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Advances in space food processing: From farm to outer space

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ABSTRACT

Space is the final frontier and mankind has long desired to explore the vast expanse of the universe in the pursuit of finding new worlds. The need for nutritious and long-lasting food during deep space missions have however, been an impediment to this quest. Although challenging, researchers from different public and private space organizations and institutes have come together striving hard to develop food processes, product quality and safety protocols for advancing the field of space foods. Even NASA has proposed nanomaterial-based packaging to preserve space foods longer than 5 years. Therefore, a fresh outlook is required on processing and packaging technologies currently adopted for the preparation of space foods. This review provides an overview of the inception of space foods followed by its physico-chemical and microbiological quality considerations, and processing and packaging technologies. The market opportunities available for space foods has also been covered highlighting the major players in the space food processing sector. Literature review indicates that freeze-drying has been used as a space food preservation technology of choice for years, but the combination of high-pressure processing and thermal treatment is now gaining attention due to its potential in extending the shelf life of space foods upto 5 years. Besides, 3D printing has also emerged as an economically viable technology for producing more nutritious and organoleptically appealing space foods. Currently, the major constraint for space food research is simulating the environment of space for testing food processes and packaging materials which could be explored.

1. Introduction

With the advancement in space exploration technologies, the concept of deeper space missions is now within grasp. Prolonged space missions necessitate the requirement of space food that can be preserved for years and could fulfil the nutritional requirements of astronauts. Hence, space food, also known as astronaut food, is specially designed and prepared for consumption in the unique environment of space. Since German Titov, a Soviet cosmonaut, became the first person to eat in space in August 1961, space food has been transforming into more advanced forms (Perchonok & Bourland, 2002). Processing of food for space missions makes this category of edibles different from regular foods that is consumed on Earth. The main disparity between space and regular food lies in their preservation methods, packaging, nutritional content, and taste/texture considerations, all of which are tailored as per the unique needs and constraints of space exploration. The food processed for space comply with strict specifications imposed by spacecraft design and mission durations. However, the quality of space foods has

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since improved due to the advancements in spacecraft habitability. The need for improved nutrition, variety, taste, and ease of consuming foods increases for extended space missions. Moon missions are anticipated to last for 20 to >30 days (Evans & Graham, 2020), but Mars missions are anticipated to last anywhere between 800 and 1100 days, with 500 days or so expected to be spent on the surface of Mars (Douglas et al., 2020; Simonsen et al., 2020). For success of such extended missions, a steady supply of nutritious food that satisfies the crew's dietary and psychological demands must be made available. Advances in food processing research has made it possible to have different varieties of foods for the astronauts posted at the International Space Station (ISS). The main objective of space food processing is to offer palatable foods with taste comparable to the ones that are consumed on Earth. Extended planetary missions will call for considerably more innovation and technology. The food that astronauts presently consume at ISS or outer space are cultivated and processed on Earth, these are passed through different processes to include dehydration, canning and soft-packaging as puree. Space food processing majorly focuses on shelf life of the product. Earlier, the shelf life of space foods was limited to 2.5 years, which was suitable for shorter space missions (Cooper et al., 2011) but with the advent of longer missions such as the Mars mission, the task of increasing the shelf life to 5 years is being focussed upon (Douglas et al., 2020).

The development of space food is a collaborative effort involving different government agencies such as the National Aeronautics and Space Administration (NASA), European Space Agency (ESA), Russian Space Agency and even private companies (SpaceX, Blue Origin, and Virgin Galactic), along with research institutions. These organizations work together to create nutritious, palatable, and sustainable food options for astronauts and other space travellers. Some of the famous space foods that are currently available includes astronaut ice cream, space bars, vacuum-packed meals, dehydrated fruits and vegetables, rehydratable fruit juices, and sports drink tubes of pureed food. Space foods are processed to be lightweight, easy to store, and nutrient-dense, simultaneously catering to the need of variety and a pleasant eating experience for astronauts.

Considering the vast expanse of the mysterious universe surrounded with aura of curiosity and quest for mankind in space, this review focuses on the salient points needed to be considered for processing of space foods. The review highlights different quality considerations of space food products, advancements in processing technologies along with possible perspectives for research in this area.

2. Quality considerations for space foods

2.1. Physico-chemical quality

Proper intake of nutrition during space missions is critical for the health and social psychology of the astronauts. Foods prepared for space missions are compact, light weighted, easily portable and able to withstand the harmful effects of radiation, vibration, and other environmental variables such as low pressure. Beverages such as coffee, apple cider, tea and orange juice are sent in powdered form which are rehydrated in space. Salt and pepper are used in liquid form as they cannot be sprinkled in space due to the danger of clogging of particles in the spacecraft. Additionally, flour tortillas used for making sandwiches and condiments such as mayonnaise, mustard, ketchup are supplied in their regular form (Pandith et al., 2022). According to Watkins et al. (2022), for space, dried food products are more convenient than fresh food as they are light in weight, less susceptible to changes by radiation, microbiologically safe (due to low water activity), convenient for micronutrients fortification and have less occurrence of chemical reactions, therefore, minimum effect on product quality. John Glenn, whose mission was for just 5 h, was the first person who tested the space food (applesauce and xylose sugar tablets with water) in weightlessness conditions of space, to make the design of future space foods easy. He experienced easy consumption, swallowing and digestion of food in space just like on Earth but with reduced ability of taste bud to recognize flavors in zero gravity (National Aeronautics and Space Administration, 2004). Therefore, to enhance the flavor perception in space, Obrist et al. (2019) designed the spice bomb mix which is a flavor-enhancing seasoning. This mix has various spice ingredients put into a single container that is shaken and mixed before dissolving in the food.

On the other hand, on the mercury mission (1961–1963), apple sauce from toothpaste-like tubes, freeze-dried food and small-bite sized dehydrated cubes (0.5 inch^3) that were rich in protein, fat, sugar, fruits, and nuts were successfully ingested by astronauts. However, it was not appealing and tempting for astronauts due to difficulty in squeezing the food from the tube, rehydrating the food, and floating of crumbs from bite sized cubes. Additionally, there was a risk associated with food cubes and their tiny crumbs blocking the instruments or entering the eyes, mouth, and nose of astronauts (Perchonok & Bourland, 2002). This problem was rectified in the next mission i.e., Gemini (1965–1966). At this time, the bite size dehydrated cubes were coated with edible gelatin to reduce the crumbling. Along with food items that were used in the mercury mission, a variety of other food products such as bread cubes toasted with cinnamon, chocolate cubes, fruit as well as shrimp cocktail, fruit drinks, beef stew, butterscotch pudding, chicken, rice, turkey, and gravy with improved packaging were used for the crews. However, crews faced various challenges in both the missions that included difficulty in rehydrating the food, unable to see or smell the food taken directly from the tube and also, food was in the minced form that was unappetizing and hence, astronauts lost weight during these missions (NASA, 1999; Tang et al., 2021). After receiving their feedback, various advancement in food were introduced in the Apollo mission (1968–1972) as for the first time, hot water was available (onboard) that was produced as a by-product from the fuel cells which enabled easy rehydration of food and improved the taste as compared to the Mercury and Gemini missions, as water used in those missions was under ambient temperature. In addition to this, the food was also thermostabilized (wet packs) so that it remained moist and could stick to the eating spoon when taken out from packs. During this period irradiated food was also introduced (Perchonok et al., 2012). Therefore, coffee, bacon squares, cornflakes, scrambled eggs, cheese crackers, beef sandwiches, chocolate pudding, tuna salad, peanut butter, beef pot roast, spaghetti, and frankfurters were also consumed in the Apollo mission (Casaburri & Gardner, 1999). It was observed during the mission that, due to crumbliness and decrease in freshness of bread, sandwiches were not found ideal for space eating (Uri, 2020).

Food scientists have strived to make space foods far tastier than before and also introduced 72 different food items in the Skylab mission (1971–1973) such as ice-cream, lobsters, chilled drinks, desserts, filet steak as refrigerators and food heaters were made available for crew members (Jiang et al., 2020). In the Space Shuttle Program (ISS), three balanced meals were provided along with snacks that included thermostabilized butterscotch pudding and peach yogurt, rehydratable coffee, cream, shrimp and cocktail, intermediate moisture apricots, beef tips and mushrooms, and fresh fruits as well as vegetables (Pandith et al., 2022). There was an upgradation in this station as the crew's urine was processed by vapor compression distillation unit and further purified to get clean drinking water. This technology was introduced with the aim to reduce the cost of resupply in future missions to the moon, Mars or beyond. According to Grace Douglas, the lead scientist of NASA's Advanced Food Technology division, addressing the need to produce foods in space for longer and self-reliant future missions is crucial (NASA, 2021a).

Even though macronutrients (protein, fat, and carbohydrate) and micronutrients (zinc, folic acid, vitamin D and iron), are consumed in smaller quantities, they play an important role in proper functioning of the human body (Savarino et al., 2021). Most space foods include high content of carbohydrate and fat and low amount of fiber (Pandith et al., 2022). Micronutrients such as vitamins A, vitamin C, vitamin E and β-carotene are lost notably more than macronutrients in the pre-packed foods with time. Deficiency of micronutrient such as vitamin C and niacin lead to scurvy and pellagra, respectively. It is important to maintain proper micronutrients in diet such as sodium, potassium, and vitamin D, along with water and energy as deficiency of these can cause various diseases. In space, requirement of potassium, energy, protein, and water are the same as recommended on Earth, but sodium intake is reduced as its higher uptake leads to calciuria which results in problem of osteoporosis. Apart from this, requirement of other nutrients such as calcium and iron increases during longer space mission. The recommended intake of these nutrients increases from 900 to 1200 mg/d and 10–18 mg/d, respectively during long space missions (Raut et al., 2021). Despite vitamin D supplementation, it is difficult to maintain its level in crew members due to lack of exposure to sunlight which is essential for vitamin D synthesis (Olabi et al., 2015; Pandith et al., 2022). Considering this, scientists are working on growing supplement crops such as plums, leafy greens, bell pepper and tomatoes during the space mission so that the crew members could receive the recommended amount of vitamin C, B_1 and dietary antioxidants which generally are degraded in packed food (Johnson et al., 2021; Taylor et al., 2020).There is also a need to develop suitable encapsulation technologies for vitamin stabilization and fortification to provide adequate nutrient to astronauts and prevent its degradation during their journey in space.

2.2. Microbiological quality

NASA along with Pillsbury and US Army Department have developed the Hazard Analysis and Critical Control Point (HACCP), a food safety management system, in 1960s, in order to ensure the safety of space food which was further admitted by World Health Organization (WHO) as the most successful way to control food borne diseases (Weinroth et al., 2018). Utilizing this information, total aerobic count is measured on surfaces, packaging material, food processing machinery, and air in the food production area because monitoring the food preparation area could lower the danger of microbial contamination during the preparation process (Kim & Rhee, 2020). Mainly, intermediate moisture foods, thermostabilised foods, dehydrated foods and irradiated foods are delivered in space in which microorganism growth is inhibited by lowering the water activity, reducing moisture, or killing bacteria and their spores by using high temperature or ionising radiation (Watkins et al., 2022). NASA has set the standard for non-thermostabilized food i. e., total aerobic count- 2×10^4 CFU/g, yeasts and molds- 10^3 CFU/g, coliform or coagulase positive *Staphylococci*- 10^2 CFU/g and no *Salmonella*. Products that contain live microorganism such as probiotics and fermented food are not allowed in space and unconsumed food is thrown away within 2 h of preparation. Till date, no report of food illness has been reported during spaceflights (National Aeronautics and Space Administration, 2021b). However, microbial standards set by the Russian Institute of Biomedical Problems that certify the space foods used on ISS are stricter than NASA such as, for non-thermostabilized food products, the recommended criteria are: coliform- <10 CFU/g, coagulase-positive *Staphylococci*-negative/g, *Salmonella*-negative/25 g, yeast and molds- <50 CFU/g, *Escherichia coli*-negative/g and *Bacillus cereus*- <10 CFU/g. For thermostabilized or irradiated food, limit is <10 CFU/g for sporogenic mesophilic bacillus, negative/5 g for mesophilic anaerobes, negative/2 g for yeast and fungi items whose pH is greater than 4.2. However, no microbiological testing has been conducted in Johnson Space Center for thermostabilized and irradiated space food and they are tested only for packaging integrity and swelling (Kim & Rhee, 2020). As it is difficult to resupply the food on longer missions, scientists are working on growing fresh crops during space missions and checking their microbial load. Khodadad et al. (2020) found in their study that red romaine lettuce grown on ISS exhibited high microbial load but they were not harmful for human health and therefore, provided safe as well as nutritious food to astronauts. Currently, no standard limit has been set for microbial level for fresh produce grown in space which is a researchable issue.

3. Space food processing technologies

Food in microgravity is not only required to be nutritious, but it must also be appetizing. Space food processing not only ensures organoleptic acceptability, nutritional quality, and safety for a 3–5 years period but also solves the difficulties of limited storage space, limited preparation options, and the difficulties of eating (Cooper et al., 2011; Jiang et al., 2020). There are eight food processing techniques used by the Space Food Systems Laboratory, USA (Fig. 1). These techniques include rehydration, thermostabilization, irradiation, and foods are in intermediate moisture, natural form, fresh, refrigerated, and frozen form (Trimarchi, 2022). However, the processing techniques largely depend on the food's perishability and ingredient composition. The primary objective of these processing techniques is to provide astronauts with foods that tastes like the foods we eat on Earth.

3.1. Freeze-drying

The shelf-life of any food material can be improved by reducing its moisture content by drying. Freeze drying (FD), which sublimes the water from the material, has been used for years to produce space foods such as beverage powders, cookies, candy, and other dried foods. The FD process allows obtaining dried products of the highest quality (in terms of color, flavor, and nutrients) due to the retention of heat-labile components in the food, which are lost during thermal drying processes (Fan et al., 2019). Further, due to the removal of water by the sublimation process, the dried foods exhibit a highly porous structure which helps the foods rehydrate rapidly compared to thermally dried food (Long et al., 2022). In 1968, freeze-dried ice cream developed under a NASA contract was provided to Apollo 7 astronauts for snacking but was difficult to eat as it crumbled easily (Palmer, 2013). FD has made it possible to provide fruits and vegetables in spaceflight due to minimum loss in quality and nutrients, except for heat-labile vitamins, which are lost upon storage over the years (Cooper, Perchonok, & Douglas, 2017; Douglas et al., 2021; Perchonok & Douglas, 2019). Venir et al. (2007) observed that the nutritional, viscoelastic, and rheological properties of yoghurt were retained after FD, whereas a reduction in lactic acid bacteria was observed, which can be mitigated by the addition of blueberries or sucrose. The authors observed poor structural properties in the reconstituted yoghurt, which can be regained by water modulation (Venir et al., 2007). Although FD preserves the original nutrition and flavor in foods, it requires longer drying times, consumes higher energy and is more expensive than traditional drying techniques (Tarafdar et al., 2019). Therefore, advance techniques to provide higher quality of food at reduced cost is being explored. Several studies have been conducted on the combination of freeze-drying with other techniques, such as microwave FD of soups (Wang et al., 2010), fruits and vegetables (Zhang et al., 2006); pulse-spouted microwave FD of fruits and vegetables (Jiang et al., 2014), to reduce drying times as well as energy consumptions.

3.2. High-pressure processing

High-pressure processing (HPP) is another emerging non-thermal technology that uses high-pressure treatment to inactivate the enzymes and microbes present in food, extending its shelf life. HPP preserves the natural flavor, texture, color, as well as nutrition of foods and hence attracts the attention of space food manufacturers. Earlier, HPP was used to preserve jams, jellies, and juices, but currently, food items such as fruits and vegetables, milk, meat, yoghurt etc., are also preserved using HPP (Jiang et al., 2020a). Practically, HPP itself is not sufficient for the sterilization of foods due to equipment and cost limitations. So, researchers have combined high pressure and thermal treatments to obtain high quality and safe foods compared to conventional heat

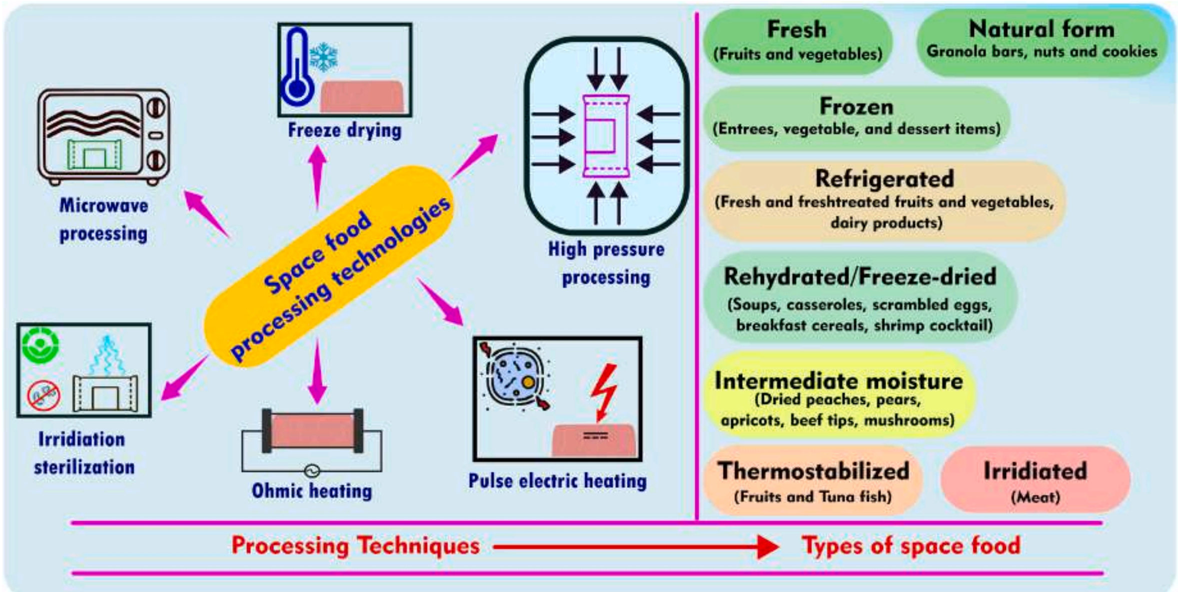

Fig. 1. Different space food processing techniques and types of space food.

treatments. Studies have reported that retort processing causes vitamin losses in the food, but emerging techniques such as pressure-assisted thermal sterilization (PATS) can provide high-quality, vitamin-rich food to astronauts (Perchonok, 2014). In addition to quality, shorter sterilization times have also been reported in PATS of low-acid foods compared to conventional thermal sterilization (Balasubramaniam et al., 2016). Commercially, the pressure between 600 and 800 MPa at 100 °C and higher temperatures is sufficient to inactivate the spores of *Clostridium sporogenes* (Rovere et al., 1999). In another study, a 1.2 log reduction of *C. botulinum* was observed during PATS of mashed carrots at 600 MPa, 80 °C for 16 min (Margosch et al., 2004). During high-pressure sterilization, the coldest spot is near the vessel wall due to heat loss occurring at this region, so it is important to note the temperature at various spots in a vessel to ensure complete sterilization during the process (Matser et al., 2004). Fruits treated with PATS exhibited better color and texture and showed three years of shelf storage compared to retort samples. Further, the combination of refrigeration and PATS has the potential to be used to obtain organoleptically acceptable fruits with five-year of shelf-life (Cooper & Douglas, 2015). HPP can also be combined with good barrier property pouches to prevent browning and other undesirable changes in minimally processed fruits (Perera et al., 2010).

3.3. Microwave processing

Thermal sterilization at an industrial scale is aimed at reducing the *Clostridium botulinum* load to an acceptable level, but this extensive heating process (high temperature, long time) degrades the food quality. Microwave-assisted thermal sterilization can be used as an alternative to sterilize space food due to more efficient heating and shorter processing time (Dhawan et al., 2014). Microwave-assisted thermal sterilization has been used to reduce mass and bacterial populations, preserve quality, and improve the shelf-life, texture, aroma, and color of space foods, making them more appealing to astronauts (Zhang et al., 2016). The drying efficiency and product quality can be improved by combining microwave treatment with other techniques such as microwave-hot air drying, microwave freeze drying, microwave vacuum drying, microwave air spouted drying etc. (Punathil & Basak, 2016). Studies have reported that microwave-assisted drying can be utilized as an alternative to traditional thermal conduction methods due to higher drying rates, lesser drying times, and better product quality (Zhang et al., 2010). Certain processing techniques such as microwave and high pressure can cause physical changes to the packaging material. The physical damage may appear as increased water vapor and oxygen permeability of packaging, leading to a decrease in the shelf life of the packaged product; therefore, choosing the right type of packaging material is essential. During microwave-assisted thermal sterilization (MATS) of mashed potatoes, Zhang et al. (2016) observed that samples in pouches with higher barrier properties exhibited lesser color, and oxidation changes than those packed in pouches with lower barrier properties. Metal-oxide-coated high-barrier polymer pouches can replace aluminium foil-based pouches during MATS of garlic mashed potatoes for better retention of Vitamin C, garlic flavor, and color (Patel et al., 2020). MATS can be combined with polymeric packaging to provide shelf-stable, safe, high-quality, and nutrition-rich foods for military and space missions (Dhawan et al., 2014; Patel et al., 2020).

3.4. Irradiation sterilization

Irradiation sterilization has been considered an effective method to extend space foods' shelf-life without compromising their nutritional properties (Farkas, 2006). Song et al. (2012) developed freeze-dried miyeokguk (Korean seaweed soup) and sterilized it by gamma irradiation. The result showed that 10 kGy of irradiation was sufficient to sterilize space foods as per microbiological requirements without deteriorating the sensory qualities. The combined effect of heat treatment (60 °C, 30 min) and gamma irradiation (>10 kGy) improved the shelf-stability of kimchi by inhibiting microbial growth but changed its sensory characteristics such as flavor, color, and texture (Kim et al., 2006). Lee, Byun, Kim, Song, Park, et al. (2007) irradiated (0–25 kGy) kimchi to develop shelf-stable food for Korean astronauts and observed a significant reduction in microbial load as well as poor sensory characteristics. The sensory characteristics can be improved by combining irradiation with heat treatment, N_2 packaging and adding additives such as vitamin C, calcium salt, and artificial kimchi flavor (Lee, Byun, Kim, Song, Park, et al., 2007). In another study, upon a combination of heat treatment (60 °C, 30 min), irradiation (25 kGy) and nitrogen packaging, no significant change was observed in the acidity and pH of samples during storage (at 35 °C for 30 days), whereas the hardness of kimchi started increasing after 10 days of storage (Lee, Byun, Kim, Song, Choi, et al., 2007). Irradiation (25 kGy) combined with vitamin C (0.1%) treatment and vacuum packaging improved the sensory score of ready-to-cook Bibimbap (a traditional Korean dish) than only irradiation treatment (Park et al., 2012).

3.5. Ohmic heating

Ohmic heating, also known as electric resistance heating, is a type of non-conventional sterilization technique which has the potential to be utilized as an alternative to conventional heating owing to its compact design, rapid heating, minimal heating of surroundings and capability to deliver high-quality products (Jun & Sastry, 2005). Research has been conducted on developing multi-layered laminate pouches, which can be utilized to conduct ohmic sterilization inside the pouch. However, studies have reported that hot and cold zones are formed in the pouch during ohmic heating, which can be encountered by proper simulation of the process. Jun and Sastry (2005) optimized ohmic heating of food items from the ISS menu with electrical conductivity of 0.01–0.03 S/cm and developed a 2D thermos-electric model to predict hot and cold spots in the pouch, which helped to reduce the cold spots to 2% of the total area. Additional studies reported 3D modelling, which helped remove the drawbacks of 2D modelling and ensured that all the parts of the pouch were sterilized properly (Jun & Sastry, 2007; Somvat et al., 2012). These sealed electrode pouches can sterilize the food using ohmic heating and can be reused for waste stabilization to reduce equivalent system mass during a long-term space mission (Somavat et al., 2012). Further design optimization of this process is required, as in pouches with V-shaped electrodes, a lower current density is observed within the V as well as at the edges of the pouch (Jun & Sastry, 2007).

3.6. 3D printing technology

3D printing technology is expected to play a significant role in the future of space food (Enfield et al., 2022; Pandith et al., 2022). It allows the creation of customized food items with precise control of the ingredients and ensures safe and nutritionally balanced food (Nachal et al., 2019). Creating a customized and wider variety of food tailored to individual astronauts' needs and preferences is particularly important in a space environment. In addition, 3D food printing can streamline the space food supply chain by reducing the amount of food stored on a spacecraft, ultimately reducing the weight of the spacecraft and lowering launch costs. For instance, ready-to-print food inks for different formulations could be shipped as a paste or a powder depending on desired shelf life, stability of the product, ease of use, and compatibility with the specific food formulation.

In 2013, NASA awarded a Small Business Innovation Research (SBIR) contract to Systems and Materials Research Corporation (SMRC) to develop a novel 3D food printing technology (NASA, 2019). The goal was to build food from scratch using a 3D printer that could deliver the key components of a balanced diet, such as starch, protein, and fat, in the form of edible structures. This project represented a significant step forward in developing 3D food printing technology and demonstrated the potential for this approach to overcome some of the challenges (micronutrient degradation from dried and pre-packaged food due to long-term storage and exposure to radiation) associated with traditional food preparation methods. By printing food in space, astronauts could have access to a more varied and nutritious diet, which would help to support their physical and mental well-being during extended missions. Moreover, incorporating micronutrients directly into astronauts' meals could improve their bioavailability and ensure they get the full health benefits of the nutrients (Cahill & Hardiman, 2020). By using 3D food printing to incorporate micronutrients into astronauts' meals, NASA and other space organizations could provide a more convenient, efficient, and effective way to deliver essential nutrients to astronauts. Despite the exciting potential of 3D food printing, the field is still in its early stages of development, and there are many technical and regulatory challenges to overcome before it becomes a widespread and accessible technology. Therefore, further research is needed to refine the technology, establish safety and quality standards, and ensure that the food produced is palatable and acceptable to astronauts.

3.7. Other technologies

In addition to the techniques mentioned above, other emerging techniques such as pulse electric heating, radio frequency heating, high-power ultrasounds, and hybrids of various techniques discussed above have been explored to develop safe and nutritious foods for astronauts. Radiofrequency (RF) heating has been considered an alternative to conventional heating, which uses dielectric heating to sterilize solid or semi-solid foods. RF energy can penetrate deeper into the food than microwave energy due to its lower frequency (13.56, 27.12, and 40.68 MHz) and longer wavelength (Wang et al., 2003). In a study on RF treatment of scrambled eggs, it was observed that RF-treated eggs were less brown and exhibited lower hardness and springiness values compared to retort-treated eggs. Moreover, the microbial load of RF-treated eggs agreed with the sterilization thresholds (Luechapattanaporn et al., 2005). RF heating at 6 kW, 27.12 MHz, 20 mm plate spacing, 100 °C for 20 min provided yam/chicken-based paste with equivalent organoleptic characteristics as observed in traditional high-pressure steam (@ 121 °C, 30 min) treated product (Jiang et al., 2020b). Another notable technology is pulsed electric field (PEF) which uses high-intensity electric field pulses for microbial inactivation in foods at temperatures less than 60 °C while imposing minimal detrimental effects on color, flavors, and nutrition of the product (Wan et al., 2009). Another sterilization technique, pulsed light technology, has been used to destroy nucleic acid, enzymatic activity, and cytoplasmic membrane structure for sterilization of aviation foods such as fruit and vegetables, porridge, and other intermediate moisture foods (Niu et al., 2022).

3.7.1. Hurdle technology

Hurdle technology is a multi-disciplinary approach to food preservation that offers a more comprehensive and effective solution for extending the shelf life of food products than relying on a single preservation method (Giannakourou & Tsironi, 2021; Legan & David, 2020). The earlier discussed processing technologies could be combined and optimized with physical barriers, chemical preservatives, antimicrobial agents, and pH control to meet the specific requirements for safe and high-quality space food (Khan et al., 2017). Cooper et al. (2018) suggested that if the hurdles are adequate, the combination of formulation, processing, and storage can be specifically designed to achieve a five-year shelf life for processed food. Thus, using multiple hurdles, each targeting different preservation factors, can create a preservation system that provides multiple barriers to spoilage and help to achieve a longer shelf life for food. However, the selection of hurdles and their combination and levels depend on the specific food matrix and the desired shelf life. In contrast, hurdle technology also includes major challenges in managing the trade-off between preservation and sensory quality and must ensure that preservation methods are compatible with the equipment available on the spacecraft, do not interfere with the safety and reliability of the spacecraft's systems while not adding significant weight or volume to the spacecraft. Therefore, carefully selecting hurdles and testing them in relevant simulated space environments to determine the best combination can ensure the shelf life and maintain the sensory quality of space foods (Cooper et al., 2018; Pirozzi et al., 2021).

4. Space food packaging technologies

The packaging material is a crucial component of the space food system and must meet several requirements to function properly. Packaging not only protects the food in the intended storage environment, but also aids in food preparation specially when certain equipment (microwave-convection oven) is being used. Such enhanced packaging methods makes the packaged food relatively simple to open and consume, interaction with the restraint/storage system, being particle-free and easily compactible, not posing any burn hazards, and meeting off-gassing and flammability specifications (Cooper et al., 2011).

Package materials for space foods, are regarded as the most critical aspects in food innovation, as they have a significant role in mass, volume, and waste allocations for space missions (Douglas et al., 2020). Space missions are expected to last up to 2.5 years and provide the greatest challenge of providing acceptable food with a shelf life of 3–5 years (Perchonok et al., 2012). Food products of lower mass is easier to transport to the space station (Phadtare, 2021) and an effective packaging solution can serve as a protective barrier between the food product and its environment. A correct packaging material ensures food safety, nutritional adequacy, and acceptability because it prevents microbial development, reduces oxygen levels, maintains acidity and pH, extends shelf life, and makes food items more stable for consumption. The higher the barrier given by the packaging, the better the protection the food has against oxygen and water entry from the outside environment.

With the advent of plastics and metal cans, the era of packaging began with the Apollo mission (Chang, 2019). During the Apollo mission, the first thermo-stabilized pouches (wet packs) and serving utensils (spoon-bowl system) were designed. To keep dried food moist for a long time, wet packs were utilized. Bimetallic cans and aluminium foil were replaced during the Apollo mission (Vodovotz & Bourland, 2002). To increase the shelf life of beverages by up to 12 months, they were packaged in several foil layers to prevent the entry of nitrogen and oxygen. Several advancements in food and beverage packaging have been made throughout various space missions. The first culinary choices for roughly 70 food items were presented in the space station between 1970 and 1980 (Phadtare, 2021). Many astronauts claim that the foods served in aluminium tubes in the form of bite-sized cubes, freeze-dried powders, and semi-liquids taste unappetizing and are difficult to eat from (Oluwafemi et al., 2018). The cubes were first wrapped in aluminium foil, which was eventually replaced with a lamination of clear plastic. Although the initial components were the same, cubed meals had certain issues comparable to those with tubes: the manufactured cubes lacked the recognizable mouthfeel and texture. Many cubes were returned from missions uneaten, despite being well-liked in pre-flight taste testing (Shafiee, 2017).

Retort pouches are thought to be one of the most effective packaging materials for minimizing mass and volume requirement during food and beverage storage. Irradiated and thermostabilized foods are frequently packed in retort pouches (Casaburri & Gardner, 1999). Food safety and nutritional value may both be guaranteed via retort processing, which also increases consumer acceptance of the final product and had high chance to keep food acceptable during its three to five-year storage term even at room temperature. It may be used easily and can reduce the energy required for preservation by being consumed hot or cold. Since the container is made of a quad-laminate of polyolefin, aluminium foil, polyamide, and polyester, there is nearly no oxygen or moisture permeability. To assess long-term storage, 13 products went through a series of 36-month accelerated shelf-life assessments. Meat products and other imported vegetables are expected to have a shelf life of 2–5 years without refrigeration, while fruits and confectioneries are likely to last for 1.5–5 years, dairy products for 2.5–3.25 years, and starches, vegetables, and soup items for 1–4 years (Catauro & Perchonok, 2012).

Aluminium cans are mostly used in packaging of freeze-dried foods and heat stabilized products that require heating. To avoid the spilling under microgravity, these cans had membrane inside the lid during heating for easy opening (Sun et al., 2016). All these cans were designed so that they can withstand pressure change between ground and spacecraft. During the Skylab mission, the pressure change was ~5 psi, where atmospheric pressure was ~15 psi at the time of sealing of canisters in another tank (Bourland et al., 1989). Good barrier qualities of metal cans typically extend food storage up to three years (Perchonok & Bourland, 2002). Most of the food was stored during the Skylab programme in metal cans to preserve its two-year shelf life. The sole drawback of this packing material is that it is heavy and difficult to dispose of, making it unsuitable for use on long-term missions. On the other hand, dehydrated foods were packed in thermoformed polyethylene from inside and sealed in nitrogen atmosphere.

High-barrier packaging material with high water vapor and oxygen barrier qualities was designed during the Gemini mission (1965–1966). Barrier films possess a flexible, solvent-free, impermeable co-extruded structure (single or several layers) that does not react with the packed food (Sun et al., 2019). The qualities of food, such as colour, taste, texture, fragrance, and flavour, are also preserved by this rigid barrier, which was created utilizing specific materials. Biaxially oriented polypropylene/Cast polypropylene (BOPP/CPP)-based film with a multi-layered structure that delivers equivalent Moisture Vapor Transmission Rate (MVTR< 0.15 g/m^2.day) and Oxygen Transmission Rate (OTR< 0.1 cc/m^2.day) has been specifically created for packaging applications demanding strong sealing and act as a substitute for aluminium foil (Perchonok & Bourland, 2002).

Edible packaging film is a novel packaging technique that prevents changes in the flavour and texture of food items during storage and transportation. It blocks the migration of gas, water vapor, solute, and aroma components, assuring food quality and extending food shelf life. NASA has also supported other researchers by provided funding to the Southwest Research Institute to create a biodegradable polypeptide film that can isolate germs, stop water loss, and shield food from damage (Jiang et al., 2020). The in-suit food bar was a special product and package designed for the Apollo mission. This fruit bar was employed inside the astronaut's suit for consumption without the need for hands. It was manufactured from compressed fruit "leather" and was packed with an edible starch film (Patrick et al., 1998). The astronaut can reach the packed bar through a sleeve with their lips and take bite-sized pieces. The in-suit food bar was utilized decades ago on Apollo, Skylab, and the joint Apollo-Soyuz Test Project (Hartsfield and Hartsfield, 1985). By coating the food, the nutrients may also be improved. The study on the product that might be employed as a storage container for condiments or any other ingredients via encapsulation was supported by NASA Johnson Space Centre (Krishen, 2007). In terms of long-term missions, edible films are unable to offer a shelf life of up to 5 years. Recent research has revealed that the performance, barrier, tensile, sealing, and water resistance of edible films is subpar. It can be preferable for short missions that need the storage of only dry food items.

The concept of customized food packaging design was applied to keep a fixed width dimension for all packages. There was a "lip-lock" mechanism in the meal trays and storage compartments of this design (Bourland, 1993). These meal trays had a variety of designs and were mostly intended for single-service to prevent the transfer of food from one container to another in microgravity. Additionally, a single service container replaces the need for a dishwasher. The dimensions of the packaging were optimized through a series of tests and engineering evaluations that considered the interaction between packages and storage facilities (Perchonok & Bourland, 2002). The fact that many items are combined into two distinct containers is one of the main flaws in the existing packaging system in terms of quality and volume. The food is overwrapped in a second piece of foil-containing packaging with stronger barrier qualities to offer the required protection for 18-month shelf life. The technique of utilizing an additional overwrap pouch to better protect foods in freeze-dried and in natural form was first examined by advanced food technology (AFT) researchers in 2009 (Cooper et al., 2011). It was suggested to use a single, wide overwrap rather than several smaller ones to preserve and confine one container's amount of food products.

One method to lessen packaging waste in space is the bulk overwrap. Utilization of an alternative and novel type of packaging material might be an additional strategy. In order to achieve light packaging, even NASA suggested (sixth section of the 2015 Technology Roadmap) that the amount of food packaging needs to be lowered in the manned missions to the moon and Mars (Menezes et al., 2015). As a result, another packaging research was conducted with the objective to lower the whole food system's proportion of the total available resources from 15% to less than 5%, by creating novel packaging and processing technologies to promote nutritional stability and food acceptability by occupants. Food products exclusively prepared for space missions are expected to have a longer average shelf life than the shelf life of present space foods (1–5 years). To accomplish that NASA has proposed specifications for new packaging. *Nanomaterials* have a vast application promise in space food packaging due to their capacity to provide light weight, high strength, excellent barrier, multi-function, and other food packaging properties. In addition to having greater gas resistance, polymer nanocomposites (such as those made of polyethylene, polypropylene, polystyrene, polycaprolactone, polycarbonate, PAS, vinyl alcohol, and polyethylene terephthalate, etc.) also have good physical properties and are more likely to be employed in manned long-term missions (Long et al., 2022). Packaging for space food can also make advantage of *Hurdle technology*. It will be easier to regulate food quality and nutrition if aspects such as alternate storage temperatures, processing, formulation, ingredient source, packaging, and preparation techniques are integrated with the hurdle approach to achieve a shelf life upto 5 years (Sirmons et al., 2020). Another type of special packaging used by NASA is *Gas flushing*. They developed an inert gas (nitrogen) flushing technique to preserve the appearance and flavour of fresh bread (Hartung et al., 1973). To achieve this, the bread packet was cleaned with 70% ethyl alcohol, followed by three rounds of nitrogen flushing, before each piece of bread was individually packaged in a sterile environment. Bread samples were kept without mould for more than 14 weeks.

The ideal packaging for future space missions would have been intended to prevent food from losing water, to avoid degradation, to prevent the exchange of oxygen, to prevent the loss of photosensitive nutrients, and to prevent microbial contamination. It is anticipated to be easier to transport, lightweight, robust, able to withstand physical force that might change the structure of the food, without adding more volume, and to produce less waste.

5. The space food market

In 2023, the space food market was estimated to be worth USD 0.513 billion, which is expected to expand at a compound annual growth rate (CAGR) of 12.3% between 2024 and 2032, from USD 0.576 billion in 2024 to USD 1.457 billion by 2032. The main factors propelling the market's expansion include growing interest in space exploration, the necessity for food during protracted missions, and the advancement of food technology and preservation techniques (Market Research Future, 2024). The projected US market for space food is around 47% by 2028 and China will account for 19% of the worldwide market for space food, which will be worth 140 million US$. In the case of the European space food market, Germany is anticipated to increase their market size up to 3.5% over time. Other important markets, such as Japan and South Korea, are expected to develop at the rates of 3.4% and 3.1%, respectively, during the next six years (SFMRR, 2022).

Fresh food and beverages are the main food categories, whereas snacks and irradiated meat share second place in terms of the global space food market. Mitsui Norin, Nissin Foods, Onisi Foods, Morinaga milk industry, and House Food corporation are the major space food players, which are active at the global level (Table 1). Besides this, the space food company, space food laboratory, astronaut foods, and Shanxi Shenzhou space food are other organizations working at the regional levels in North America, Asia-Pacific, Europe, South America, and Middle East, and Africa.

It is forecasted that North America and Asia-Pacific will be the leading regions consisting of America, China, and Russia in the global space food market. On the other hand, Europe, Latin America, Middle East, and Africa will also play an important role in the global market.

Table 1
Major space food market players.

Company	Headquarters	Food Type
House Foods Corporation	Japan	Irradiated meat
Morinaga Milk Industry	Japan	Beverages
Mitsui Norin	Japan	Beverages
Nissin Foods	Japan	Fresh foods
Onisi Foods	Japan	Snacks

Source: Space food market research report, 2022

Further, with emerging commercial space travel and diverse space tourism opportunities being offered by notable companies such as SpaceX, Virgin Galactic, Blue Origin, Orion Span, Boeing, Space Adventures, and Zero 2 Infinity, the significance of the space food market is driven with the need for taste and dietary preferences of civilians interested in space travel (Barten, 2024). These new demands have advanced the space food processing sector through increased impact and funding while boosting the income of the space food industry.

Other important key players driving the space food market include Orbital ATK, ISSpresso, BeeHex, NanoRacks, JAXA, AEB, Boeing, Lockheed Martin, SpaceX, Blue Origin, NASA, European Space Agency, Roscosmos, SpaceX, Helios Biosciences, and Northrop Grumman Corporation. Zero-G Kitchen in partnership with Kellog's have also started developing space-friendly food whereas the company Space Garden has partnered with NASA to work on sustainable food systems for astronauts.

6. Conclusions and perspectives

Space food processing is important in space missions to ensure that astronauts receive nutritious and appetizing food. This review has discussed the different space food processing and packaging technologies along with their quality considerations. It is evident from the data from the physico-chemical perspective, incorporation of macronutrients (protein, fat and carbohydrate) and micronutrients (zinc, folic acid, vitamin D and iron), in space foods is essential to maintain a normal metabolism of the astronauts. Moreover, the use of a 'spice bomb' could be helpful for enhancing the taste of space foods as the human taste perception declines under zero gravity. Microbiologically, space foods processed on Earth can be brought under the strict regulations of the space organizations. Also, there are no regulations in place for fresh produce grown in space. To establish such protocols, research must be conducted either in simulated space environments or in the space station, both of which will require thorough consideration. In terms of processing technologies, FD has been used for decades to produce space foods such as beverages, cookies, candy, and other dried foods. It allows the retention of heat-labile components and rapid rehydration but requires longer drying times and higher energy consumption. High-pressure processing also looks promising as it uses high-pressure treatment to inactivate enzymes and microbes present in food, preserving its natural flavor, texture, color, and nutrition. Researchers have combined high-pressure and thermal treatments to obtain high-quality and safe foods. The combination of refrigeration and high-pressure sterilization also has potential to increase the shelf life of fruit-based space foods to five years. Further, development of processes and technologies for 3D printing of food in space using shelf stable food inks could provide a long-term solution to the food problems during space missions. However, testing the effect of processing methods on space food is challenging for researchers as recreating the exact environment of space is difficult. Additionally, space agencies have strict requirements for the type and amount of packaging material that can be used in space, further complicating the testing process.

CRediT authorship contribution statement

Shikhangi Singh: Writing – original draft, Investigation, Formal analysis. **Taru Negi:** Writing – original draft, Investigation, Formal analysis. **Narashans Alok Sagar:** Writing – review & editing, Writing – original draft, Validation, Formal analysis. **Yogesh Kumar:** Writing – original draft, Methodology, Investigation, Formal analysis. **Samandeep Kaur:** Writing – original draft, Investigation, Formal analysis. **Rajneesh Thakur:** Writing – original draft, Methodology, Formal analysis. **Kiran Verma:** Writing – review & editing, Validation, Resources. **Ranjna Sirohi:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Ayon Tarafdar:** Writing – review & editing, Validation, Supervision, Data curation, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used QuillBot in order to improve the language of some of the sentences (<5%). After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

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.

Data availability

No data was used for the research described in the article.

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