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Space Food: Feeding Astronauts Beyond Earth

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ABSTRACT: Space food is a specialized category of sustenance designed to meet the unique challenges of space travel, ensuring astronauts receive essential nutrients while maintaining health and morale during their missions. Given the constraints of microgravity, space food must be compact, lightweight, have a long shelf life and require minimal preparation. Foods like thermostabilized entrees, freeze-dried snacks, tortillas and powdered beverages are commonly used with each designed to cater to specific needs in space. Challenges such as loss of appetite, bone and muscle loss and limited fresh food availability are addressed through fortified meals, while innovative solutions like 3D-printed food, space farming and microbial protein production are being explored to improve food sustainability on long-duration missions. These advancements are essential for future space exploration, particularly for missions to the Moon, Mars and beyond.

Keywords: Space food, 3D printed food, Space Farming, Artificial Intelligence, Food Safety.

The evolution of space food: The evolution of space food reflects advancements in space exploration, transitioning from rudimentary cubes and puréed meals in the 1960s to sophisticated, culturally diverse diets designed for long-term missions. Early missions prioritized basic nutrition, but the Gemini and Apollo programs introduced freeze-dried and vacuum-sealed foods, improving variety and morale. The Space Shuttle era added fresh items, thermostabilised meals and personalized menus to enhance psychological well-being. On the ISS, international collaboration expanded meal diversity and introduced in-space agriculture, such as growing fresh lettuce. Innovations like 3D food printing and hydroponics are now shaping sustainable systems for future deep-space missions, emphasizing nutrition, variety and self-sufficiency.

Characteristics of Space Food: Space food plays a vital role in ensuring the health, safety and morale of astronauts on extended missions. The unique conditions of space, including microgravity, limited storage, long-duration space travel and radiation exposure, present numerous challenges for food design. Therefore, space food must possess a set of characteristics that guarantee its effectiveness in these extreme conditions. Below is a comprehensive review of these characteristics, along with relevant literature.

1. Long Shelf Life. Space food must have a long shelf life, remaining safe, nutritious and palatable for months or even years without refrigeration, a necessity for missions beyond low Earth orbit where resupply is impossible. Key characteristics include extended shelf stability to preserve nutrients, flavor and texture, as well as strict food safety to prevent microbial growth. Innovations such as freeze-drying, which removes water to extend shelf life while preserving nutrients and flavor and thermostabilization, which uses heat to destroy bacteria and enzymes, have been pivotal. Perchonok *et al.* (2012) emphasized the importance of shelf life for deep-space missions, while Smith *et al.* (2005) highlighted the challenge of maintaining nutrient stability, particularly for vitamins and minerals, during prolonged storage.

2. Lightweight and Compact. Space food must be lightweight and compact to optimize spacecraft resources by minimizing the mass and volume of cargo, essential for efficient space missions. This is achieved by reducing water content through freeze-drying and similar preservation methods, significantly lowering weight and using flexible, durable packaging to save storage space. Innovations such as vacuum-sealing and retort pouches enhance food preservation while reducing bulk and space-saving meal kits include dehydrated foods in compact pouches that expand upon rehydration. NASA (2001) reported that freeze-drying and vacuum-sealing could reduce food weight by up to 80%, while Cooper *et al.* (2011) highlighted the convenience and manageability brought by advanced packaging technologies.

3. Nutritional Adequacy. Space food must ensure nutritional adequacy by providing all essential macronutrients (proteins, carbohydrates, fats) and micronutrients (vitamins, minerals) required for long-duration missions. It must meet daily energy and nutritional needs, often customized for individual astronauts based on age, activity level and health conditions. To address the health challenges of space travel, such as bone loss and muscle atrophy, space food is fortified with nutrients like vitamin D, calcium and omega-3 fatty acids and personalized diets are being developed. Zwart *et al.* (2011) highlighted the importance of counteracting bone loss through diet, while Massa *et al.* (2016) emphasized that a balanced, supplemented diet is critical to mitigating the effects of microgravity on muscle and bone health.

4. Safety and Microgravity Suitability. Space food must be safe and suitable for consumption in microgravity, where traditional food preparation is unfeasible and floating particles can pose risks. Foods are designed to be crumb-free, minimizing hazards like choking or equipment interference and generate minimal waste through efficient packaging and utensils. Packaging must also withstand extreme temperatures and prevent leakage. Innovations include crumb-free options like tortillas and pre-portioned meals to reduce waste, along with reusable or recyclable packaging materials. Perchonok *et al.* (2012) highlighted the need to eliminate loose particles in microgravity, while Cooper *et al.* (2011) emphasized the importance of designing safe, particle-free foods to protect astronauts and spacecraft systems.

5. Palatability and Variety. Space food must be palatable and diverse to ensure astronauts enjoy their meals and avoid menu fatigue, which is vital for maintaining morale and psychological well-being. Microgravity dampens taste and smell, so foods are often enhanced with stronger flavors, spices and seasonings. A diverse menu, including international cuisines, helps reduce monotony and provides familiarity. Innovations such as flavor boosters, spice kits and fresh vegetables grown on the ISS enhance the sensory experience. Lane & Feeback (2002) emphasized the psychological benefits of variety in space food, while Massa *et al.* (2016) highlighted the positive impact of fresh produce like ISS-grown lettuce on astronauts' food satisfaction.

6. Ease of Preparation and Consumption. Space food must be easy to prepare and consume in microgravity, where traditional cooking methods are impractical. It should require minimal preparation, such as heating or rehydrating without complex tools and be convenient to reduce time spent on food preparation. Innovations like self-heating meal kits, which only need water to heat and hydration systems for freeze-dried soups, enhance ease of consumption. Douglas *et al.* (2009) highlighted the importance of ready-to-eat meals in reducing preparation time, while Cooper *et al.* (2011) emphasized the need for simple, quick food preparation to optimize astronauts' efficiency and time management.

7. Packaging and Waste Management. Packaging for space food must be durable, space-efficient and designed for easy disposal or recycling to address the significant concern of waste management in space. It must withstand the harsh conditions of space travel, including temperature fluctuations, pressure changes and radiation exposure, while generating minimal waste. Innovations like edible packaging materials reduce waste and provide additional nutrients, while recyclable or compostable materials are being explored to lessen the environmental impact. Smith *et al.* (2019) discussed advancements in packaging that ensure food safety and ease of handling, while Douglas *et al.* (2009) focused on reducing the environmental impact of packaging through biodegradable materials.

Popular Space Foods: Food plays an integral role in supporting astronauts' physical and mental well-being during space missions. Over the years, various types of foods have been developed and optimized to suit the unique conditions of space. This article explores popular space foods, their evolution and the literature surrounding their development.

1. Freeze-Dried Foods. Freeze-dried foods are lightweight, shelf-stable and retain much of their original flavor and nutrients, making them ideal for space missions. Prepared through sublimation, which removes water and leaves a porous texture for easy rehydration, they include items like freeze-dried fruits (strawberries, apples) and entrees (beef stew, spaghetti). Their long shelf life (3–5 years), ease of storage and transport and minimal nutrient loss make them highly advantageous. Perchonok *et al.* (2012) highlighted freeze-drying as a breakthrough in space food preservation, allowing food to maintain its flavor and nutritional content for extended periods, while NASA (2001) noted that freeze-dried foods accounted for a significant portion of the Apollo missions' diet due to their lightweight nature and ease of preparation.

2. Thermostabilized Foods. Thermostabilized meals are pre-cooked foods that undergo heat processing to kill bacteria and extend shelf life, allowing them to remain stable for months without refrigeration. Common examples include beef stew, chicken curry, spaghetti with meat sauce and vegetable lasagna. These meals are ready-to-eat, long-lasting and flavorful, requiring minimal preparation as they can be heated in a special food warmer or consumed directly from the pouch. Cooper *et al.* (2011) demonstrated that thermostabilized foods retain nutrients like protein and carbohydrates effectively for up to three years. Perchonok *et al.* (2012) emphasized the importance of thermostabilized entrees in creating variety and improving the palatability of space diets.

3. Rehydratable Foods. Rehydratable foods, dehydrated for reduced weight and volume, require water for consumption and are ideal for space missions due to their lightweight, compact nature and ease of use. Examples include scrambled eggs, instant oatmeal and soups, which can be quickly rehydrated using limited onboard water. Smith *et al.* (2005) noted that rehydratable foods significantly reduce launch weight while still offering adequate nutrition, while Douglas *et al.* (2009) reported that astronauts appreciate the convenience and flavor of rehydratable foods, especially for breakfast options.

4. Fresh Produce. Fresh produce, such as lettuce, radishes and microgreens, has become part of space diets due to advancements in onboard crop cultivation. These foods provide essential vitamins and minerals, contributing to a balanced diet for astronauts. Additionally, they offer psychological benefits by breaking the monotony of processed foods, enhancing morale and providing a sense of normalcy during long missions. Massa *et al.* (2016) detailed the success of the "Veggie" experiment on the International Space Station (ISS), enabling astronauts to cultivate and consume fresh lettuce in space. Similarly, Kozai *et al.* (2020) emphasized that fresh produce plays a vital role in supporting both physical health and mental well-being during long-duration missions.

5. Packaged Snacks. Packaged snacks, such as nuts, energy bars and trail mix, play a vital role in space missions by providing quick energy and boosting morale. These snacks are convenient, ready-to-eat and offer a sense of variety and comfort, making them an essential component of astronauts' diets during long missions. Lane and Feeback (2002) highlighted the crucial role of snacks in maintaining energy levels and boosting morale during long missions. Similarly, Perchonok *et al.* (2012) emphasized the importance of providing a variety of snacks to satisfy astronauts' cravings and address their psychological needs.

6. Commercial Off-The-Shelf (COTS) Foods. Commercial Off-The-Shelf (COTS) foods are commercially available products that are adapted for space by repackaging them into astronaut-friendly containers. Examples include tortillas, which are used instead of bread to minimize crumbs and candy like M&Ms. These foods offer the advantage of familiarity, which boosts crew morale and also help reduce development costs. Douglas *et al.* (2009) reported that tortillas became a staple on space missions due to their versatility and crumb-free nature, while Smith *et al.* (2009) highlighted the psychological benefits of familiar COTS foods, which provide astronauts with a reminder of home.

7. 3D-Printed Foods. 3D-printed foods are created by layering edible ingredients to produce customized meals tailored to individual nutritional needs. Examples include protein-based snacks and nutritionally balanced entrees. The advantages of 3D-printed foods include the ability to customize flavor, texture and nutrients, as well as reducing food waste by providing precise portions. NASA (2020) investigated the use of 3D printing to meet individual dietary needs and minimize packaging waste during long-duration missions. Massa *et al.* (2021) highlighted that 3D printing could facilitate real-time meal preparation, providing astronauts with greater variety and flexibility in their food choices.

8. Irradiated Foods. Irradiated foods are treated with ionizing radiation to eliminate pathogens and extend shelf life. Examples include beef steak and pork chops. This method ensures microbial safety while preserving the texture and flavor of food for longer durations, making it an effective preservation technique for space missions. Cooper *et al.* (2011) showed that irradiation effectively preserves the safety and quality of meat products for space missions, while Lane & Feeback (2002) highlighted the importance of irradiated foods in preventing foodborne illnesses in the confined environment of a spacecraft.

9. Beverages. Astronauts consume beverages in specially designed pouches to prevent spills in microgravity, with examples including coffee, fruit juices and electrolyte drinks. These beverages offer the advantages of hydration and nutrient supplementation, which are essential for astronauts' well-being during missions. Additionally, familiar drinks help boost morale, providing a sense of comfort and normalcy while in space. NASA (2015) developed rehydratable beverage pouches that enable astronauts to prepare drinks with minimal spillage, while Douglas *et al.* (2009) highlighted the psychological benefits of beverages such as coffee in helping astronauts maintain normal routines.

10. Food Supplements. Food supplements provide concentrated doses of essential nutrients that may degrade during storage, such as vitamin C tablets and omega-3 capsules. These supplements compensate for nutrient losses in stored foods and address specific dietary deficiencies. Smith *et al.* (2005) recommended supplementation of vitamins and minerals, particularly for long-duration missions where nutrient degradation is significant, while Douglas *et al.* (2009) highlighted their role in preventing health issues like bone loss and muscle atrophy.

Challenges in Space Nutrition: Ensuring astronauts' nutritional health in space is critical for the success of missions, especially as humanity ventures into long-term space exploration. However, several unique challenges arise due to the extreme environment of space. These challenges impact the formulation, storage, preparation and delivery of food systems. Below is a detailed analysis of the key challenges in space nutrition, supported by insights from scientific literature.

1. Microgravity-Induced Physiological Changes. Microgravity-induced physiological changes present key challenges for astronauts, including bone loss, muscle atrophy, fluid redistribution and alterations in taste and smell. Bone density loss occurs due to reduced gravitational loading, necessitating higher calcium and vitamin D intake, while muscle atrophy results from the absence of gravitational resistance, increasing the need for high-protein diets. Fluid shifts to the upper body affect digestion, nutrient absorption and appetite and changes in fluid distribution can dull taste perception, potentially reducing food intake. Smith *et al.* (2005) emphasized the importance of calcium and vitamin D supplementation to counteract bone demineralization, while Douglas *et al.* (2009) noted that dietary protein supplementation helps mitigate muscle loss. Additionally, Lane & Feeback (2002) reported that astronauts often experience reduced appetite and calorie intake due to altered taste and smell perceptions.

2. Nutrient Stability and Shelf Life. Nutrient stability and shelf life are key challenges for space food, as essential vitamins, particularly vitamins C and B, degrade over time during storage. Additionally, long-term storage can affect the texture and palatability of food, impacting its appeal and nutritional value. Developing preservation methods that maintain nutrient content without adding bulk or weight remains a significant challenge. Cooper *et al.* (2011) found that while thermostabilized and freeze-dried foods can retain nutrients for up to three years, sensitive vitamins still undergo significant degradation. Perchonok *et al.* (2012) emphasized the need for advanced packaging and preservation technologies to extend food shelf life while preserving both nutrient integrity and food quality.

3. Limited Space and Weight Constraints. Limited space and weight constraints are significant challenges in space food design, as spacecraft require foods that are both nutrient-dense and lightweight to maximize space efficiency and reduce payload weight. Many foods also require rehydration, which competes with the limited water resources available aboard spacecraft. NASA (2001) addressed these challenges by developing freeze-dried foods, which have become a staple in space nutrition due to their compactness and low weight. Douglas *et al.* (2009) emphasized the need for efficient water recycling systems to ensure sufficient water is available for rehydrating food during long-duration missions.

4. Food Safety in Space. Food safety in space is a critical concern due to the closed environment of spacecraft, which increases the risk of microbial growth and foodborne illnesses. Ensuring sterility in food packaging is essential to prevent contamination during both storage and consumption. Perchonok *et al.* (2012) highlighted the importance of sterilization techniques, such as radiation and thermostabilization, in maintaining the safety of space food. Cooper *et al.* (2011) identified multi-layered packaging as a significant advancement in preventing microbial contamination, contributing to the overall safety of food during space missions.

5. Radiation Effects on Food and Nutrition. Radiation exposure in space presents significant challenges for food and nutrition, as it accelerates the degradation of sensitive nutrients like vitamins A, C and E. Standard food packaging may not provide sufficient protection against this radiation, further compromising the nutritional quality of space food. Smith *et al.* (2005) noted that cosmic radiation exacerbates the instability of vitamins in stored foods, while Perchonok *et al.* (2012) emphasized the need for research into radiation-resistant packaging materials to safeguard both food and nutrients during long-duration space missions.

6. Psychological and Cultural Factors. Psychological and cultural factors play a crucial role in space food systems, as menu fatigue can lead to reduced food intake and dissatisfaction from the repetitive consumption of similar foods. Additionally, multinational crews require diverse food options to accommodate various cultural preferences and providing familiar comfort foods is essential for maintaining mental well-being during extended missions. Douglas *et al.* (2009) stressed the importance of offering culturally diverse menus to support crew morale and cohesion, while Massa *et al.* (2016) highlighted that incorporating fresh produce grown in space can help reduce menu fatigue and contribute to better psychological health.

7. Water Availability for Food Preparation. Water availability for food preparation is a significant challenge in space due to the limited water resources aboard spacecraft, which must be carefully managed to meet various essential needs. Efficient rehydration systems are critical to ensure that water is not wasted during the preparation of freeze-dried foods. NASA (2015) developed water-efficient rehydration systems to optimize water usage for this purpose, while Schmid *et al.* (2006) emphasized the need for integrated water recycling systems in spacecraft designs to ensure sustainable food preparation and conserve water for other uses.

8. Adaptation for Long-Duration Missions. Adaptation for long-duration space missions, such as those to Mars or deep space, presents significant challenges, particularly the need for self-sustaining food systems where astronauts must grow and process their own food. Ensuring that all essential nutrients remain available and stable over the course of multi-year missions is crucial. Massa *et al.* (2016) studied the "Veggie" project aboard the ISS, which successfully demonstrated the feasibility of growing crops like lettuce and radishes in space. Kozai *et al.* (2020) highlighted the importance of incorporating bioregenerative life support systems, such as hydroponic farming, into space mission planning to address these challenges.

9. Individual Nutritional Requirements. Individual nutritional requirements present a challenge for space missions, as astronauts have varying dietary needs based on factors such as age, gender and health status. Additionally, these needs evolve over time due to physiological adaptations and the demands of the mission. Smith *et al.* (2009) recommended implementing personalized nutritional plans to optimize astronaut health and performance during space missions, while Lane & Feeback (2002) emphasized the importance of monitoring individual dietary intake and making adjustments as needed throughout the mission to ensure astronauts receive the appropriate nutrition.

10. Emerging Research Needs. Emerging research in space food systems focuses on key challenges such as 3D food printing, bioregenerative systems and nutrient stabilization. 3D food printing offers the potential for creating customizable meals that meet diverse nutritional needs, while bioregenerative systems aim to provide sustainable methods for growing and recycling food in spacecraft. Additionally, finding innovative ways to stabilize essential nutrients over long durations is crucial for ensuring the health of astronauts. NASA (2020) explored the use of 3D food printing to create meals tailored to individual needs and Massa *et al.* (2021) highlighted the importance of integrated food production systems, such as algae-based bioreactors, for future space missions.

Innovations in Space Food: Space exploration requires continuous advancements in food technology to meet the nutritional, logistical and psychological needs of astronauts. From the early days of squeezable tubes to modern 3D food printing and in-space farming, the field of space food has undergone remarkable transformations.

1. Freeze-Drying Technology. Freeze-drying technology, which removes water from food through sublimation, has been a pivotal advancement in space food, offering lightweight, shelf-stable and nutritionally preserved options. Developed initially for the Apollo missions, freeze-drying continues to be essential in space food production. Key innovations include enhanced nutrient retention, improved flavor and better texture after rehydration, making it more palatable. Perchonok *et al.* (2012) recognized freeze-drying as a revolutionary method for reducing food weight while preserving its nutritional value and Cooper *et al.* (2011) emphasized its crucial role in long-duration missions where space and weight are limited.

2. Thermostabilization. Thermostabilization, which involves heat-treating food to eliminate pathogens and enzymes, ensures both safety and extended shelf life, making it ideal for space missions. It is commonly used for meals like stews and curries. Key innovations in this method include the development of retort pouches, which offer lighter and more flexible packaging, as well as advanced heating techniques that help preserve the texture and flavor of food. NASA (2001) noted that thermostabilized foods provided improved safety and flavor compared to earlier canned alternatives and Smith *et al.* (2005) highlighted its role in creating a more diverse and palatable menu for astronauts.

3. 3D Food Printing. 3D food printing involves creating customized meals by layering edible materials, allowing for tailored nutritional profiles based on individual astronaut needs and preferences. Key innovations in this technology include the ability to customize nutrient profiles, create a variety of textures and shapes that enhance palatability and morale and reduce food waste by using precise portions. NASA (2020) explored 3D printing as a sustainable solution for deep-space missions, enabling on-demand meal production, while Massa *et al.* (2021) emphasized its potential to improve meal variety and meet specific dietary requirements.

4. Space Farming. Space farming, or bioregenerative life support, is a crucial innovation for sustaining long-term space missions by enabling the growth of crops that provide fresh produce and recycle carbon dioxide into oxygen. Innovations in space farming include LED lighting systems for plant growth in microgravity and hydroponic and aeroponic systems that allow crops to grow without soil. Massa *et al.* (2016) highlighted the success of the "Veggie" experiment on the ISS, which allowed astronauts to grow and eat fresh lettuce, while Kozai *et al.* (2020) emphasized the significance of vertical farming systems in maximizing crop yield within the confined space of spacecraft.

5. Edible Packaging. Edible packaging is an innovative solution that reduces waste while providing additional nutrients, designed to be safe, biodegradable and nutritionally beneficial. Key innovations in this field include edible films made from proteins, polysaccharides, or lipids, as well as the integration of nutrients and flavors into the packaging. Douglas *et al.* (2009) highlighted the potential of edible packaging to address waste management challenges in space, while Miller *et al.* (2018) explored the use of edible films enriched with vitamins and minerals to supplement astronaut diets.

6. Bioengineered Foods. Bioengineered foods involve the genetic modification of plants, microorganisms, or cell cultures to produce high-value nutrients, proteins, or even complete meals. Key innovations include the use of algae and yeast to produce proteins and vitamins in space, as well as the development of cultured meat as a sustainable protein source. Smith *et al.* (2019) noted that algae-based systems could serve as a sustainable food source for long-duration missions, while Douglas *et al.* (2020) explored the potential of cultured meat production in microgravity, highlighting its ability to replace traditional protein sources.

7. Radiation-Resistant Packaging. Radiation-resistant packaging uses advanced materials to protect food from cosmic radiation, preserving both its safety and nutritional quality. Key innovations include multi-layered packaging with radiation-shielding properties and the integration of antioxidants to counteract radiation-induced nutrient degradation. Cooper *et al.* (2011) identified radiation-resistant packaging as a crucial research area for long-duration missions, while Perchonok *et al.* (2012) emphasized the need for innovative materials to safeguard sensitive nutrients during extended storage.

8. Nutrient Stabilization. New methods are being developed to stabilize vitamins and other sensitive nutrients in space food, ensuring their effectiveness over long durations. Key innovations include microencapsulation of nutrients to prevent degradation and the use of antioxidants to extend shelf life. Smith *et al.* (2005) recommended microencapsulation as an effective technique for stabilizing vitamins in space food, while NASA (2020) highlighted advancements in nutrient preservation techniques, particularly for long-duration missions to Mars.

9. Ready-to-Eat Meals (RTEs). Ready-to-eat meals (RTEs) are pre-packaged, fully cooked foods designed for minimal preparation, offering a wide range of dishes with improved flavor and texture. Key innovations in RTEs include advanced heat stabilization techniques that enhance flavor and the expansion of culturally diverse menu options. Lane & Feeback (2002) highlighted the importance of RTEs for quick and convenient consumption in microgravity, while Douglas *et al.* (2009) emphasized that offering variety in RTEs helps prevent menu fatigue during long-duration missions.

10. Functional Foods and Supplements. Functional foods and supplements are designed to offer health benefits beyond basic nutrition, addressing issues such as bone loss, muscle atrophy and immune suppression in space. Key innovations include fortifying foods with omega-3 fatty acids, probiotics and antioxidants, as well as offering personalized supplements tailored to individual astronaut needs. Smith *et al.* (2005) recommended omega-3 supplements to mitigate bone and muscle loss, while Zwart *et al.* (2011) studied the benefits of antioxidant-enriched diets in reducing oxidative stress during space missions.

11. Artificial Intelligence (AI) in Space Food Management. Artificial Intelligence (AI) is increasingly being utilized in space food management to optimize meal planning, monitor nutrient intake and minimize food waste during missions. Key innovations include real-time tracking of individual astronaut dietary needs and predictive analytics for food inventory management. Perchonok *et al*. (2012) suggested integrating AI to enhance space food systems for long-term missions, while Douglas *et al.* (2020) highlighted that AI-based solutions could improve efficiency and reduce the logistical burden of food management in space.

CONCLUSIONS

In conclusion, space food is an essential component of successful space missions, combining innovation, nutrition, and psychological considerations to ensure astronaut health and well-being. Through advancements in food technology, including freeze-drying, thermostabilization, and emerging techniques like 3D food printing and space farming, space food systems have evolved to meet the unique challenges of space travel. As exploration extends to the Moon, Mars, and beyond, continued innovation in space food will be critical for supporting astronauts on longer missions, ensuring they are well-nourished, healthy, and prepared for the challenges of deep-space exploration.

FUTURE SCOPE

The future of space food lies in developing sustainable, nutritious and personalized solutions to support long-duration space missions and extraterrestrial colonization. Advancements in onboard farming, such as hydroponics, aeroponics and cultured meat, will enable fresh food production in space, while bioengineered crops and microorganisms will address the challenges of microgravity and resource scarcity. Innovative preservation techniques, closed-loop recycling systems and automation will enhance efficiency and minimize waste. Additionally, space food research will pave the way for personalized diets, multifunctional foods with therapeutic benefits and collaborative innovations with the food industry, benefiting both astronauts and addressing global food challenges on Earth.

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