practical quantity likely to be consumed within a balanced diet.
- **Digestibility** – Beyond nutritional composition, the digestibility of foods determines the extent to which nutrients can actually be absorbed and utilized by the body. In the context of space missions, factors such as microgravity, altered gut physiology, and limited food processing options can significantly influence digestion and nutrient bioavailability, making digestibility a critical complement to overall nutritional adequacy [73,74]. Food produced should ensure nutritional adequacy. In fact, nutritional physiology becomes increasingly important when introducing novel foods into the system [75,76]. Subsequently, the focus should, in certain cases, shift from nutrient quantity to nutrient quality, ensuring the bioavailability of the nutrients.
- **Variety** – Menu fatigue is a significant concern, and regardless of a single food's palatability or nutrient quality become an issue [1]. Aside from the psychological aspect, variety also increases the chances of a nutritionally adequate diet [77].
- **Palatability** – Regardless of how many nutrients food contains, it must be eaten to fulfill its purpose. In fact, taste and texture work as a nutrient-sensing system that determines the duration of oral exposure, and smell triggers a priming process that induces appetite, and subsequently the metabolic system, which makes flavor one of the most important determinants of quality [78]. Whereas palatability may become a secondary attribute on shorter missions, on longer missions, food becomes more than just a functional source of nutrients. Aside from the immediate sensorial qualities, food also needs to fulfill emotional, social, and cultural aspects, which all relate back to the basic human psychological and biological needs [79,80]. This may potentially be amplified in space since astronauts will have to deal with a variety of psychological challenges that can cause high levels of stress, consequently having an impact on their physiology. Living in confined spaces with limited habitation volume, as well as the absence of access to fresh air, are all aspects that negatively affect psychological health. These factors may also reduce sensory stimulation due to strictly regulated work schedules, as well as delayed communication with loved ones during long-duration missions, which may reflect upon the psychological well-being of the crew

[81]. This may, in turn, affect the physiological well-being of the crew since there are synergic effects between psychological and physiological health; if one is deficient, the other suffers. These effects may magnify in space, which amplifies the need to accommodate the fundamental human needs [80]. Therefore, food technologies and systems need to produce food that stimulates the organoleptic senses. This is crucial for maintaining psychological well-being and ensuring that the food will be consumed to fulfill its nutritional purpose.

- **Reliability** is a valid concern since system failure, equipment malfunction, or crop failure can have catastrophic effects. As stated previously, any new technology or system component may have undiscovered problems or unknown failure rates. Before being applied, all food production and management technologies should first be individually tested for reliability, determine failure rates, and fix potential design flaws. The same phases should then be evaluated and tested over time under nominal conditions in ground test system analogues, assessing their merits and potential integration into exploration architectures. In addition to system integration, all systems should also be designed and tested for the space flight environment [1].
- **Gravity adaptation:** Physics in microgravity differs from terrestrial gravity in some main respects: Hydrostatic pressure, buoyancy, potential energy, natural convection, and sedimentation all rely on gravity to exist. Food production systems will need to be adjusted to accommodate these changes since this will alter key factors (e.g., physicochemical properties, fluid dynamics, foam stability, rheology, and colloidal behavior) [82–86]. This may have implications for food processing, preparation, storage, food safety, and stability, requiring careful consideration to ensure the functionality and quality of food in space. Further research is needed to fully understand how these microgravity-induced changes impact food systems and ensure safe and efficient food production for future space missions. Moreover, the extent to which these issues will be impacted by the partial gravity of Lunar and Martian environments has yet to be demonstrated. It is likely that some processes will be dependent on the adjustments for the gravitational situation on the Lunar or Martian surface, whereas for others, it may not be. Nevertheless, gravity should be accounted for where necessary.
- **Usability** differs depending on the mission scenario. Early exploration missions will be purely focused on science and exploration and will not have dedicated cooks or food production crew, which will eventually be the case for future colonization efforts. This means that ideally, the crew will not want to spend more time and effort preparing food than the average person after a long day of work [1]. Additional concerns involve preparation, containment of resources, and cleaning processes that may differ from Earth in terms of both gravity and resource availability.

By virtue of this, any systems or appliances should also be easy to operate, maintain, and repair, and require little specific crew training. As future mission scenarios evolve, the definition of useability this criterion will change across temporal and spatial scales.

- **Resource efficiency** – This topic is threefold. First, a production technology is weighed against the output that it creates, including amount, nutrition, acceptability, and variety. Second, any technology should be designed to minimize waste production and to maximize resource recovery and recycling. This includes the integration with other innovations and systems that are capable of doing so, since the byproduct of one system may act as feedstock for another. Similarly, the competition for resources required for other technologies and nested subsystems should be taken into consideration to optimize overall resource efficiency. Third, all other resources, such as mass, volume, crew time, water, and power consumption, need to be considered. Mission planners will ultimately determine the

performance of the food support systems within mission and vehicle constraints [1].

- **Integration** – It is essential that food technologies and systems are compatible with other spacecraft and habitat infrastructures. Proposals for individual technologies should not aim to replace the food system as a whole, but rather to be integrated with existing and future technologies to form a cohesive, flexible, and functional food system. Variety across production, processing, storage, and waste management solutions is crucial to ensure redundancy, adaptability, and crew acceptability. Cross-compatible equipment and shared resource interfaces can enable technologies to work synergistically across current and emerging systems. Moreover, employing common interfaces and modular architectures supports capability evolution, the integration of new components, and overall mass and volume efficiency.
- **Evolvability** – Technologies and systems should be durable and adaptable, capable of meeting advancing technologies and changing mission requirements. Designing for evolvability helps avoid obsolescence by enabling systems to integrate new discoveries, upgrades, and innovations as they become available, or to adapt to new mission objectives as they emerge. This approach ensures that investments in infrastructure and hardware remain relevant across successive mission phases and support long-term sustainability in space food production.
- **Resilience and robustness to technological and programmatic challenges** – Systems should be designed for redundancy and fail-safes to ensure robustness to withstand technical and programmatic challenges, including unexpected failures and emergencies. The incorporation of self-diagnostic tools and automated recovery systems should be implemented where possible.
- **Adaptability** – Systems must be flexible to accommodate changing crew needs or unexpected disruptions, or to function across scales. This may not always apply to individual technologies, but more on a systems level to foster self-organization.

Any individual unit, module, or method of the food system should be fully vetted against the aforementioned requirements before attempting integration into future exploration architectures. However, these criteria are relative depending on the element. While some are directly applicable to consumable products, other technologies, such as bioreactors, may serve secondary production purposes or where the output primarily functions as feedstock for aquaculture or insect production. Similarly, waste management technologies will not require e.g., palatability requirements, whereas food safety is still an applicable requirement if the purpose is to feed back the waste into the system.

6. Conclusion

Designing and implementing a bioregenerative food production system for exploration missions on the Lunar or Martian surface requires extensive research, development, and innovation, along with comprehensive supporting measures such as specialized crew training, operational protocols, and ground-based analog validation. Given the complexity of these correlated challenges, solving them may require a longer timeframe than the available time before the need for them arises. Recognizing these challenges as early as possible is therefore crucial for tackling them properly and strategically. Part of this strategic approach involves acknowledging that creating a food production system is more than simply combining multiple food production technologies. Instead, it calls for a systems-based mindset that accounts for multiple elements, scales, and the feedback loops connecting them.

Similarly, having a comprehensive understanding of the relationships between elements and their layered subsystems will promote cohesion and integration into future mission architectures. Cohesion is a fundamental aspect of developing a functional food system to ensure that all components work seamlessly together. This type of systematic

testing will become increasingly important as technologies should not only be evaluated for reliability, but also for how they function in a system configured to a specific scenario and architecture. This type of joint testing will ensure that all technologies function seamlessly together under realistic conditions, highlighting their interplay, allowing for resource optimization and material balances, or exposing dependencies or integration challenges that may arise. Equally important is the focus on iterative learning, integrating feedback from ground-based testing and partial system simulations to evolve systems over time. This also emphasizes attributes such as self-organization, subsystem redundancy, and modularity, as they become important system design considerations, both allowing the system to self-organize, but also to ensure that unforeseen stressors do not cascade into mission-compromising failures. By doing this, system drivers can more easily be identified, which will feed back into the criteria for future technologies and nested subsystems.

This interdependence underscores why unsystematic approaches fall short; the production, post-harvest management, waste management, preparation, and socio-cultural elements of a food system must be developed in concert, with robust pathways for exchange of resources and knowledge. Recognizing the socio-ecological nature of the space food production system is also essential to creating solutions that are not only technically reliable but also psychologically and culturally attuned to crew well-being.

Ultimately, the development of space food systems must follow an iterative pathway from conceptual design and virtual assessment to physical validation. Early in the design process, candidate components and system configurations should be virtually modeled to evaluate feasibility within specific vehicle or habitat constraints, mission durations, and crew sizes. These virtual assessments serve as an early validation step before investing in high-fidelity ground test demonstrators, where integrated systems can be tested under realistic mission conditions. While certain elements and interfaces may become standardized, each food system will ultimately be bespoke, tailored to the unique configuration, objectives, and constraints of a given mission scenario.

CRedit authorship contribution statement

Tor Blomqvist: Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Ralph Fritsche:** Writing – review & editing, Writing – original draft, Supervision.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [1] G.L. Douglas, S.R. Zwart, S.M. Smith, Space food for thought: challenges and considerations for food and nutrition on exploration missions, *J. Nutr.* 150 (9) (2020) 2242–2244.
- [2] M. Cooper, M. Perchonok, G.L. Douglas, Initial assessment of the nutritional quality of the space food system over three years of ambient storage, *npj Microgravity* 3 (17) (2017).
- [3] G.L. Douglas, M. Cooper, D. Bermudez-Aguirre, T. Sirmons, Human Research Program risk of performance decrement and crew illness due to an inadequate food System. Lyndon B. Johnson Space Center, National Aeronautics and Space Administration, Houston, Texas, 2016.
- [4] S.M. Smith, S.R. Zwart, G.L. Douglas, M. Heer, Human adaptation to spaceflight: the role of food and nutrition, in: Lyndon B. Johnson Space Center, second ed., National Aeronautics and Space Administration, Houston, Texas, 2021, pp. 19–20.

- [5] G.L. Douglas, R.M. Wheeler, R.F. Fritsche, Sustaining astronauts: resource limitations, technology needs, and parallels between spaceflight food systems and those on Earth 13 (9424) (2021).
- [6] N.M. Hussin, S. Shahar, N.I.M.F. Teng, W.Z.W. Ngah, S.K. Das, Efficacy of Fasting and Calorie Restriction (FCR) on Mood and Depression Among Ageing Men vol. 17, 2013, pp. 674–680.
- [7] M. Singh, Mood, Food, and Obesity vol. 5, 2014.
- [8] D.A. Zellner, S. Loazia, Z. Gonzalez, J. Pita, J. Morales, D. Pecora, A. Wolf, Food selection changes under stress 87 (4) (2006) 789–793.
- [9] M.S. Anderson, D. Barta, G. Douglas, R. Fritsche, G. Massa, R. Wheeler, C. Quincy, M. Romeyn, B. Motil, A. Hanford, Key gaps for enabling plant growth in future missions, in: AIAA SPACE and Astronautics Forum and Exposition, Session: Artificial Gravity and Enabling Life Support, 2017. Orlando, FL.
- [10] L.H. Gunderson, S.H. Crawford, Panarchy: Understanding Transformations in Human and Natural Systems, Island Press, Washington, 2003.
- [11] D.W. Cash, N.W. Adger, B. Fikret, P. Garden, L. Lebel, P. Olsson, L. Pritchard, O. Young, Scale and cross-scale dynamics: governance and information in a multilevel world 11 (2) (2006).
- [12] J. Fanzo, C. Davis, Drivers shaping food systems, in: Global Food Systems, Diets, and Nutrition, Palgrave Macmillan, Cham, 2021, pp. 85–105.
- [13] C. Béné, S.D. Prager, H.A. Achiacoy, P. Alvarez Toro, L. Lamotte, C. Bonilla Cedrez, B.R. Mapes, Understanding Food Systems Drivers: a Critical Review of the Literature, vol. 23, 2019, pp. 149–159.
- [14] J. Kast, Y. Yu, C.N. Seubert, V.E. Wotring, H. Derendorf, Drugs in Space: Pharmacokinetics and Pharmacodynamics in Astronauts, 2017, pp. 2–8.
- [15] R.S. Blue, J.C. Chancellor, E.L. Antonsen, T.M. Bayuse, V.R. Daniels, V.E. Wotring, Limitations in predicting radiation-induced pharmaceutical instability during long-duration spaceflight, npj microgravity 5 (2019).
- [16] J. Jiang, M. Zhang, B. Bhandari, P. Cao, Current Processing and Packing Technology for Space Foods: a Review, 2019.
- [17] E. Antonsen, Risk of Adverse Health Outcomes and Decrements in Performance due to In-flight Medical Conditions, NASA Johnson Space Center, 2017. Houston TX.
- [18] A. Bergouignan, P.T. Stein, C. Habold, V. Coxam, D. O'Gorman, S. Blanc, Towards human exploration of space: the THESEUS review series on nutrition and metabolism research priorities, npj microgravity 2 (2016).
- [19] M. Obrist, Y. Tu, L. Yao, C. Velasco, Space Food Experiences: Designing Passenger's Eating Experiences for Future Space Travel Scenarios, vol. 1, 2019.
- [20] K. Szocik, S. Abood, M. Shelhamer, Psychological and Biological Challenges of the Mars Mission Viewed Through the Construct of the Evolution of Fundamental Human Needs, vol. 152, 2018.
- [21] D. Chao, This International Space Station (ISS) Researcher's Guide. S.L., NASA ISS Program Science Office, 2020. NASA ISS Program Science Office, 2020.
- [22] H. Caps, N. Vandewalle, A. Saint-Jalmes, L. Saulnier, P. Yazhgur, E. Rio, A. Salonen, D. Langevin, How Foams Unstable on Earth Behave in Microgravity? vol. 457, 2014.
- [23] H. Caps, G. Delon, N. Vandewalle, R.M. Guillermic, O. Pitois, A.L. Biance, L. Saulnier, P. Yazhgur, E. Rio, A. Salonen, D. Langevin, Does Water Foam Exist in Microgravity?, vol. 43, 2014, 3.
- [24] H. C. G. D. A. S.-J. E. R. L. S. M. A. L. B. O. P. S. C. A. N Vandewalle, Foam Stability in Microgravity, vol 327, 2011.
- [25] J. Zhu, M. Li, R. Rogers, W. Meyer, R.H. Ottewill, STS-73 Space Shuttle Crew, Russel, W.B. and Chaikin, P.M., Crystallization of hard-sphere Colloids in Microgravity, vol. 387, 1997.
- [26] R.v. d. Sman, Soft Matter Approaches to Food Structuring, 2012, pp. 176–177, vol. s.
- [27] J.A. Rosenzweig, O. Abogunde, K. Thomas, A. Lawal, Y.U. Nguyen, A. Sodipe, O. Jejelowo, Spaceflight and modeled microgravity effects on microbial growth and virulence 85 (2010) 885–891.
- [28] S. Sheet, S. Yesupatham, K. Ghosh, M.S. Choi, K.S. Shim, Y.S. Lee, Modulatory effect of low-shear modeled microgravity on stress resistance, membrane lipid composition, virulence, and relevant gene expression in the food-borne pathogen *Listeria monocytogenes* 133 (2020).
- [29] J. Gandolph, A. Shand, A. Stoklosa, A. Ma, I. Weiss, D. Alexander, M. Perchonok, L. J. Mauer, Foods for a Mission to Mars: Investigations of Low-Dose Gamma Radiation Effects, 2013.
- [30] H.W. Jones, Going beyond reliability to robustness and resilience in space life support systems, in: 50th International Conference on Environmental Systems, 2021.
- [31] P.J. Ericksen, What is the vulnerability of a food System to global environmental change? 13 (2) (2008).
- [32] F. Berkes, J. Colding, C. Folke, Navigating Social-Ecological Systems: Building Resilience for Complexity and Change, Cambridge University Press, 2003.
- [33] J.M. Bunckek, M.E. Hummerick, S.E. LaShelle, M.W. Romeyn, M. Young, R. C. Morrow, C.A. Mitchell, G.L. Douglas, R.M. Wheeler, G.D. Massa, Pick-and-eat space crop production flight testing on the International Space Station, J. Plant Interact. 19 (1) (2024).
- [34] J.J. Marquez, S. Hillenius, M. Healy, J. Silva-Martinez, Lessons Learned from International Space Station Crew Autonomous Scheduling Test, 2019.
- [35] J.K. Bedree, K. Kerns, T. Chen, B.P. Lima, G. Liu, J. Shi, H. Chuan Pan, J.K. Kim, L. Tran, S.S. Minot, E.L. Hendrickson, E.I. Lamont, F. Schulte, M. Hardt, D. Stephens, M. Patel, A. Kokaras, L. Stodieck, Y. Shirazi-Fard, B. Wu, J.H. Kwak, K. Ting, C. Soo, J.S. McLean, X. He, W. Shi, Specific Host Metabolite and Gut Microbiome Alterations are Associated with Bone Loss During Spaceflight vol. 42, 2023.
- [36] M. Perchonok, G. Douglas, M. Cooper, Risk of performance decrement and crew illness due to an inadequate food System, National Aeronautics and Space Administration (NASA) Lyndon B. Johnson Space Center (2012). Houston, Texas.
- [37] T. Clemmensen, M. Tourchi Moghaddam, J. Nørbjerg, Cyber-physical systems with Human-in-the-Loop: a systematic review of socio-technical perspectives, J. Syst. Software 226 (2025).
- [38] A. Riera, O. Duluins, C. Antier, P.V. Baret, Which types of quantitative foresight scenarios to frame the future of food systems? A review, Agric. Syst. 225 (2025).
- [39] M. Reilly, D. Willenbockel, Managing uncertainty: a review of food system scenario analysis and modelling, Phil. Trans. Biol. Sci. 365 (1554) (2010).
- [40] E. Burnett, Essential elements of self-organization illustrated through localized agri-food systems 47 (5) (2023) 745–770.
- [41] J.M. Andeiros, C. Folke, B. Walker, E. Ostrom, Aligning key concepts for global change Policy: robustness, resilience, and sustainability, Ecol. Soc. 18 (2) (2013).
- [42] I. Darnhofer, S. Bellon, B. Dedieu, R. Milestad, Adaptiveness to enhance the sustainability of farming systems. A review, Agronomy for Sustainable Development 30 (2010) 545–555.
- [43] I. Darnhofer, J. Fairweather, H. Moller, Assessing a farm's sustainability: insights from resilience thinking, Int. J. Agric. Sustain. 8 (3) (2010).
- [44] J.F. Cabell, M. Oelofse, An Indicator framework for assessing agroecosystem resilience, Ecol. Soc. 17 (1) (2012).
- [45] A.J. Lamond, C.A. Depp, M. Allison, R. Langer, J. Reichstadt, D.J. Moore, S. Golshan, T.G. Ganiats, D.V. Jeste, Measurement and predictors of resilience among community-dwelling older women, J. Psychiatr. Res. 43 (2) (2008) 148–154.
- [46] J.M. Anderies, B.H. Walker, A.P. Kinzig, Fifteen weddings and a funeral: case studies and resilience-based management, Ecol. Soc. 11 (1) (2006).
- [47] D. Tendall, J. Joerin, B. Kopainsky, P. Edwards, A. Shreck, Q. Le, P. Kruetli, M. Grant, J. Six, Food system resilience: defining the concept, Global Food Secur. 6 (2015) 17–23.
- [48] B. Fridolin Simon, J. Kurt, Focusing the meaning(s) of resilience: resilience as a descriptive concept and a boundary object, Ecol. Soc. 12 (1) (2007).
- [49] T.Y. Melesse, C. Franciosi, V. Di Pasquale, S. Riemma, Analyzing the implementation of digital twins in the agri-food supply chain 7 (2) (2023).
- [50] S. Aslam, A. Wileman, S. Perinpanaygam, Digital Twin in Aerospace Industry: a Gentle Introduction, vol. 4, 2016.
- [51] M. Guo, X. Lv, D. Wang, H. Chen, F. Wei, Innovative Integration of Computer Vision, Iot, and Digital Twin in Food Quality and Safety Assessment, vol. 163, 2025.
- [52] E. Purlis, Digital Twin Methodology in Food Processing: Basic Concepts and Applications, vol. 13, 2024, pp. 914–920.
- [53] P. Verboven, T. Defraeye, A.K. Datta, B. Nicolai, "Digital Twins of Food Process Operations: the next Step for Food Process Models?," vol. 35, 2020 (79–87).
- [54] G. Paolo Tancredi, G. Vignali, E. Bottani, "Integration of Digital Twin, Machine-Learning and Industry 4.0 Tools for Anomaly Detection: an Application to a Food Plant," vol. 22, 2022, 11.
- [55] E.E.M. Abdurrahman, G. Ferrari, Digital Twin Applications in the Food Industry: a Review, vol. 9, 2025.
- [56] C. Krupitzer, T. Noack, C. Borsum, "Digital Food Twins Combining Data Science and Food Science: System Model, Applications, and Challenges," 2022 vol. 10, no. 9.
- [57] B. Guidani, M. Ronzoni, R. Accorsi, Virtual agri-food supply chains: a holistic digital twin for sustainable food ecosystem design, control and transparency, Sustain. Prod. Consum. 46 (2024) 161–179.
- [58] W. Purcell, T. Neubauer, Digital Twins in Agriculture: a state-of-the-art review, Smart Agric. Technol. 3 (2023).
- [59] Food and Agriculture Organization of the United Nations (FAO), Food security - policy brief, FAO's Agriculture and Development Economics Division (ESA) (2006).
- [60] J. Clapp, W.G. Moseley, B. Burlingame, P. Termine, Viewpoint: the Case for a six-dimensional Food Security Framework, vol 106, 2022.
- [61] HPLPE, Food Security and Nutrition: Building a Global Narrative Towards 2030. A Report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, HPLPE, Rome, 2020.
- [62] FAO, IFAD, UNICEF, WFP, WHO, The State of Food Security and Nutrition in the World (SOFI), FAO, Rome, Italy, 2023. IFAD ; UNICEF ; WFP ; WHO.
- [63] P.B. Thompson, "From world hunger to food sovereignty: food ethics and human development," 11 (3) (2014) 336–350.
- [64] G.L. Douglas, R.M. Wheeler, R.F. Fritsche, Sustaining Astronauts: Resource Limitations, Technology Needs, and Parallels Between Spaceflight Food Systems and those on Earth, vol. 13, 2021.
- [65] J.A. Rosenzweig, O. Abogunde, K. Thomas, A. Lawal, Y.-U. Nguyen, A. Sodipe, O. Jejelowo, Spaceflight and modeled microgravity effects on microbial growth and virulence, Appl. Microbiol. Biotechnol. 85 (2010) 885–891.
- [66] S. Sheet, Y. Sathishkumar, K. Ghosh, M.-S. Choi, K. Seob Shim, Y. Soo Lee, Modulatory effect of low-shear modeled microgravity on stress resistance, membrane lipid composition, virulence, and relevant gene expression in the food-borne pathogen *Listeria monocytogenes*, Enzym. Microb. Technol. 133 (2020).
- [67] J.A. Lee, J.K. Brecht, S. Castro-Wallace, F.M. Donovan, J.A. Hogan, T. Liu, G. D. Massa, M. Parra, S.A. Sargent, M.A. Settles, N. Kumar Singh, Y.-A. Velez Justiniano, K. Venketeswaran, Microbial Food Safety in Space Production Systems: a White Paper Submitted to the Decadal Survey on Biological and Physical Sciences Research in Space 2023–2032, National Aeronautics and Space Administration (NASA), 2023.

- [68] C. Khodadad, M. Hummerick, L. Spencer, A. Dixit, J. Richards, M. Romeyn, *Microbiological and Nutritional Analysis of Lettuce Crops Grown on the International Space Station*, vol. 6, 2020, 11.
- [69] S.M. Smith, S.R. Zwart, *Nutritional biochemistry of spaceflight*, *Adv. Clin. Chem.* 46 (2008) 87–130.
- [70] H. Tang, H.H. Rising, M. Majji, R.D. Brown, *Long-Term Space Nutrition: a Scoping Review*, vol. 14, 2022, 1.
- [71] S.M. Smith, S.R. Zwart, *Nutritional biochemistry of spaceflight*, *Adv. Clin. Chem.* 46 (2008) 87–130.
- [72] P.H. Sandal, D. Kim, L. Fiebig, A. Winnard, N. Caplan, D.A. Green, T. Weber, *Effectiveness of nutritional countermeasures in microgravity and its ground-based analogues to ameliorate musculoskeletal and cardiopulmonary deconditioning—A Systematic Review*, *PLoS One* 15 (6) (2020).
- [73] P. Pittia, S. Blanc, M. Heer, *Unraveling the intricate connection between dietary factors and the success in long-term space missions* 9 (89) (2023).
- [74] P. Sun, X. Gao, D. Wei, J. Ge, X. Deng, H. Chen, H. Yang, J. Gao, J. Yang, *The digestive system under microgravity environment: changes, mechanisms and the prospects of the future* 3 (2) (2025) 108–115.
- [75] B. Juillet, H. Fouillet, C. Bos, F. Mariotti, N. Gausserès, R. Benamouzig, D. Tomé, C. Gaudichon, *Increasing habitual protein intake results in reduced postprandial efficiency of peripheral, anabolic wheat protein nitrogen use in humans*, *Am. J. Clin. Nutr.* 87 (3) (2008) 666–678.
- [76] C. Gaudichon, C. Bos, C. Morens, K.J. Petzke, F. Mariotti, J. Everwand, R. Benamouzig, S. Daré, D. Tomé, C.C. Metges, *Ileal losses of nitrogen and amino acids in humans and their importance to the assessment of amino acid requirements*, *Gastroenterology* 123 (1) (2002) 50–59.
- [77] J.A. Foote, S.P. Murphy, L.R. Wilkens, P.P. Basiotis, A. Carlson, *Dietary variety increases the probability of nutrient adequacy among adults*, *J. Nutr.* 134 (7) (2004) 1779–1785.
- [78] S. Boesveldt, K. de Graaf, *The differential role of smell and taste for eating behavior*, *Perception* 46 (3–4) (2017) 307–319.
- [79] M. Obrist, Y. Tu, L. Yao, C. Velasco, *Space food experiences: designing passenger's eating experiences for future space travel scenarios*, *Frontiers in Computer Science, Sec. Human-Media Interaction* 1 (2019).
- [80] K. Szocik, S. Abood, M. Shelhamer, *Psychological and biological challenges of the Mars mission viewed through the construct of the evolution of fundamental human needs*, *Acta Astronaut.* 152 (2018) 793–799.
- [81] G.G. De La Torre, B. van Baarsen, F. Ferlazzo, N. Kanas, K. Weiss, S. Schneider, I. Whiteley, *Future perspectives on space psychology: recommendations on psychosocial and neurobehavioural aspects of human spaceflight*, *Acta Astronaut.* 81 (2) (2012) 587–599.
- [82] J. Zhu, M. Li, R. Rogers, W. Meyer, R.H. Ottewill, , STS-73 Space Shuttle Crew, W. B. Russel, P.M. Chaikin, *Crystallization of hard-sphere colloids in microgravity*, *Nature* 387 (1997) 883–885.
- [83] F. Chiramonte, J. McQuillen, H. Nagra, P. Manoharan, H. Vanhala, 2019 NASA Division of Space Life and Physical Sciences Research and Applications Fluid Physics Workshop Report, NASA Glenn Research Center, Cleveland, Ohio, 2019.
- [84] H. Caps, N. Vanderwalle, A. Saint-Jalmes, L. Saulnier, P. Yazhgur, E. Rio, A. Salonen, D. Langevin, *How foams unstable on Earth behave in microgravity? Colloids Surf. A Physicochem. Eng. Asp.* 457 (2014) 392–396.
- [85] P. Weichun, R. Zhang, K. Tsukamoto, A. Li, *Microgravity influence on the instability of phase separation in protein solution*, *Appl. Phys. Lett.* 107 (12) (2015).
- [86] M. Kostoglou, T. Karapantsios, *Cooking in space: current situation, needs, and perspectives*, *Curr. Opin. Food Sci.* 51 (2023).