



Nutrition in space: A comprehensive review of dietary requirements and health challenges—an overview

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Abstract

Human spaceflight exposes astronauts to a unique combination of microgravity, ionizing radiation, confinement, isolation, altered circadian rhythms, limited food availability, and psychological stress. These conditions can substantially influence energy metabolism, body composition, bone and muscle homeostasis, cardiovascular function, immune regulation, gastrointestinal health, oxidative balance, and cognitive performance. Nutrition therefore represents a critical component of human spaceflight medicine and an important countermeasure against physiological deterioration. The space food system must provide adequate energy and essential nutrients while also meeting stringent requirements related to food safety, shelf life, mass, volume, packaging, preparation, palatability, and crew acceptability. Evidence from International Space Station missions and ground-based analog studies indicates that inadequate energy intake, altered fluid balance, changes in protein and amino acid metabolism, bone mineral loss, vitamin D insufficiency, altered iron metabolism, oxidative stress, and gastrointestinal and microbiome changes may occur during prolonged spaceflight. Nutritional strategies involving adequate energy and protein, calcium and vitamin D, appropriate iron management, antioxidants, omega-3 fatty acids, dietary fibre, hydration, and individualized dietary monitoring may help mitigate these risks. However, nutrient requirements during exploration-class missions remain incompletely defined. Future missions to the Moon and Mars will require more autonomous, sustainable, personalized, and resilient food systems, potentially integrating precision nutrition, artificial intelligence, bioregenerative food production, and in-situ resource utilization. This review summarizes current knowledge of nutritional requirements during spaceflight, major health challenges associated with inadequate nutrition, characteristics of space food systems, potential nutritional countermeasures, and emerging research priorities for long-duration human exploration.

Keywords: Space nutrition, astronauts, microgravity, space food, dietary requirements, bone health, muscle loss, oxidative stress, immune function, gut microbiome, long-duration spaceflight, precision nutrition

Introduction

Human exploration of space represents one of the most demanding environments in which the human body must function. Unlike terrestrial environments, spaceflight combines microgravity, exposure to ionizing radiation, confinement and isolation, restricted resources, altered sleep-wake cycles, and limited opportunities for food preparation and resupply. These environmental and operational stressors interact with physiological adaptation to influence energy metabolism, body composition, fluid and electrolyte balance, musculoskeletal health, endocrine function, immune regulation, and overall nutritional status (Lane *et al.*, 1994; Lane *et al.*, 2002) [21, 23]. Consequently, maintaining adequate nutritional status is essential for astronaut health, physical performance, cognitive function, and mission success. Nutrition is now recognized by NASA as a specific human-system risk because inadequate food and nutrition may contribute to decrements in health and performance during missions as well as longer-term health consequences (National Aeronautics and Space Administration [NASA], 2025) [31].

The importance of nutrition in spaceflight has been recognized since the earliest crewed missions. Historical evidence from Apollo, Skylab, and Space Shuttle missions indicated that energy and fluid intakes were frequently lower than predicted, while prolonged spaceflight was associated with alterations in body composition, energy

utilization, endocrine function, and musculoskeletal physiology (Lane *et al.*, 1992; Lane *et al.*, 1994) [22, 23]. Research has subsequently demonstrated that spaceflight-related changes in energy intake, body composition, bone metabolism, and fluid regulation are closely interconnected. In particular, reduced energy intake and altered energy metabolism can contribute to negative energy balance and loss of body mass, while microgravity-induced unloading promotes muscle and bone loss (Heer *et al.*, 2001; Lane *et al.*, 2002) [17, 21]. With the transition from relatively short orbital missions to extended stays aboard the International Space Station (ISS), nutritional research has increasingly focused on maintaining physiological health during missions lasting several months and on identifying nutritional strategies suitable for future exploration-class missions.

NASA's current approach to space nutrition has evolved from a nutrient-by-nutrient perspective toward a broader physiological systems-based framework. The most recent NASA review examines the relationships between nutrition and major physiological systems, including bone, muscle, ocular, cardiovascular, immune, gastrointestinal, and behavioral health. It also integrates evidence from ISS missions with findings from ground-based analog environments such as head-down bed rest, Antarctic isolation, and undersea habitats (Smith *et al.*, 2021 [9]; NASA, 2024). These analog studies are particularly

valuable because they allow investigators to examine individual components of the spaceflight environment, including physical unloading, confinement, isolation, limited sunlight exposure, and altered environmental conditions.

The nutritional problem in space is therefore more complex than simply supplying sufficient calories and essential nutrients. Astronauts require a food system that is nutritionally adequate, microbiologically safe, stable during prolonged storage, palatable, acceptable to individual crew members, practical to prepare and consume, and compatible with spacecraft constraints. Space food systems must also account for limitations in mass, volume, power, storage capacity, preparation time, packaging, shelf life, and crew preferences (NASA, 2024, 2025). Although nutritional adequacy and food safety have been demonstrated for approximately six-month missions and, in some circumstances, limited one-year missions, maintaining food-system acceptability, nutritional adequacy, and safety during longer missions with limited resupply remains a major challenge (NASA, 2025).

Nutrition also has important psychosocial functions during spaceflight. Meals provide opportunities for routine, enjoyment, cultural expression, and social interaction, while changes in appetite, taste, food preference, and menu variety can influence dietary intake. Earlier spaceflight research emphasized that nutrition contributes not only to the provision of essential nutrients but also to crew morale and psychosocial well-being (Lane *et al.*, 1994)^[23]. More recent research has identified several major priorities for space nutrition, including maintenance of energy balance, altered feeding behavior, metabolic stress, micronutrient adequacy, changes in gut microbiota, and fluid and electrolyte regulation (Smith *et al.*, 2017)^[41].

As missions extend beyond low-Earth orbit, these nutritional challenges are expected to become increasingly important. Future lunar and Martian missions will involve longer periods without routine resupply, greater exposure to radiation, more restrictive food systems, and increased demands for food stability and nutritional resilience. NASA's current food and nutrition research therefore focuses on defining nutritional requirements for exploration missions, evaluating the nutrient content and safety of space foods, improving food acceptability, developing nutritional countermeasures, and validating these strategies using analog and spaceflight studies (NASA Human Research Program, 2024)^[29]. These developments emphasize the need to consider space nutrition as an integrated component of human health and mission design rather than simply as a means of providing food.

This review provides a comprehensive overview of current knowledge regarding nutrition during spaceflight, with particular emphasis on dietary requirements, physiological and health challenges, nutritional countermeasures, space food technology, nutritional assessment, and emerging approaches such as precision nutrition and sustainable food production. Understanding these areas is essential for developing effective nutritional strategies capable of supporting astronaut health and performance during future long-duration missions to the Moon, Mars, and beyond.

Spaceflight Environment and Its Nutritional Implications

1. Microgravity and altered mechanical loading

Microgravity is one of the principal environmental factors affecting astronaut physiology. In the absence of normal

gravitational loading, the mechanical stimuli required for maintaining bone and skeletal muscle tissue are substantially reduced. Prolonged exposure to microgravity consequently results in muscle atrophy, reductions in muscle strength, and accelerated bone resorption, with astronauts also experiencing alterations in cardiovascular function and aerobic capacity (Lang *et al.*, 2004; Fitts *et al.*, 2010; Smith *et al.*, 2021)^[9, 11, 24]. Bone loss is particularly pronounced in weight-bearing skeletal regions, where the reduction in mechanical loading disrupts the normal balance between bone formation and bone resorption (LeBlanc *et al.*, 2000; Smith *et al.*, 2012)^[25, 44].

Skeletal muscle is similarly affected by the unloading environment. Reduced mechanical stimulation decreases muscle protein synthesis and promotes alterations in muscle fibre characteristics, contributing to reductions in muscle mass, strength, and functional capacity during prolonged spaceflight (Fitts *et al.*, 2010)^[11]. Although individual responses vary according to mission duration, exercise participation, age, sex, and other physiological factors, maintenance of muscle and bone health remains a major challenge for long-duration human spaceflight. Structured exercise, particularly resistance exercise combined with aerobic training, is therefore considered one of the principal countermeasures against microgravity-induced physiological deterioration (Smith *et al.*, 2021)^[9].

Nutrition interacts closely with exercise in maintaining musculoskeletal health. Adequate energy availability is essential because insufficient energy intake can limit tissue repair and adaptation and may increase the utilization of body protein as an energy substrate. Dietary protein and essential amino acids provide the substrates required for muscle protein synthesis, while adequate protein intake combined with resistance exercise can support the maintenance of skeletal muscle during periods of unloading (Paddon-Jones *et al.*, 2009; Smith *et al.*, 2021)^[9, 35]. In addition, calcium and vitamin D are particularly important for skeletal metabolism, while phosphorus and magnesium contribute to bone mineralization, cellular energy metabolism, and neuromuscular function (Smith *et al.*, 2021)^[9].

Vitamin D is of particular concern during spaceflight because astronauts have limited exposure to ultraviolet radiation and therefore cannot rely on cutaneous vitamin D synthesis. Maintaining adequate vitamin D status, together with sufficient calcium intake and regular exercise, may help support bone health during prolonged missions (Smith *et al.*, 2021)^[9]. However, nutritional interventions alone are unlikely to completely prevent microgravity-induced bone and muscle loss. Current evidence supports an integrated approach combining adequate energy and nutrient intake with appropriately designed resistance and aerobic exercise programs (Smith *et al.*, 2021)^[9]; NASA, 2024).

Thus, nutritional strategies for spaceflight should not be considered independently from exercise and other physiological countermeasures. The combined optimization of energy availability, protein quality and distribution, calcium and vitamin D status, and exercise loading represents an important strategy for preserving musculoskeletal function and physical performance during long-duration space missions.

2. Radiation exposure

Beyond the protection provided by Earth's atmosphere and geomagnetic field, astronauts are exposed to substantially greater levels of ionizing radiation during spaceflight. The

radiation environment includes galactic cosmic rays, solar particle events, and trapped radiation, with exposure becoming an increasingly important concern as missions extend beyond low-Earth orbit. Ionizing radiation can induce direct and indirect cellular damage through the generation of reactive oxygen species (ROS), DNA damage, alterations in cellular signaling, and inflammatory responses. These processes may contribute to both acute and long-term health risks, including carcinogenesis, cardiovascular dysfunction, neurobiological effects, and tissue degeneration (Durante & Cucinotta, 2011; Cucinotta & Durante, 2006; Chancellor *et al.*, 2014)^[3, 5, 10].

Oxidative stress represents an important biological mechanism underlying several radiation-induced effects. Excessive production of ROS can overwhelm endogenous antioxidant defense systems and result in oxidative modification of lipids, proteins, and nucleic acids. In addition, radiation exposure may activate inflammatory pathways and alter mitochondrial function, potentially amplifying cellular damage (Kennedy & Wan, 2011; Chancellor *et al.*, 2014)^[3, 20]. The combination of radiation exposure with other spaceflight stressors, including microgravity, psychological stress, sleep disruption, and altered metabolism, may further influence redox homeostasis and physiological adaptation.

Nutrition has therefore attracted considerable attention as a potential component of radiation countermeasure strategies. Antioxidant nutrients and bioactive food compounds, including vitamins C and E, carotenoids, selenium, zinc, polyphenols, and omega-3 fatty acids, participate in antioxidant defense, cellular signaling, immune regulation, and inflammatory processes. A nutritionally adequate diet containing a diverse range of fruits, vegetables, whole grains, legumes, nuts, seeds, and other nutrient-dense foods may provide a broad spectrum of antioxidant and anti-inflammatory compounds that support endogenous defense mechanisms (Smith *et al.*, 2021)^[9]. Nutritional adequacy is particularly important because deficiencies of antioxidant-related micronutrients could compromise physiological resilience during prolonged exposure to environmental stressors.

However, the potential protective effects of individual antioxidant nutrients against space radiation should be interpreted cautiously. Radiation-induced biological responses are complex and involve multiple pathways, and evidence from terrestrial radiation research does not necessarily translate directly to the unique radiation environment encountered during spaceflight. Furthermore, excessive antioxidant supplementation may alter physiological redox signaling and does not necessarily provide additional protection. Current evidence therefore does not support a single antioxidant nutrient or standardized high-dose antioxidant supplementation regimen as an established countermeasure for radiation-induced health effects (Kennedy & Wan, 2011; Smith *et al.*, 2021)^[9, 20].

Consequently, nutritional management of radiation risk should emphasize overall dietary adequacy and maintenance of antioxidant capacity rather than reliance on isolated high-dose supplements. Future research should investigate interactions among diet, antioxidant status, inflammation, mitochondrial function, the gut microbiome, and radiation exposure. Such research may contribute to the development of individualized nutritional countermeasures for astronauts undertaking long-duration missions beyond low-Earth orbit.

3. Confinement, isolation, and psychological stress

Long-duration missions involve restricted living environments, separation from family and normal social surroundings, limited food variety, and considerable operational demands. These factors may influence appetite, food preference, meal timing, and dietary adherence. Nutrition has a psychosocial function in addition to its physiological role; enjoyable meals and variety may contribute to crew morale and psychological well-being. Earlier space nutrition research specifically highlighted the psychosocial importance of food during missions (Smith *et al.*, 2021; Kennedy and Wan, 2011)^[9, 20].

4. Circadian disruption

Space missions can disrupt normal circadian rhythms because of unusual light-dark cycles, demanding work schedules, and altered sleep patterns (Smith *et al.*, 2021)^[9]. Circadian disruption can affect metabolic regulation, appetite, glucose homeostasis, and gastrointestinal function. Consequently, future space nutrition strategies may need to consider not only what astronauts consume but also when food is consumed (Chancellor *et al.*, 2014)^[3].

Energy Requirements and Energy Balance

Energy balance is one of the central challenges in space nutrition. Historical observations from human spaceflight have consistently indicated that energy intake may be lower than expected during missions, with reductions in both food and fluid consumption reported during some periods of spaceflight (Lane *et al.*, 1994; Lane *et al.*, 2002)^[21, 23]. More recent evidence from long-duration missions aboard the International Space Station (ISS) suggests that inadequate energy intake can remain a concern, particularly when dietary intake does not adequately match the metabolic demands associated with exercise and other mission activities (Smith *et al.*, 2021)^[9]. Maintaining energy balance is therefore an important component of preserving body mass, lean tissue, physical performance, and overall nutritional status during prolonged spaceflight.

Reduced energy intake during spaceflight is likely to result from multiple interacting physiological, sensory, behavioral, and operational factors. These may include reduced appetite, changes in taste and smell, gastrointestinal disturbances, menu fatigue, psychological stress, altered circadian rhythms, and practical difficulties associated with eating and food preparation in microgravity (Lane *et al.*, 1994; Smith *et al.*, 2021)^[9, 23]. Changes in fluid distribution and hydration status may also influence appetite and dietary behavior. If energy intake remains chronically below energy expenditure, astronauts may develop negative energy balance, resulting in loss of body mass and lean tissue. Inadequate energy availability may also compromise muscle protein synthesis and reduce the effectiveness of exercise-based countermeasures designed to maintain muscle and bone health (Smith *et al.*, 2021)^[9].

Adequate energy availability should therefore be considered a foundation of space nutrition. Individual energy requirements vary according to body size, age, sex, body composition, physical activity, exercise workload, mission duration, environmental conditions, and metabolic adaptation. The increased exercise requirements used to counteract microgravity-induced muscle and bone loss may further influence energy expenditure during long-duration missions (Smith *et al.*, 2021)^[9]. Consequently, energy

requirements should ideally be individualized rather than based exclusively on a single population-level recommendation.

Current astronaut nutrition standards rely substantially on established terrestrial dietary reference values and energy requirements, adjusted where necessary for mission-specific conditions. However, uncertainty remains regarding the extent to which microgravity, altered fluid distribution, radiation exposure, confinement, and prolonged exercise modify energy metabolism and nutrient requirements. NASA has identified inadequate food and nutrition as an important human-health risk, particularly for exploration missions where opportunities for resupply are limited and food-system resources must be carefully managed (National Aeronautics and Space Administration [NASA], 2025) ^[31].

Accurate assessment of energy intake and expenditure is consequently an important research priority for future exploration missions. Traditional dietary records may be affected by under-reporting, menu complexity, and the operational constraints of spaceflight. Emerging technologies, including wearable activity monitors, physiological sensors, indirect calorimetry, metabolic biomarkers, digital food-recording systems, and automated dietary assessment, may improve estimation of individual energy requirements. Integration of these technologies with real-time physiological monitoring could allow dynamic adjustment of food intake according to changes in exercise workload, body composition, and metabolic status (Smith *et al.*, 2021) ^[9].

For future lunar and Martian missions, individualized energy management may become increasingly important because prolonged negative energy balance could impair physical performance and reduce the effectiveness of other physiological countermeasures. Therefore, future space nutrition programs should combine adequate energy availability with sufficient protein and micronutrient intake, structured exercise, regular assessment of body composition and metabolic status, and personalized dietary planning. Such an integrated approach may help maintain energy balance and preserve astronaut health during increasingly prolonged missions.

Protein and Amino Acid Requirements

Protein is particularly important because microgravity promotes muscle unloading and muscle atrophy. Resistance exercise can reduce these changes, but adequate protein and energy availability are also required to support muscle protein synthesis.

High-quality protein sources supplying essential amino acids, particularly leucine and other branched-chain amino acids, may be useful components of astronaut diets. However, increasing protein intake alone cannot completely prevent muscle loss. The interaction among protein intake, energy availability, exercise, hormonal regulation, and nutrient timing must be considered (Lane *et al.*, 2002) ^[21].

Long-duration missions may therefore benefit from distributing protein across meals rather than concentrating intake in a single meal. Future research should establish optimal protein quantity, quality, timing, and amino acid composition under different gravity environments and exercise conditions (Smith *et al.*, 2014) ^[46].

Carbohydrates and Dietary Fibre

Carbohydrates represent an important source of dietary energy and are particularly relevant to astronauts participating in regular aerobic and resistance exercise during spaceflight. Adequate carbohydrate availability supports physical activity by providing glucose for energy metabolism and by contributing to the maintenance of muscle glycogen stores. This is particularly important during long-duration missions, when astronauts are required to perform structured exercise as a primary countermeasure against microgravity-induced muscle and cardiovascular deconditioning (Smith *et al.*, 2021) ^[9]. Carbohydrate intake should therefore be sufficient to support energy requirements while being balanced with adequate protein and dietary fat to maintain overall nutritional adequacy.

The quality of carbohydrate sources is also important. Whole grains, fruits, vegetables, legumes, and other minimally processed plant foods can provide carbohydrates together with dietary fibre, vitamins, minerals, and phytochemicals. Such nutrient-dense foods may be preferable to highly refined carbohydrate sources because they contribute to overall dietary quality and provide multiple nutrients relevant to metabolic and gastrointestinal health (Smith *et al.*, 2021) ^[9]. However, the selection of carbohydrate sources in space is constrained by food processing requirements, storage stability, water availability, packaging, mass, volume, and shelf-life considerations.

Dietary fibre may have particular importance during long-duration spaceflight because changes in diet, confinement, stress, altered physiology, and the spaceflight environment may influence gastrointestinal function and the gut microbiome. Dietary fibre provides substrates for intestinal microbial fermentation and can contribute to normal bowel function. Research on spaceflight nutrition has identified gastrointestinal physiology and the gut microbiome as important areas for further investigation because alterations in microbial composition and function may influence immune regulation, metabolism, intestinal barrier integrity, and overall health (Smith *et al.*, 2017; Douglas *et al.*, 2020) ^[8, 41].

A diverse supply of plant-derived foods may therefore be advantageous because different types of dietary fibre—including soluble, insoluble, and fermentable fibres—can support different physiological and microbial functions. Fermentable fibres can serve as substrates for microbial production of short-chain fatty acids, which have important roles in intestinal and systemic physiology. Nevertheless, the effects of individual fibre types and the optimal amount of dietary fibre required during spaceflight remain insufficiently characterized. Moreover, reliance exclusively on isolated or highly processed fibre ingredients may not provide the same combination of micronutrients, phytochemicals, and food-matrix effects associated with a diverse diet rich in whole plant foods.

The potential relationship between dietary fibre and the gut microbiome is particularly relevant to exploration missions. Spaceflight-associated changes in the microbiome may be influenced by diet, environmental exposure, stress, and other physiological factors, and these changes could have implications for immune and gastrointestinal health (Voorhies *et al.*, 2019) ^[50]. Consequently, future space food systems should, where operationally feasible, incorporate a variety of fibre-containing plant foods and other nutrient-

dense carbohydrate sources rather than relying predominantly on highly processed foods.

Overall, carbohydrate intake during spaceflight should emphasize nutritional quality, adequate energy availability, and compatibility with exercise requirements. Whole grains, fruits, vegetables, legumes, and other nutrient-dense carbohydrate sources should be incorporated into astronaut menus whenever food-system constraints permit. Such an approach may simultaneously contribute to energy provision, dietary fibre intake, micronutrient adequacy, gastrointestinal function, and maintenance of a healthier gut microbial environment (Smith *et al.*, 2017; Smith *et al.*, 2021)^[9, 41].

Dietary Fat and Omega-3 Fatty Acids

Dietary fat is a concentrated source of energy and is important for cell membranes, hormone synthesis, and absorption of fat-soluble vitamins. The quality of dietary fat may be more important than simply total fat intake.

Omega-3 fatty acids have received particular interest because of their potential roles in inflammation, cardiovascular function, bone metabolism, and oxidative stress. However, the precise dosage and long-term effectiveness of omega-3 supplementation as a spaceflight countermeasure require additional research.

Future menus should aim for appropriate proportions of unsaturated fats while limiting excessive saturated fat and highly processed foods (Douglas *et al.*, 2020)^[8].

Micronutrient Requirements

1. Vitamin D

Vitamin D is a major nutritional concern because astronauts have little or no direct exposure to sunlight during spaceflight. Adequate vitamin D is essential for calcium metabolism and skeletal health, and it also contributes to immune and muscle function (Jesús, 2025)^[19].

NASA identifies vitamin D among the specific nutrients requiring attention during long-duration missions. Dietary provision and supplementation may therefore be necessary, with status monitored using biochemical measurements (Gomes *et al.*, 2026)^[12].

2. Calcium

Calcium is essential for skeletal mineralization and neuromuscular function (Nguyen *et al.*, 2025)^[33]. Microgravity-induced bone loss increases the importance of maintaining adequate calcium availability. Calcium metabolism during spaceflight is closely associated with bone resorption and changes in urinary calcium excretion.

Adequate calcium intake should be combined with vitamin D sufficiency and mechanical loading through exercise to support skeletal health (Binesh *et al.*, 2026)^[2].

3. Iron

Iron metabolism during spaceflight is complex. Changes in red blood cell mass and body-fluid distribution may influence iron biomarkers. Recent reviews have noted that iron levels may increase during spaceflight, suggesting that indiscriminate iron supplementation could be inappropriate. Individual assessment is therefore preferable to routine high-dose supplementation. Future nutrition programs should integrate iron intake with biomarkers of iron status, erythropoiesis, inflammation, and hemolysis (López Garzón *et al.*, 2025)^[26].

4. Folate and other B vitamins

Folate and B vitamins participate in DNA synthesis, methylation, red blood cell production, and energy metabolism. NASA identifies folate among nutrients of particular interest in spaceflight nutritional assessment.

Because long-duration missions may involve limited food diversity and prolonged storage, maintaining adequate levels of heat- and storage-sensitive vitamins represents an important food-system challenge (Schmidt and Schmidt, 2025)^[39].

5. Antioxidant nutrients

Vitamin C, vitamin E, carotenoids, selenium, and other antioxidant compounds may help maintain redox balance. Oxidative stress is a significant concern in spaceflight because of radiation, altered metabolism, and other environmental stressors.

However, antioxidant supplementation should not be interpreted as a substitute for a diverse diet. Excessive supplementation can itself produce adverse effects and may interfere with normal redox signaling (Gómez *et al.*, 2021).

Bone Health and Nutritional Countermeasures

Bone loss is one of the most important long-duration spaceflight health concerns. Reduced mechanical loading stimulates bone resorption and can increase urinary calcium loss. This creates a potential risk of decreased bone strength during and after missions.

Nutritional management should include:

- Adequate energy intake.
- Sufficient dietary protein.
- Appropriate calcium intake.
- Vitamin D sufficiency.
- Adequate magnesium and phosphorus.
- Regular resistance and weight-bearing exercise where feasible.
- Monitoring of bone-related biomarkers.

Nutrition alone cannot fully counteract microgravity-induced skeletal unloading. The most effective strategy is likely to combine diet, exercise, pharmacological approaches where appropriate, and individualized monitoring (Stavnychuk *et al.*, 2020)^[47].

Muscle Loss and Physical Performance

Muscle atrophy and loss of strength are well-established consequences of reduced gravitational loading. Astronauts may experience reductions in muscle mass, strength, and aerobic capacity despite structured exercise programs (Smith *et al.*, 2012; Pavy-Le Traon *et al.*, 2007)^[36, 44]. Protein and amino acids are central to muscle maintenance, while adequate energy availability helps prevent the body from using amino acids as an energy source. Nutrient timing around exercise may also influence muscle protein synthesis (Phillips & Van Loon, 2011; Jäger *et al.*, 2017)^[18, 37]. The combination of resistance exercise, adequate protein, sufficient energy, and appropriate micronutrient intake should therefore be considered a central nutritional strategy for maintaining physical performance during spaceflight (Smith *et al.*, 2012; Jäger *et al.*, 2017)^[41, 44].

Cardiovascular Health

Spaceflight produces substantial cardiovascular adaptations, including changes in blood volume, vascular function, and orthostatic tolerance. Nutrition may influence these changes

through energy intake, fluid and electrolyte balance, dietary quality, and micronutrient status (Smith *et al.*, 2012; Watenpaugh, 2001)^[44, 52].

Sodium and fluid intake require careful management because fluid redistribution occurs during microgravity. Dietary patterns that support cardiovascular health on Earth—rich in plant foods, fibre, unsaturated fats, and micronutrients—may also provide benefits during spaceflight, although space-specific requirements require further study (Smith *et al.*, 2012; Heer & Smith, 2008)^[16, 44].

Immune Function

Spaceflight is associated with alterations in immune regulation. Nutritional deficiencies can exacerbate immune dysfunction, whereas adequate protein, essential fatty acids, vitamins, minerals, and antioxidant compounds support normal immune processes.

Nutrients such as vitamin D, zinc, selenium, vitamin C, vitamin E, folate, and protein are therefore relevant to immune nutrition. Nevertheless, the immune system is influenced by multiple stressors—including sleep disruption, psychological stress, radiation, and microgravity—making isolated nutrient interventions difficult to evaluate (Dakkumadugula *et al.*, 2023)^[6].

Gastrointestinal Health and the Gut Microbiome

The gastrointestinal system is increasingly recognized as an important target of space nutrition research. Changes in diet, confinement, psychological stress, radiation exposure, and altered physiology may influence the composition and function of the gut microbiome (Mora *et al.*, 2020; Winer *et al.*, 2026)^[28, 53]. The gut microbiome participates in nutrient metabolism, immune regulation, intestinal barrier function, and production of bioactive metabolites, making it potentially important for maintaining astronaut health during prolonged missions (Mora *et al.*, 2020^[28]; Qi *et al.*, 2023). A diet containing adequate fibre and diverse plant-derived substrates may help support a diverse and functional microbial community, although the optimal dietary composition for maintaining microbiome health during spaceflight remains uncertain (Mora *et al.*, 2020)^[28]. A major research priority is therefore to determine whether targeted probiotics, prebiotics, fermented foods, or specific dietary components can provide reliable health benefits during long-duration missions. The potential interactions among the microbiome, immune system, metabolism, and radiation response make this an important multidisciplinary area of research (Winer *et al.*, 2026)^[53]. Alteration of gut microflora has also been identified as a priority area in space nutrition research, highlighting the need for further investigation of microbiome-directed nutritional countermeasures (Warriner *et al.*, 2017)^[51].

Hydration and Fluid-Electrolyte Balance

Fluid redistribution is an immediate physiological consequence of microgravity. Astronauts experience shifts of body fluids toward the upper body, accompanied by changes in plasma volume and cardiovascular regulation.

Adequate fluid intake is necessary to maintain hydration, cardiovascular function, renal function, and exercise performance. At the same time, electrolyte intake must be balanced with fluid requirements and individual physiological status.

Historical studies indicate that fluid intake may be lower than predicted during space missions. Therefore, monitoring hydration status should form part of routine nutritional assessment (Graebe *et al.*, 2004)^[14].

Oxidative Stress and Radiation Protection

Oxidative stress is generated by multiple aspects of spaceflight, including exposure to ionizing radiation and physiological adaptations to microgravity. These conditions can increase the production of reactive oxygen species (ROS), which may damage lipids, proteins, and DNA when antioxidant defenses are insufficient (Dakkumadugula *et al.*, 2023; Winer *et al.*, 2026)^[6, 53].

A diet rich in antioxidant-containing foods may provide a broad spectrum of protective compounds. Fruits, vegetables, whole grains, nuts, seeds, and legumes provide vitamins, minerals, carotenoids, polyphenols, fibre, and other bioactive compounds that may contribute to antioxidant defenses and overall physiological resilience. Evidence from astronauts on 4–6-month International Space Station missions has also shown that greater fruit and vegetable intake was associated with higher vitamin C status and lower markers of inflammation and oxidative stress (Smith *et al.*, 2021)^[9].

Nevertheless, the use of high-dose antioxidant supplementation specifically for radiation protection requires careful evaluation. Current evidence suggests that antioxidant countermeasures may have potential, but their effectiveness depends on the specific compound, dose, timing, and physiological context, and further research is required before routine high-dose supplementation can be recommended for spaceflight (Bergouignan *et al.*, 2021; Winer *et al.*, 2026)^[1, 53]. Nutritional protection should therefore emphasize maintaining adequate physiological antioxidant capacity through a diverse and nutritionally adequate diet rather than relying primarily on megadose supplements.

Space Food Systems

The food system is a critical engineering and nutritional component of crewed missions. Space food must be safe, nutritionally adequate, stable over extended periods, convenient to consume, and acceptable to astronauts. NASA notes that space food systems must address constraints related to mass, volume, power, storage, preparation, crew time, and individual food preferences (Cooper *et al.*, 2011; NASA, 2023)^[4, 6].

Current space foods commonly include rehydratable foods, thermostabilized foods, natural-form foods, beverages, and specially packaged products. Packaging must protect food from microbial contamination and maintain product quality while also minimizing crumbs and free-floating particles that could interfere with spacecraft equipment and crew activities (Cooper *et al.*, 2011^[4]; NASA, 2023).

For future exploration missions, these challenges become more demanding because resupply opportunities may be limited or unavailable. Food systems designed for missions to Mars and other destinations beyond low-Earth orbit will therefore require greater shelf stability, nutritional reliability, variety, and resource efficiency than systems developed primarily for low-Earth orbit (Douglas *et al.*, 2021^[9]; NASA, 2023). NASA's advanced food-system research consequently focuses on developing technologies

and food products capable of supporting crew health and performance during missions beyond low-Earth orbit.

Sensory Changes and Food Acceptability

Food acceptability is an important determinant of dietary intake. Astronauts may experience changes in taste and smell during spaceflight, which can influence appetite and food preference. If foods become less appealing, energy and nutrient intake may decline.

Consequently, menu development should consider:

- Flavour intensity.
- Texture.
- Aroma.
- Variety.
- Familiarity.
- Cultural food preferences.
- Meal presentation.
- Psychological satisfaction.

Food is not merely a nutrient-delivery system. It also provides comfort, routine, social connection, and psychological stimulation. Maintaining food enjoyment may therefore help preserve adequate intake and crew morale.

Food Safety and Shelf-Life Challenges

Food safety is especially important during spaceflight because medical and food-production resources are highly limited aboard spacecraft, and a foodborne illness could compromise crew health and potentially jeopardize mission objectives (Cooper *et al.*, 2011; Douglas *et al.*, 2021)^[4, 9].

Space foods must therefore undergo stringent processing, packaging, microbial control, and shelf-life testing. NASA's food-system research has demonstrated that nutritionally adequate and microbiologically safe food systems can support missions of approximately six months, while longer-duration exploration missions introduce additional challenges related to food stability and nutritional adequacy (Cooper *et al.*, 2011; NASA, 2023)^[4, 6].

Future food systems will need to address nutrient degradation during prolonged storage. Vitamins and other bioactive compounds may deteriorate over time as a result of factors such as temperature, oxygen, light, moisture, and food-processing conditions. Consequently, food formulation and packaging should be considered together to preserve nutritional quality and ensure food safety throughout long-duration missions (Cooper *et al.*, 2011; Douglas *et al.*, 2021)^[4, 9].

Nutritional Assessment During Spaceflight

Nutritional assessment is essential for identifying deficiencies and evaluating the effectiveness of countermeasures. NASA's nutritional assessment activities include dietary intake monitoring, body-mass measurements, and biochemical assessment of blood and urine (Hardy *et al.*, 2025)^[15].

Important indicators may include:

- Body mass and body composition.
- Energy and protein intake.
- Vitamin D status.
- Calcium metabolism.
- Iron status.
- Bone turnover markers.

- Muscle-related biomarkers.
- Hydration status.
- Oxidative stress markers.
- Immune markers.
- Gastrointestinal and microbiome parameters.

Future missions may increasingly rely on minimally invasive or non-invasive technologies for continuous monitoring.

Precision Nutrition in Space

Astronauts differ in genetics, metabolism, body composition, sex, age, fitness, dietary preferences, and physiological responses to spaceflight. Consequently, a standardized diet may not provide optimal nutritional support for every crew member. Precision nutrition offers a potential approach by integrating individual dietary intake, metabolic measurements, physiological biomarkers, genetic characteristics, microbiome profiles, physical activity, and mission-specific conditions to develop more individualized nutritional strategies (Matsumoto *et al.*, 2014; Ordovas *et al.*, 2018)^[27, 34]. NASA's current nutritional research includes detailed dietary assessment and biochemical monitoring, as well as investigations into how genetics may influence nutritional requirements during spaceflight.

Recent research has proposed combining precision nutrition with food biomanufacturing and intelligent life-support systems for long-duration missions. Such integrated approaches could support more individualized nutritional interventions while also enabling on-demand production of selected nutrients and other biologically important compounds during missions where resupply is limited (Zhang *et al.*, 2026)^[54].

Artificial intelligence may further support dietary monitoring, nutritional-status prediction, menu optimization, inventory management, and personalized recommendations. NASA is actively investigating AI, machine learning, digital twins, and multimodal data integration for precision health and real-time health decision-making during long-duration spaceflight. However, these technologies require rigorous validation under operational spaceflight conditions before they can be routinely used for individualized nutritional decision-making.

Sustainable Food Production for Long-Duration Missions

Resupply from Earth is feasible for the ISS but becomes increasingly difficult and expensive for lunar or Martian missions. Future missions will therefore require greater independence from Earth-based food supplies.

Potential approaches include:

- Controlled-environment agriculture.
- Hydroponic and aeroponic crop production.
- Plant-based food production.
- Microbial biomass production.
- Algae and fermentation systems.
- Cellular and biotechnological food production.
- Nutrient recycling.
- In-situ resource utilization.

Plant cultivation could provide not only food but also psychological benefits, carbon dioxide utilization, oxygen production, and water recycling. NASA's future food

research increasingly considers food systems as integrated components of spacecraft life support rather than isolated meal-provisioning systems.

Major Nutritional Challenges in Long-Duration Missions (Tang *et al.*, 2021; Smith *et al.*, 2005)^[42, 48]

The major nutritional challenges can be summarized as follows:

Challenge	Nutritional implication	Potential strategy
Reduced energy intake	Weight and muscle loss	Individualized energy monitoring
Microgravity	Bone and muscle loss	Protein, calcium, vitamin D + exercise
Radiation	Oxidative and cellular stress	Nutrient-dense antioxidant-rich diet
Limited sunlight	Vitamin D risk	Dietary vitamin D/supplementation
Altered iron metabolism	Risk of inappropriate iron intake	Individual biomarker monitoring
Fluid redistribution	Hydration and electrolyte changes	Fluid/electrolyte monitoring
Altered taste and smell	Reduced food intake	Flavour and menu optimization
Confinement	Appetite and dietary behaviour changes	Menu variety and psychological support
Gut microbiome alterations	Gastrointestinal and immune effects	Fibre, diverse plant foods, targeted interventions
Long storage	Nutrient degradation	Advanced formulation and packaging
Limited resupply	Food-system sustainability	In-situ food production
Individual variability	Different nutritional needs	Precision nutrition

Nutritional Countermeasures: An Integrated Approach

Nutrition should not be considered independently from other countermeasures. The strongest strategy is likely to integrate nutrition with exercise, sleep management, pharmacological interventions where appropriate, environmental control, psychological support, and continuous health monitoring (Trappe *et al.*, 2007)^[49].

An integrated nutritional countermeasure program may include:

1. Adequate energy intake.
2. Sufficient high-quality protein.
3. Appropriate carbohydrate and healthy fat intake.
4. Calcium and vitamin D optimization.
5. Individualized iron management.
6. Adequate fibre and plant-derived bioactive compounds.
7. Appropriate hydration and electrolyte intake.
8. Regular resistance and aerobic exercise.
9. Dietary monitoring and biochemical assessment.
10. Menu personalization.
11. Food safety and shelf-life control.
12. Sustainable food production for exploration missions.

NASA's Human Research Program continues to identify research gaps involving nutritional requirements, food-system safety and acceptability, countermeasure development, and validation under analog and flight conditions.

Implications for Human Health on Earth

Research in space nutrition also has important terrestrial applications. Astronauts experience conditions that resemble several Earth-based health challenges, including immobilization, muscle wasting, bone loss, ageing-related physiological changes, confinement, circadian disruption, and altered metabolism.

Consequently, research into nutritional countermeasures for spaceflight may contribute to strategies for preventing muscle and bone loss during hospitalization, rehabilitation, ageing, prolonged bed rest, and other conditions associated with physical inactivity.

The reciprocal relationship between space nutrition and terrestrial nutrition research makes bioastronautics an important field for understanding human adaptation and nutritional resilience.

Conclusion

Nutrition is a fundamental determinant of astronaut health, performance, and mission success. Spaceflight creates a complex nutritional environment in which microgravity, radiation, confinement, circadian disruption, altered appetite, limited food variety, and restricted resupply interact to influence energy balance, muscle and bone metabolism, cardiovascular function, immune regulation, gastrointestinal health, and oxidative status. Adequate energy and high-quality protein, together with appropriate calcium, vitamin D, iron, fibre, essential fatty acids, vitamins, minerals, and bioactive compounds, are important components of an effective nutritional strategy.

However, the nutritional requirements of astronauts cannot be fully addressed using conventional terrestrial dietary recommendations. Long-duration exploration missions will require individualized nutritional assessment, integrated countermeasures, highly stable and acceptable foods, improved monitoring technologies, and sustainable food-production systems. Current NASA research emphasizes that nutritional requirements, food-system constraints, and nutritional countermeasures remain important areas of investigation for future exploration missions.

The future of space nutrition is therefore moving from a simple model of transporting food from Earth toward a more sophisticated model of precision, personalized, sustainable, and bioregenerative nutrition. Integration of nutrition science with food technology, microbiology, biotechnology, artificial intelligence, exercise physiology, and human systems engineering will be essential for enabling safe and successful long-duration missions to the Moon, Mars, and beyond.

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