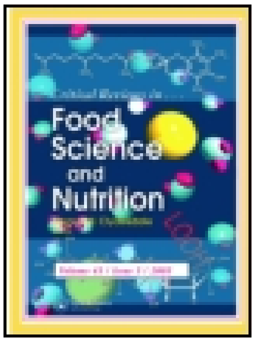

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REVIEW

Current processing and packing technology for space foods: a review

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ABSTRACT

With the launch of aerospace business, the national space agency has been working actively to improve the living environment of astronauts in outer space. Since 1980s, space food has been greatly enriched, except the differences in form, most of the foods on earth can be enjoyed in space. In this article, the space foods are classified, in general divided into five parts that include natural form food, intermediate moisture food, thermostabilized food, rehydrating food and irradiated food. New type of space food processing technology is also reviewed, including freeze-drying, irradiation sterilization, high pressure processing, microwave assisted thermal sterilization, food 3 D printing and the packaging of space food products, mainly including the packaging materials already used by the present space food system, and the feasibility analysis of some emerging high barrier packaging materials in the research stage. Finally, the review highlights the prospects of future space food system, including the development of in-orbit food preparation technology and the research of life support system.

KEYWORDS

Space food; food system; food production; food packaging; life support system

Introduction

Space food is a special variety of food for astronauts to eat under space weightlessness environment. Dietary nutrition is extremely important to the life security of astronauts, not only because the proper nutrition can be maintained through the intake of appropriate nutrients, but also because the appropriate food plays an important role in social psychology in the long-term space flight. Space foods should have the characteristics of small size, light weight, easy to carry and eat, and can overcome the adverse effects of vibration and radiation and adverse environmental factors, such as low pressure. Compared with general food, space food is different in composition and storage, and also in nutritional value and edible way. The spaceflight environment elicits various physiological changes that include bone loss, decreased muscle mass, and immune function, as well as slower intestinal transit time and gastrointestinal motility that may reduce nutrient bioavailability (Sun et al. 2014). It is an important to assure a good health of astronauts by providing sufficient food and nutrition for spaceflight. But during the period of space flight, dietary intake of astronauts may often be insufficient, which can greatly reduce the nutritional status of astronauts, causing or aggravating the physiological changes in the weightlessness environment damaging their health. Therefore, space food will need continuous development and perfection. The space food development should have two objectives, one is to meet the physiological needs of astronauts to support life, the other is to meet the psychological freshness and pleasure of astronauts in the long and difficult space missions (Katayama et al. 2009).

With the development of science and technology, the quantity and quality of space food have been improved rapidly. Apart from morphological differences, spaceflight diets are almost the same as on Earth. Nowadays, astronauts can enjoy totally different recipes in a week. American astronauts have enjoyed their own fast-food culture while in space, with burgers, salads, sausage patties, brownies and even turkey for Thanksgiving (Space Food Photos: What Astronauts Eat in Orbit 2013). The Russian crew has more than 300 dishes to choose from their menu on the ISS, four meals a day, and many options for each meal, including mashed potatoes with nuts, jellied pike porc, broccoli and cheese, dried beef and so on (Sudakov 2009). Japan's space food also follows its traditional taste, dominated by Japanese cuisine, including sushi, ramen, natto rice, and fruit, curry steak, fish, pork soup and so on ("The certification of Japanese cuisine in space(In Japanese)" JAXA 2007). Chinese cuisine is now available to provide astronauts with more than 100 kinds of foods, such as yuxiang pork, Kung Pao chicken, lotus seed porridge, steamed beef, rice dumplings, Eight Treasures rice, along with Chinese herbal tea (Zhang 2003). The development of such a rich and diverse diet has benefited from the progress of food processing and preservation technologies.

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The crew's psychological freshness needs have been met, and the physiological safety also needs to introduce a more standardized quality assurance process. In early production, a large portion of each batch of food had to be used for testing, and only a small portion was available for space flight (Bauman 1995). Thus, the Hazard Analysis and Critical Control Points (HACCP) system, developed in collaboration with NASA, Pillsbury, and the U.S. Department, was launched in the 1960s (Perchonok 2014). The use of this preventative system addresses the limitations of end product testing, and practically provides high-quality aerospace food. It has been recognized by the World Health Organization (WHO) as the most effective approach to control foodborne disease and has driven innovation across the food industry (Jones 2007).

Evolution and classification of space food

Evolution of space food

During the Mercury project in the early 1960s, space food came in three forms. The first was tube foods, such as applesauce (Lachance, Michel, and Nanz 1967), which are squeezed into the mouth like toothpaste. The second was cubed foods, which was a compressed food in a cube form of about 0.5 inch (Heidelbaugh 1966), so that it can be swallowed in one mouthful. The third was freeze dried powders which can be eaten after rehydration.

In the process of further development, the food system for the Apollo missions (1968–1972) was improved, mainly by improving the food packaging and increasing the varieties of foods. The use of retort pouches and cans allowed thermostabilized foods to be stored at ambient temperatures for a long period, so the thermostabilized foods were added to the menu (Perchonok and Bourland 2002). The Apollo mission was also the first to be equipped with hot water, which made it easier to rehydrate the dehydrated food (Perchonok and Bourland 2002).

The 1973 Skylab food system was described as by far tastier and most diverse food system in space missions. There were 72 kinds of food to choose from, with a 6-day menu cycle (Perchonok and Bourland 2002). Sky Lab also had refrigerators and food heaters, and thanks to these machines, crews could enjoy foods such as ice cream, filet steak, lobster, as well as chilled drinks and desserts.

There are many factors that have contributed to the change of the space system, including the study of physiological processes in microgravity environment, the availability of processing technology and the satisfaction of the crew (Perchonok 2016). In the 1960s, research on the physical condition of astronauts focused on swallowing and digestion in space, which was later confirmed to be related only to throat muscle activity (Paula 2018). However, there were indeed many astronauts who reported that their appetite deteriorated in space, but this was actually because the food smell was scattered under microgravity, making the food bland (Jim 2009). After 2000, research focus shifted to the effects of salt on bone resorption, as microgravity was found to cause bone loss (NASA 2013). Therefore, foods rich in calcium and vitamin D have be provided in sufficient quantities.

Astronauts now enjoy as many kinds of food as they do on the ground, food has developed from merely ensuring the basic energy needs to satisfying their hobbies and psychological needs as much as possible. The following section will classify and describe the space foods as per the criteria of type or forms and processing methods.

Natural form foods

Natural forms of food include fresh fruits and vegetables, nuts, cookies, granola bars, etc. Vegetables and fruits have a short shelf life, but they are an important psychological support for crews (Maya, Grace, and Michele 2015). Cookies, granola bars, etc. are often bite size, made by compression. Their surfaces are generally coated with an edible protective film, convenience for astronauts to eat. The compressed food consumption method is simple, does not need too much processing before ingestion and also does not need auxiliary feeding equipment. They are a mixture of protein, high melting point fat, sugar and fruit or nuts, often with high calorie content. Their volume and the weight are relatively small, saving the space of the space capsule (Smith et al. 2006). But this kind of foods have a low moisture content and may not have the original texture and the mouth feel. On Mercury project, many bite size foods were wasted (Perchonok and Bourland 2002). Apollo adopted a unique product called fruit bar, which was designed to be used inside the astronauts' suits for consumption without using their hands. This fruit bar was made from compressed fruit leather and packaged with an edible starch film (Perchonok and Bourland 2002). Natural form foods provide energy, vitamins, and moisture needed by human body, as well as support the mental health of the crews. But the natural food weight can be heavy and can't be preserved for a long period.

Intermediate moisture foods

Intermediate moisture foods are shelf-stable because their water activity and moisture content are not high, causing microbial activities inhibited. Dried dates and figs are typical intermediate foods, in addition to dry sausage, beef jerky, country ham, fruit cake, jams and jellies, marshmallows, etc. (Hartung et al. 1973). An astronaut, John Glenn, who opened up the beginning of space diet, ate the intermediate moisture food such as applesauce during his mission (Lachance, Michel, and Nanz 1967).

In comparison with canning, dehydration, and freezing foods, the preparation of intermediate moisture foods is less stringent and less nutrient loss occurs (Taoukis and Richardson 2007). This is because unlike other processing technologies, intermediate moisture foods' processing technology requires lower temperature and pressure and does not involve water immersion of nutrients (Leistner and Gould 2002). Moreover, compared with conventional processes including canning and freezing, intermediate moisture foods can be produced with more energy saving since they do not require refrigeration (Fellows 2011). NASA has funded research on intermediate moisture foods that aim to develop more natural food by using additives other than salt or sugar (Hartung et al. 1973).

Thermostabilized foods

Thermostabilized foods, make up a large part of the space food menu. NASA thermostabilized products include pouched soups, noodles, desserts, and some entrees (Maya, Grace, and Michele 2015).These foods are canned foods in flexible or metal packaging after heating and sterilization (Su 2012). Their characteristic is not only containing the normal amount of water, but also closest to the common food from the point of view of taste and shape. Canned food is a kind of food which is produced and processed after a series of technological processes, such as filling, exhausting, sterilizing and cooling. This kind of food has the characteristics of resistance to storage damage and easy to carry, but its weight and volume are large. Compared with the aluminum cans, the flexible pouches are lighter and save storage space. From the point of view of contents, thermostabilized foods have higher viscosity to reduce the influence of weightlessness and the flavor of thermostabilized foods can be quite different from that of common food, which may make the food less tasty and difficult to swallow.

Rehydrating foods

Since the mid-1960s, the Gemini and Apollo spacecrafts have been powered by hydrogen and oxygen fuel cells, which by-product is water, so about 50 percent of the space foods are dehydrated (Bourland 1993). Rehydrating foods using the by-product water include staple foods and beverages, which are packed in trait packs with an one-way intake valve bags for rehydration. During the Mercury project, freeze-dried powders were first used, but at that time it had some trouble to rehydrate the food as it was critical to prevent the powder from contaminating the machine. In Apollo mission, because of the hot water, were able to rehydrate foods easier and thus improved the taste of the food (Perchonok and Bourland 2002). The development of freeze drying increased meal and snack variety to include items like ice cream, shrimp cocktail, chicken and vegetables, butterscotch pudding (Bannister 1968). Use of rehydrating freeze-dried foods have the advantages of quick rehydration, less nutrient loss, light weight and easy preservation. Freeze-drying technology is widely used in the processing of fresh vegetables and fruits. It can concentrate the aroma of fruits and vegetables to the maximum extent and effectively protect the original vitamin C. Astronauts can also enjoy many types of rehydration drinks in space. In China's Tiangong 2, the crews steeped tea in space for the first time. Black tea and green tea were available. Before drinking, the rehydration is completed by water injection, and then heated through the heater (China Xinhuanet News 2016).

Irradiated foods

Irradiated foods are sterilized by high energy rays produced by ionizing radiation such as X-ray, γ-ray or high-speed electron beam (Zhang et al. 2007). In 1981, food irradiation was approved by the FAO/IAEA/WHO. The maximum irradiation doses can reach 10 KGy (Khan et al. 2016). Irradiation sterilization is a special cold working technology, which can inactivate living organisms without thawing frozen food. It has very little effect on food quality, and can maintain the unique flavor of foods to the maximum extent. Another advantage of irradiation is that the product can be packaged before irradiation, thus eliminating the possibility of contamination of the packaging material and the packaging process (Farkas 1998).

The Apollo astronauts were the first to use irradiated food in space (Bourland 1999). All missions from Apollo 12 to 17 carried irradiated fresh bread and on Apollo 17, in collaboration with the Natick laboratory, a ham sandwich made from irradiated bread and irradiated sterile ham was introduced (Hartung et al. 1973). Currently, irradiation sterilization technology is often used in combination with freeze-drying technology.

Processing of current space food

Freeze-drying technology

Freeze drying, also known as lyophilization or cryodesiccation, is a low temperature dehydration process which involves wet material pre-freezing, sublimation of frozen solvents under vacuum, and desorption of residual bound water from material matrix (Ratti 2009; Zhang et al. 2017). Compared with conventional dehydration, freeze-dehydration can successfully apply to most foods including the cooked and raw animal products. The product structure is not solid dried particle but porous dried particle, with natural odor and color and has lower density than original food (Huang and Zhang 2012; Wang et al. 2009). Freeze-drying technology can not only preserve the original nutrition, flavor and taste of food, but also does not need to add preservatives, so is more natural and healthier. In addition, the cellular structure of food remains basically unchanged, so that the physical structure of rehydrated food is approximately the same as that of thawed frozen food (NASA 1995).

The earliest freeze-dried space food, ice cream, was developed by Whirlpool Corp. under a NASA contract, but the product was a bit difficult to eat in space since it crumbled easily (Palmer 2013). Now, many freeze-dried entrees are used in space flight, including ethnic foods, such as Chinese, Indian and Mexican dishes, among which the most popular is the freeze-dried shrimp bowl with seasoned cocktail sauce (Smith et al. 2006). NASA has also co-developed a new process to produce truly "instant" ready-to-eat rice, which, by repeatedly freezing and thawing, destroys the basic structure of grains so that rice can be rehydrated quickly. The process consists of three cycles of freezing and thawing of previously cooked rice under conditions of -14 °F for 2 hours. After the

Figure 1. Photograph of freeze-dried miyeokguk as a space food (Song et al. 2012).

third freezing, the rice is freeze-dried to reduce the moisture to a very low level. The instant rice is now on the astronaut menu and has also been used in the development of a chicken rice soup which was eaten by the Apollo 14 crew (NASA 1995). By freeze-drying ordinary yoghurt and blueberry yoghurt, the Italian space agency has developed a space food with unique flavor, rich in calcium and probiotics, which can resist the degradation of intestinal flora caused by microgravity (Venir et al. 2007). The Korea Atomic Energy Research Institute processed the Korean miyeokguk, a seaweed soup, in order to develop a freeze-dried food with Korean characteristics, see Figure 1. The soup was certified by IBMP, as a space food, which was used on the Russian international space station in 2010 (Song et al. 2012). Thai Geo-informatics and Space Technology Development Agency is committed to researching and developing the potential of Thai food as a space food, and has tested the specially processed durian dried fruit in space in July 2018. This is the first Thai food to be sent to space, and it would be sent back to earth to evaluate what happens to the dried durian and whether the packaging will maintain its integrity (Sun 2018). Lane, Nillen, and Kloeris (1995) carried out experiments to determine whether sufficient folacin was found in freeze-dried space foods and thermostabilized space foods. The results showed that folic acid decreased in some kinds of freeze-dried vegetables while increased in some vegetables. Although the folic acid content in some freeze-dried foods was not high, the folic acid content was sufficient to meet the requirements of RDA guidelines.

However, the low drying rate of freeze-drying leads to high energy consumption, low production yield and high operating costs. Therefore, a combined two- or three-stage drying process can be used, such as microwave freeze-drying (MFD) and pulse-spouted microwave vacuum drying (PSMVD) (Xu et al. 2005). Many studies have shown that the use of microwave heating as an alternative to traditional thermal conduction provides better heat and mass transfer rates (Song, Zhang, et al. 2009; Duan et al. 2008). Because MFD has the characteristics of heating materials by volume, it solves the problem of difficult heat transfer during freeze-drying (Zhang et al. 2006). But at the same time, its heating effect is limited by the dielectric properties of the material, if the high moisture materials want to achieve a better MFD rate, osmosis dehydration can be pretreated (Wang, Zhang, and Mujumdar 2010b, 2010a; Wang et al. 2011). PSMVD is an improvement based on MFD, aimed at solving the problem of non-uniform drying (Wang et al. 2014; Mothibe et al. 2014). Jiang et al. (2014) conducted experiments on banana cubes, confirming that both MFD and PSMVD can shorten the drying time to 50% of freeze-drying. In addition, it is worth noting that the ascorbic acid content of PSMVD samples is equivalent to freeze-drying, which is more than that of MFD samples. Yan et al. (2010) study of carrot pieces showed that the rehydration rate of MFD samples was almost the same as that of freeze-dried samples, with higher carotene and vitamin C retention. This processing method has an excellent retention rate of nutritional ingredients, making the initial product reach a high level of quality, which is very helpful for processing aerospace foods with a long shelf life of 3–5 years.

Food 3 D printing technology

3D food printing refers to using 3 D printing technology to produce food according to the principle of layer by layer printing and stack forming. The first food printer was the "Foodini", which was not very different from the normal 3 D printer in shape, uses not plastic but the edible ingredients that are extruded out of stainless steel capsules (Misal, Mahajan, and Patil 2015). In addition to the ability to complete complex designs, such as very detailed cake decorations or irregularly arranged foods, the 3 D printer can also be used effectively for foods that require precision and dexterity, such as pizza or spaghetti (Prisco).

As we break through the boundaries of Earth-Moon exploration and extend space travel to Mars and beyond, mission time will be extended to months or even years, thus new technologies must be developed to provide the crew with a long-term, adequate and pleasuring diet. 3 D printing can actualize relatively simple space cooking tasks, receive health information from astronauts and use these data to print appropriate food, and timely adjustment to meet the taste and nutritional needs of astronauts (Oko and Rice 2015). Cornell Creative Machine Lab has developed a 3 D printer that can produce biscuits of the same shape but different calorie content for two subjects which are in very different health conditions (Lin 2015). In addition, not only the appropriate material medium should be explored, but also the correlation between material formulation and processability should be further studied. Liu, Min, Bhandari, and Yang (2017) studied the relationship between the rheological

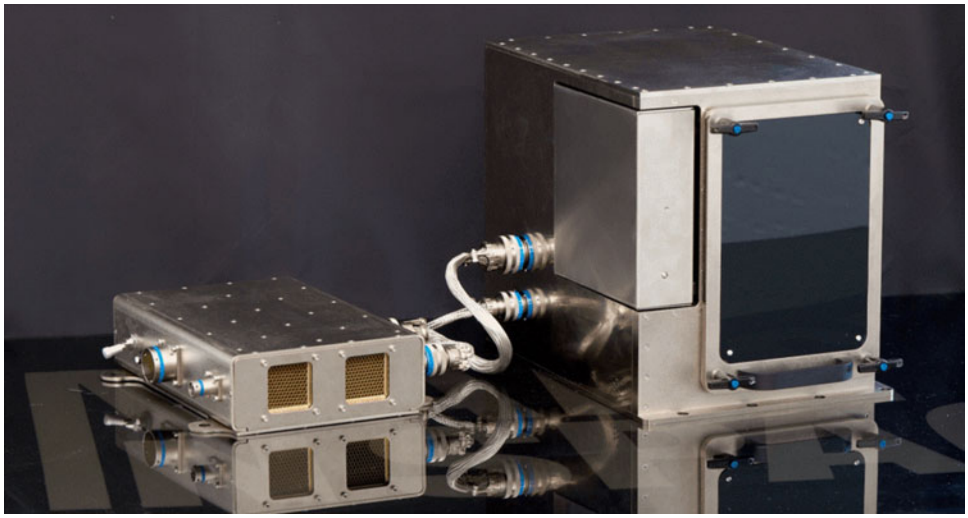

Figure 2. Photograph of Zero-G printer, available at http://madeinspace.us/projects/3dp.

properties of mashed potatoes and 3 D printing and printed the samples, as shown in Figure 5. Nutrients in space food, such as sugar, carbohydrates and proteins, will be stored in powder form in the ink cartridges of 3 D food printers. Some liquids, such as milk, can also be made in powder form and rehydrated during three-dimensional food printing. It is also possible to add vitamin supplements or spices in the form of powder during the 3 D printing process, which not only change the taste of the food, but also enriches the nutritional elements (Terfansky and Thangavelu 2013).

NASA officials believe the continued development of 3 D food printers and the expansion of nutrient-rich food media and materials available for the equipment, might help further the goal of visiting asteroids or eventually reaching Mars (Terfansky and Thangavelu 2013). Made In Space, a Northern California-based company, worked with NASA Marshall Space Flight Center to design the first 3 D printer operating in zero gravity, see Figure 2. The printer was called Zero-G Printer and launched into orbit on September 21, 2014 ('3D Printing In Zero Gravity Experiment'). The ability for the printer to filter toxic gases and nanoparticles was one of the most important technical challenges for operation approval aboard the ISS. In 2013, the US government awarded the Austin-based technology firm Systems & Materials Research Corporation (SMRC) $125,000 to develop comestible prototypes that might be used for interplanetary travel (Terfansky and Thangavelu 2013). The company immediately made headlines by announcing its first menu item would be pizza, printed entirely from cartridges. In 2016, China used food 3 D printer for the first time in the project of Green Space Interstellar, and successfully printed moon cakes (CNR 2016). The 3 D space food printer used in the Green Space Interstellar project can realize the feed material mixing, precise instant cure, three-dimensional molding, which make it easy to print nontraditional food and personalized food. In addition, it can also expand the sources of food raw materials and improve the utilization ratio of raw materials, which may become the main cooking equipment for deep space exploration in the future (SOHU 2016). The machine can also be used for refining nutritional package design. The South Institute of Space Science and Technology in Shenzhen, China, and Lee Kin-kee have jointly set up the "3 D Space Food Printing Technology and functional condiment Joint Laboratory". It plans to carry out research including 3 D space food printer miniaturization, lightweight and intelligent research. The research and development of functional condiment and the establishment of related product standard is also considered (PRNewswire 2017).

Irradiation sterilization

Irradiation technology is a promising and effective sterilization method, which has been explored by many researchers. The advantage is that it can extend the shelf life of space food without reheating it, protecting the nutritional properties (Farkas 2006). It has the outstanding advantages of simple operation, high efficiency, green, safe, minimal damage to nutrition, maximum retention of original flavor of food, and reduction of chemical additive (Zhao and Wang 2014). Today, the use of high doses of food irradiation has been extended to ready-to-eat foods, hospital diets and space food (Feliciano 2018). Food irradiation is allowed in more than 60 countries, processing about 500000 metric tons of food worldwide each year. Ionizing radiation, which was usually used in medicine and nuclear power, was patented as a microbial inactivation technique in 1905 and was first evaluated against trichinae in pork in 1921 (Negut, Bercu, and Duliu 2012).This radiation can lead to DNA and/or RNA helix breakage and damage nucleic acid through direct or indirect action leading to the destruction of normal cell function (Khan et al. 2016). The dose of irradiation depends on the product and the radiation source used. In most cases, the overall sensory characteristics of food irradiated at high doses are acceptable. However, studies have shown that irradiated food may have some undesirable sensory characteristics, such as peculiar smell, reduced viscosity, discoloration or blackening, lipid oxidation and reduced texture characteristics (Feliciano 2018). To solve this problem, radiation is

Figure 3. Photograph of ready-to-eat Kimchi as a space food (Song, Park, Park, Han, Kim, et al. 2009).

often combined with other processing techniques. Freezing, refrigeration, vacuum packaging and the use of additives (such as calcium, vitamin C and other natural antioxidants) can reduce the adverse effects of high doses of radiation. Irradiation combined with other preservation techniques, such as heat treatment, can reduce the radiation dose without affecting the quality of food (Ouattara, Sabato, and Lacroix 2001; Chen, Cao, et al. 2016; Kirkin et al. 2014).

Irradiation technology is one of the commonly used means for NASA to sterilize space food. NASA radiation tests on flour and bread showed that a single dose of 50,000 rads did not change the functional quality of flour and nutrients remained basically unchanged. Six months later the irradiated flour and bread were much better than untreated bread (Hartung et al. 1973). This research is valuable, for it helps to establish irradiation technology as an effective and safe means of food preservation. Steak is NASA's current irradiation product used on the shuttle (Song, Park, Park, Han, Kim, et al. 2009). The steaks are cooked and packaged in a vacuum package in a flexible foil bag and sterilized by ionizing radiation at ambient temperature. Bhatia et al. (2017) studied the minimum electron beam dose required for space food sterilization, indicating that 15 KGy could achieve the safety and shelf life target required for space food in the long term. In recent years, Korean Atomic Energy Research Institute have developed nutrition bar, Ramen (ready-to-cook noodle) and two traditional Korean foods (Kimchi, and Sujeonggwa) into space food by high dose gamma radiation treatment (Song, Park, Park, Han, Choi, et al. 2009; Song, Park, Park, Han, Kim, et al. 2009). In order to ensure the taste and nutrition of kimchi, calcium lactate and vitamin C were added into the product. After mild heating, deep freezing and gamma irradiation for 25 kGy, the food was processed into a ready-to-eat space food, see Figure 3. Nutrition bars, Ramen and Sujeonggwa were determined at doses of 15, 10 and 6 kGy, respectively. The above three kinds of food were all verified by the Russian institute for Biomedical Problems in its 30 days space flight. Park et al. (2012) developed ready-to-cook Bibimbap into space food by combined treatment with gamma irradiation and the results showed that 0.1% of vitamin C, vacuum packaging and gamma-irradiated at 25 kGy and -70 °C had higher sensory scores than that of pure irradiation. The product passed the shelf-life test and was certificated by Russian Institute of Bio-medical Problems so can be use in the International Space Station now (Park et al. 2012). Dakgalbi, a Korean food made mainly of chicken, has also been developed into space food or product for patients. Yoon et al. (2012) conducted a study to compare the total amount of bacteria and other physical and chemical indicators before and after product irradiation, and contrasted the difference between pre-cooking and post-cooking sterilization. Two types of Dakgalbi were prepared: Dakgalbi cooked with irradiated chicken meat and sauce ("irradiated before cooking," IBC) and Dakgalbi irradiated after cooked with raw chicken meat and sauce ("irradiated after cooking," IAC). The results showed that IBC prepared by raw chicken irradiated by 15kGy and sauce irradiated by 45kGy detected bacteria on day 2 and the number of bacteria gradually increased during 7 days of storage. On the other hand, no bacteria were detected in IAC irradiated with a single dose of 20 kGy during the 7 days storage period. This research indicated that the sequential position of gamma irradiation is also important, which will obviously affect the storage life of the product. Chen, Gao, et al. (2016) used ^{60}Co irradiation combined terminal treatment to sterilize Chinese style fried noodles. The fried noodles treated at 100 °C for 30 min, 5 or 10 kGy irradiation, and then were selected for one-year preservation test at 25 °C. The results showed that ^{60}Co irradiation combined thermal treatment could keep the fried noodles aseptic in one-year storage period, at the same time, the sensory quality of the fried noodles was better. The irradiation treatment had no obvious effect on the protein content.

High pressure processing

The current thermostabilizing process will not provide a 5-year shelf life for all formulations, as showed in Table 1, so NASA explored the emerging technologies to achieve the goal. High pressure processing (HPP) was one of the options (Perchonok and Catauro 2009). High pressure processing is a technology to process products under high pressure in order to achieve germicidal effect. High pressure conditions will result in changes in the structure of microbes and enzymes in food, resulting in the loss of physiological activity. The minimum and maximum limits of high pressure processing are 200 MPa and 600 MPa, respectively (Khan et al. 2016). In 1990s, Japan began to use high-pressure sterilization in juice, jelly and jam processing. Now, the technology has been extended to aquatic products, milk, meat, fruits and vegetables, salad dressing, yoghurt and other products sterilization (Carlez, Veciana-Nogues, and Cheftel 1995; Oey et al. 2008; Ohshima et al. 1993; Balci and Wilbey 1999; Pandrangi et al. 2014). The United States conducted a study on the processing of avocado under high pressure conditions, and the results showed that high pressure conditions do not change the taste, texture and color of the guacamole, but the shelf life of the product significantly increased from 3 days to 30 days (Brown 2000). Xu (2004) selected two kinds of Chinese traditional food, Hot and Sour Soup and Sautéed Shredded Pork in Sweet Bean Sauce, as experimental materials, and discussed the possibility of using them as space food. The results showed that the high-pressure treatment could not only maintain the flavor of fresh Hot and Sour Soup, but also partially recover the flavor loss during the process of concentration. The high-pressure treatment made the cut fiber tissue of the Sautéed Shredded Pork become blurred, but was beneficial to the improvement of texture and chewiness, without affecting the color and aroma of the finished product. However, after six months of storage, although the total number of bacteria was still lower than the national standard, the flavor changes made it unsuitable for further storage.

Due to equipment constraints in terms of cost and technical barriers, HHP technology is often used in combination with traditional heat treatment. The National center for food safety and technology in the United States has successfully developed the pressure-assisted thermal sterilization (PATS) process, which, compared with the traditional high temperature sterilization process, greatly shortens the sterilization time and improves the quality of low-acid food (Balasubramaniam, Barbosa-Cánovas, and Lelieveld 2016). The PATS process of low-acid products involves vacuum package the products in a high barrier, flexible pouch or container, followed by preheating the products to the required temperature. The temperature of the product is raised to the pressure temperature through compression heating. During the decompression period, the temperature of the product is lowered and the final product is cooled to the ambient temperature (Barbosa-Cánovas and Juliano 2008). NASA carried out a research to evaluate the shelf life of PATS food and the result showed that after three years of storage, the color and texture of PATS fruits were better than those in retort bags. Combining PATS processing with refrigeration, 5-year shelf life of the fruits can be achievable (Cooper and Douglas 2014). Besides, Vitamin content of PATS fruits can maintain longer compared with retort process fruits (Perchonok 2016).

Microwave assisted thermal sterilization

Microwave assisted thermal sterilization (MATS) is a technology that NASA had carried out in-depth research (Perchonok and Catauro 2009). It is an attractive technology that allows in-container processing and provides better nutrient retention than conventional technology. Microwave sterilization can avoid many of the problems encountered by the traditional methods, such as through the water as a heating medium can solve uneven heating and edge effects. It is a very effective food processing technique, but in some cases, it can result in the transformation of certain ingredients (Barbosa-Cánovas et al. 2014). Microwave technology has been widely used in food thawing, heating, ironing, pasteurization, cooking, drying, frying and other fields (Venkatesh and Raghavan 2004).

China has developed a new compound technology of vacuum low temperature seasoning - microwave sterilization - flexible packaging in order to solve the problems of traditional thermal treatment intensity and poor taste of canned food (Sun, Qu, and Dong 2016). On the premise of satisfying the security of storage at room temperature for a long time, the off smell of raw and auxiliary materials is eliminated, and the flavor and taste of food after sterilization are preserved to the maximum extent. NASA compared the microwave assisted thermal sterilization and the retort process to determine if a lower amount of heat input during the processing helps to protect the food micronutrients and extend the shelf life. Although the original color and texture of the MATS product were better, these advantages did not sustain, owing to the nonmetallic packaging film used in the process likely provided inadequate oxygen barrier. There was no significant difference between the MATS product and the retort processing product in terms of vitamin stability (Cooper and Douglas 2014). To achieve the 5-year shelf life of the main course and soup in wet package, it may be the future research direction to improve the packaging film used in MATS processing, and the dielectric properties formula of packaging should be optimized. There is also a need to find ways to fortify vitamins and reduce storage temperatures (Cooper and Douglas 2014).

Other promising processing techniques

Hurdle technology, a new concept of food preservation introduced decade ago, uses the interaction of various factors to control the overall quality of food and prolong the shelf life of space food. Hurdle technology refers to the scientific combination of various factors, which have synergistic effects, minimize the harmfulness of food and the deterioration of quality during processing. The potential of stabilization technologies (alternative storage temperatures, processing, formulation, ingredient source, packaging, and preparation procedures), when combined in hurdle approach, to mitigate quality and nutritional degradation is being assessed (Cooper et al. 2018).

Due to the instability of vitamin C, its content in foods may gradually decrease to below the standard value during long-term spaceflight missions, so it is necessary to study the stable strengthening method of vitamin C. To ensure that vitamins are available throughout the product life cycle, encapsulation has been identified one of the research directions (Cooper and Douglas 2014). NASA has launched a research and development project to microencapsulate probiotics, health foods, edible spices and nutrients to further ensure the nutritional health of astronauts. Neptune technologies & bioresources, Inc., has developed Marine resource health food rich in omega-3 fatty acids, and Meiners Commodity Consultants S.A. has developed sustained-release microencapsulated vitamin and trace element supplements. Heritage Fare, Ltd., has developed fat substitutes that can be used as flavor enhancers and shelf life extensions for food products (Wu and Qiang 2016).

Packaging of current space food

Requirements for space food packaging

Shelf life of foods is determined by potential of bacterial growth, nutritional degradation and quality degradation. Packaging can prevent contamination by microorganisms, protect food from physical hazards and control transmission of oxygen and water from outside environment into food (Perchonok 2014). As an important part of the space food system in manned space flight, space food packaging also has the contradiction between the protection and barrier required by the continuous extension of food shelf life and the increase of weight and volume caused by the extension of flight time (Sun, Qu, and Dong 2016). The development of safe, nutritious and acceptable food and efficient use of vehicle resources are two ends of the balance. For example, it may require more packaging mass to protect food from moisture and oxygen and meet required food system shelf life. The ideal packaging for future space missions would have to be made of nontoxic materials that do not migrate into food, without the chemical reactions that cause nutrient loss. The package is designed to prevent food from losing water or water, blocking the exchange of oxygen to prevent deterioration, blocking the light to prevent the loss of photosensitive nutrients, and to prevent microbial contamination. It should be convenient for transport, light weight, durable, capable of resisting physical strength that may alter that shape of the food, without generating unnecessary volume and producing less waste.

On current shuttle mission, most of the waste, including food packaging and food remnants, is manually compressed and wrapped in duct tape and stored until the next supply vehicle arrives (Linne et al. 2014). After the above pretreatment, they burn in the atmosphere with the returning supply vehicle (Hanford 2005). Food waste in the space shuttle accounted for 32 percent of the total domestic waste (Golub and Wydeven 1992). One of the major drawbacks of the current packaging system in terms of quality and volume is that there are actually two different packages used to combine multiple products. To provide the necessary protection and to achieve an 18-month shelf life, the food is overwrapped in a second foil containing packaging with more stringent barrier properties (Maya, Grace, and Michele 2015). NASA proposed in the sixth part of the 2015 Technology Roadmap that the proportion of food packaging should be reduced in the manned missions to the moon and Mars to achieve light packaging. The goal is to reduce the share of the entire food system from the current 15 per cent to less than 5 per cent, and to develop innovative packaging and innovative processing technologies to improve the stability of nutrients and the acceptance of food by occupants. Increase the average shelf life of food from the current one year to five years (Kliss 2016).

Edible film

Edible film materials usually include starches, polysaccharides, proteins, fats and composite materials, etc. The edible film application fields include the preservation of fresh fruits and vegetables, meat, frozen and baked products and packaging of flavoring powder in fast food (Zhang and Zhang 2011). The edible packaging film mainly prevents changes in the flavor and texture of food products during storage and transportation by preventing the migration of gas, water vapor, solute and fragrance components, thereby ensuring food quality and prolonging the shelf life of food (Hu and Zhou 2010). In addition, the purpose of nutrition strengthening can be achieved by coating. Coating materials include nontoxic biodegradable resins, beeswax, paraffin or titanium dioxide. The Food and Drug Administration has approved the safety of coatings such as jade-based resins (Sun et al. 2014). Patrick et al. (1998) conducted a research on edible peanut protein film, using the peanut flour extracted from oil, and developed two types of film. One contained 10% fat while the other contained no fat. The film containing natural peanut fat was about three times as strong as the nonfat film and almost four times as strong as the nonfat film. The study was sponsored by NASA Johnson Space Center and the product may be used as a storage package for condiments or other ingredients and as an encapsulation for pharmaceutical use. NASA has funded the Southwest Research Institute to develop a polypeptide film which could isolate bacteria and prevent water loss while prevent food from breaking. The manufactured samples have good barrier properties, but due to their high tensile strength, they are not suitable for use as food coatings but have been used in artificial temporary skin (Hartung et al. 1973).

As far as the recently developed technology is concerned, the performance of edible film is not high, the tensile strength, sealing performance, water resistance and high temperature resistance are poor, and the barrier performance does not meet the requirements of long-term manned missions yet. The effectiveness of edible films is far from meeting the requirement of 3-5 years shelf life of spaceflight food. But during long-term missions or the establishment of a Mars base it may be used for short-term storage of dry materials such as flour because it is degradable and does not produce garbage (Sun, Qu, and Dong 2016).

Metal can

Metal can packaging materials including tinplate, aluminum alloy, etc., with a good barrier properties which usually keep the food shelf life of up to 3 years. During the Skylab program, most of the food was packaged in aluminum cans to maintain the 2 years shelf life (Klicka and Smith 1982). Frozen and heat-stabilized foods are packaged in aluminum cans, with a headspace under the lid to prevent the contents from spilling over when the temperature changes. The aluminum canisters will be sealed in another tank to withstand absolute pressure variations of 14.7–5.0 lb/in^2 between ground and space (Perchonok and Bourland 2002). To reduce the oxygen content of the headspace gas, each can is evacuated and flushed a minimum of three times with nitrogen before sealing.

This packaging technology is currently used in manned missions, such as the international space station food provided by Russia, including the metal packaging form (Sun, Qu, and Dong 2016). This packing has a good barrier, but it's also heavy. In the long-manned flight mission, the heavy packaging and the difficulty in garbage disposal make this packaging form unsuitable for use.

Retort pouch

To save on volume and mass, retort pouch made from a laminate of flexible plastic and metal foils came into use. The soft packaging was developed by the United States Army Natick Research and Development Command, Reynolds Metals and Continental Flexible Packaging to replace tinplate cans for battlefield use (Demetrakakes 2006). Such packaged food can be placed at room temperature and has a long service life. It can be eaten cold or hot, which is convenient to use and can save energy needed for preservation. It replaced rigid rectangular rehydratable packaging, and a waste compactor compatible with the packaging was developed to reduce waste volume (Casaburri, Gardner, and George 1999). Thermostabilized and irradiated foods are often packaged in flexible pouches. The retort-processed products can ensure the safety and nutritional value of food, and make the products highly acceptable. This packaging method has the great potential to maintain the sensory texture acceptability of food during the storage period of 3–5 years. Fabricated from a quad-laminate of polyolefin/aluminum foil/polyamide/polyester (Prisco 2014), the oxygen and moisture permeation of the package is almost zero. NASA's research shows that the metalized film overwrap significantly decreased the progression of the rancidity of butter cookies as compared to the highest barrier non-metalized film (Cooper and Douglas 2014). Catauro and Perchonok (2012) conducted a series of 36 months accelerated shelf life studies on 13 typical retort pouch products to determine whether they are suitable for long-term space flight. Using comprehensive sensory evaluation, physical property assessment and nutritional analysis to determine the expiry date of these foods, it is expected that the shelf life of meat products and other vegetable imports can be extended to 2–5 years without refrigeration, fruits and desserts are preserved for 1.5–5 years, dairy products for 2.5–3.25 years, starch, vegetables and soup products for 1–4 years (Catauro and Perchonok 2012).

High barrier packaging

Packaging material with high water vapor and oxygen barrier properties was developed during the Gemini mission (1965–1966) (Perchonok and Bourland 2002). Its high resistance to oxygen and water vapor helps to protect the flavor of food. The barrier layers of such packaging materials include EVOH, SiOx, alumina and titanium oxide, etc. (Sun, Qu, and Dong 2016). Ethylene-vinyl alcohol (EVOH) copolymer is the most widely used high barrier materials, not only has good barrier performance, but also has advantages in physical strength. Compared with traditional materials, these high-barrier film materials have better barrier effect on oxygen and water vapor, and can guarantee the stability of packaging contents in the environment of high temperature and high humidity. This packaging material can be used to pack acidic, medium-moisture foods and dehydrated foods (Sun, Qu, and Dong 2016). During the Skylab program, cabin temperature could be as high as 54 °C, because of the effect of high barrier packaging, food with browning but still edible (Perchonok and Bourland 2002).

Other packaging with application prospects

NASA has put forward requirements for new packaging. It should have same barrier properties as the thermostabilized pouch, which oxygen permeability lower than 0.0003 cc/100 in^2/day and water vapor permeability lower than 0.0004 cc/100 in2/day (100 °F, 100% RH). It also has to be foil-free, flexible and transparent, so as to accommodate microwave or pressure assisted thermal sterilization process as well as vacuum packaging, and easy to observe broken pieces (Perchonok 2011).

Nanomaterials have a broad application prospect in the aerospace food packaging, because of its ability to produce light weight, high strength, good barrier, multi-function and other characteristics of food packaging. The nanomaterials containing composite packaging can meet the requirements of space food packaging materials. Nanomaterials have the characteristics of providing high barrier, high flame retarding and thermal stability, which can assist in extending the food shelf-life up to 3–5 years (Sun, Qu, and Dong 2016). The study of polymer nanocomposites mainly focused on the synthesis of polyethylene, polypropylene (PP), polystyrene, poly (caprolactone), polycarbonate, PAS, vinyl alcohol (EVOH), poly (ethylene terephthalate) (PET), etc. (Nguyen and Baird 2006). Polymer nanocomposites not only have better gas resistance, can reduce oxygen, water vapor diffusion and volatile food aroma, but also have excellent physical properties (Sablani 2016). With the improvement of

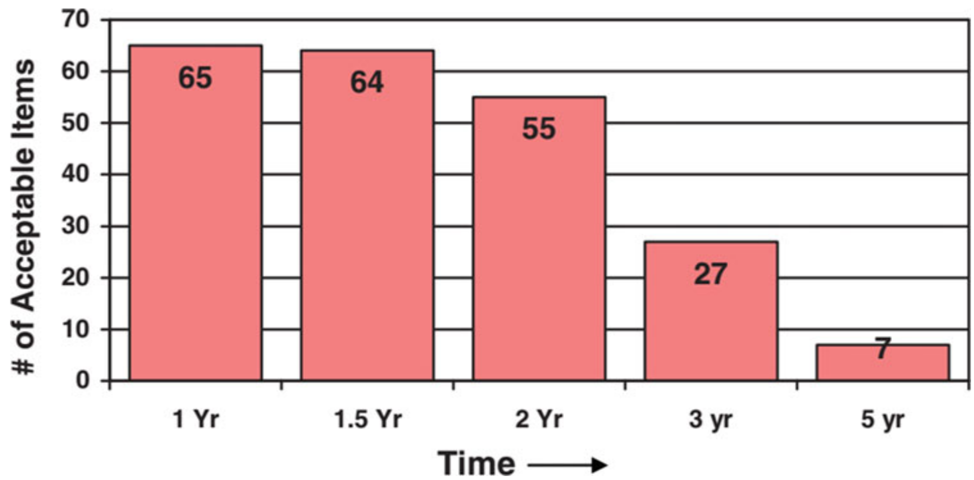

Figure 4. Number of thermostabilized space foods as shelf life extends to 5 years (Maya, Grace, and Michele 2015).

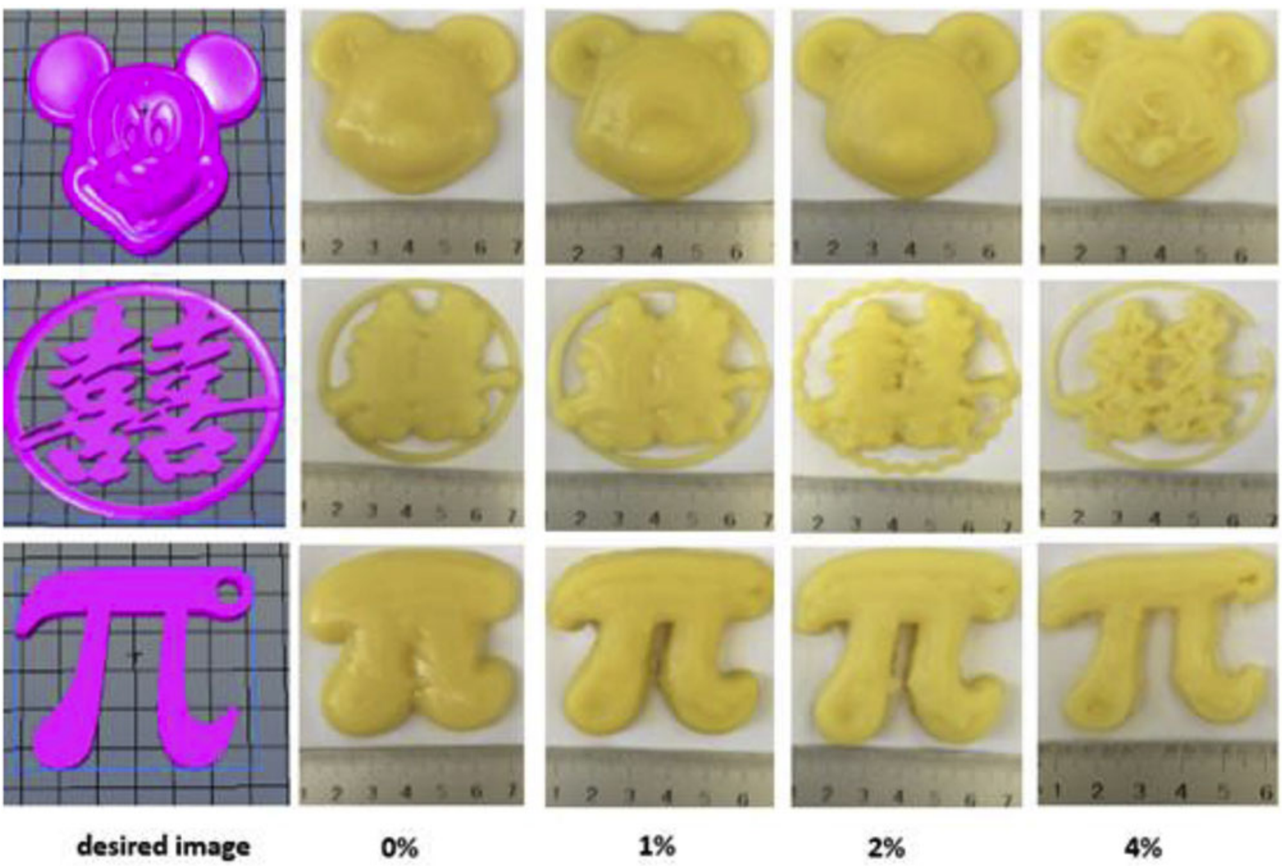

Figure 5. Desired images and printed objects using mashed potatoes with addition of different concentrations of potato starch (Liu, Min, Bhandari, and Yang 2017).

their safety and reliability and the enrichment of their functions, nanomaterials are more and more likely to be used in long-term manned missions.

Hurdle technology can also be used in food packaging. If factors such as alternative storage temperatures, processing, formulation, ingredient source, packaging, and preparation procedures are combined with hurdle approach, it will be more beneficial to control the quality and nutrition of food. NASA selected 16 representative foods from the International Space Station for evaluation and analyzed them in 1, 3, and 5 years, if necessary, for seven years. The analysis indexes included color change, texture, nutrition, sensory quality, and water replenishment rate. Packaging film barrier performance and mechanical integrity will be evaluated before and after processing and storage. If tested hurdles are adequate, formulation, processing, and storage combinations will be uniquely identified for processed food matrices to achieve a five-year shelf life (Cooper et al. 2018).

In addition to the use of special packaging materials, the shelf life of food can also be extended by means of inert gas flushed packaging. In order to maintain the appearance and taste of fresh bread, NASA designed a method that involved

Figure 6. NASA Image: ISS043E160241. Image of the ISSpresso machine taken by the Expedition 43 crew, available at https://www.nasa.gov/mission_pages/station/research/experiments/1769.html.

cleaning the package with 70% ethyl alcohol and then flushing bread and package with nitrogen three times, and then individually packaging each piece of bread in a sterile environment. Bread samples are stored for more than 14 weeks without mold (Hartung et al. 1973).

Conclusion and remarks on future space food system

On-orbit food preparation system

With the rapid development of aerospace industry, aerospace food is gradually developing toward production scale and variety diversification. At the present stage, the food supply mode is mainly the processed and prepackaged space food system (Cooper, Perchonok, and Douglas 2017). This model is not only limited by the uplink load capacity of the spacecraft, but also limits the choice of varieties and tastes of the astronauts. It is difficult to achieve a good eating experience similar to that in daily life. Space food quality and nutrition degrade to unacceptable levels in two to three years with current food stabilization technologies, as showed in Table 1. Future exploration missions will require a food system that remains safe, acceptable and nutritious through five years of storage within vehicle resource constraints. The United States and Russia are leading the world in the field of Mars exploration. In recent years, Russia has carried out the MARS 500 manned Mars simulation experiment, and the United States Mars exploration vehicle successfully landed on Mars (Salotti and Heidmann 2014). The space activities have gradually entered the Mars era.

Long-duration manned spaceflight missions, including remaining on the moon and planetary surfaces, can last up to 2.5 years (Perchonok and Bourland 2002). Food may be placed on Mars before the crew arrives, so it is expected that the food used during the mission will take 5 years of shelf life (Perchonok and Catauro 2009). A estimate carried by NASA has shown that only 7 out of 65 thermostabilized foods now on the menu are expected to be palatable after 5 years of storage (Perchonok 2014). Figure 4 shows the decline in acceptable products over a period of five years. It is imperative to develop new food system and new technology of food preparation in orbit. In these long-term exploration missions, the main goal of the food system is not only to provide the crew with safe, delicious and nutritious food, but also to minimize the volume, weight and waste of food.

The on-orbit space food preparation needs to solve many problems, the emergence of 3 D printing brings a new mode of food processing. The primary purpose of 3 D printing food is not just to be tasty, but also for the long-term preservation of food by using food raw materials when human beings survive in space. If 3 D printing can be used in space, it can save a lot of supplies. Using 3 D printer, the form, texture and flavor could be more appealing. At present, NASA has carried out the pre-research of the on-orbit processing technology of food, and has designed the prototype of the principle (Perchonok et al. 2012). In November 2014, the International Space Station ushered in the first espresso coffee machine that called ISSpresso (Tana and Hall 2015), see Figure 6. Produced by Argotec and Lavazza in collaboration with the Italian space agency (ASI), it weighs about 20 kilograms, is larger than a traditional coffee machine and works under high-pressure conditions. Instead of grinding beans, the machine uses pre-encapsulated espresso, tea and soup to produce hot beverages and consommé. In the microgravity environment, in order to successfully discharge water, the coffee machine needs to work under high pressure. The plastic pipe inside the coffee machine is changed into a steel pipe that can withstand high pressure. The coffee was sent into sealed plastic bags and the astronauts drank it

Table 1. Comparison of various processing processes.

	Process	Earliest application	Advantages	Disadvantages	Shelf-life	References
Previous advance food technology (AFT)	Freeze-drying	Mercury (1961-1963)	Odor, color and flavor of food is usually natural; light in mass	High cost, about four times more than conventional dehydration	1.5-2.5 years	(Perchonok and Douglas 2018; Casaburri, Gardner, and George 1999; Perchonok et al. 2012; Lane et al. 1995; NASA 1995)
	Retort thermostabilization	Apollo (1968-1972)	Good taste, easy to eat and less residue	The added weight of package is large	2-3 years	
	Irradiation	Apollo (1968-1972)	Using a certain dose of ionizing radiation to destroy the microbial structure of food	Irradiated food may have some undesirable sensory characteristics	2-3 years	
Emerging joint thermal technology	Pressure assisted thermal sterilization (PATS)	Still in the development stage	Less damage to vitamins A and C, thiamin, and folic acid	May have a negative effect on meat color; may exacerbate certain biochemical reactions leading to indirect nutrient destruction	Target for 5 years shelf life	(Maya, Grace, and Michele 2015; Michele 2011; Perchonok 2014; Perchonok and Douglas 2018; Barbosa-Cánovas et al. 2014; Balasubramaniam et al. 2016)
	Microwave assisted thermal sterilization (MATS)			Non-uniform distribution of electromagnetic field; possible edge overheating effect		
On-orbit food preparation technology	3D printing	International Space Station (2000-present)	Can customize according to the nutritional needs of different people	Printable materials need to be developed in depth; need to solve the problem of machine lightweight, intelligent	Product has no long shelf life requirements	(Liu, Min, Bhandari, and Yang 2017; Liu, Min, Bhandari, and Wang 2017)

through straws. Astronaut Samantha Cristoforetti drank her first espresso in space in 2015 (Povoledo 2016). ISSpresso is one of nine experiments chosen by the Italian space agency for Samantha Cristoforetti's Futura mission, and because it is difficult to make coffee in space, its birth shows that Italy has earned a place in space manufacturing (Argotec 2015).

Life support system

Life support system will become one of the major development directions for aerospace organizations in future projects. NASA has built an environmental control and life support system called ECLSS (Carrasquillo 2005). Now, space agencies are actively exploring the feasibility of growing vegetables on the International Space Station and the idea of using edible vegetables for salad making on spaceship is put forward, which is the first step of controlling ecological life support system in closed space environment(Massa et al. 2016). NASA's initial trials included red rose lettuce and Zinny, as well as cabbage and tomatoes (Massa and Gioia 2016b).Green plants plays a vital role in the life support system. On the one hand, the photosynthesis of green plants can absorb carbon dioxide to make oxygen to maintain the air circulation system, on the other hand, they can be used to increase the dietary diversity of crew members to meet vitamin and dietary fiber requirements (Kliss et al. 2000; Berkovich et al. 2009). At the same time, eating an antioxidant-rich vegetable helps to reduce the harmful effects of space radiation on the crew (Levine and Paré 2009; Smith and Zwart 2008). In addition to the dietary significance, vegetables are also considered an attractive option for improving the living conditions on board and providing psychological benefits to the crew. Many researchers are working on the development of onboard salad production facilities, and the international space station has successfully installed a small salad machine called LADA to provide an occasional source of vegetable food and entertainment (Sychev et al. 2007).

It has been established that microgravity does not considerably alter plant growth (Monje et al. 2005). Veggie is a vegetable production system with the characteristic of compact, low mass and low power (Massa and Gioia 2016b). It consists of a light cap containing red, blue, and green LEDs, an extensible transparent bellows, and a baseplate with a root mat reservoir (Massa and Gioia 2016a). Eldemire (2007) carried out an experiment to compare the effect of fluorescent lamps in an Orbitec Biomass Production System Educational (BPSE) with a combination of red, blue, and green LED's in a Deployable Vegetable Production System (Veggie), the result showed that the Veggies clearly exceeded the BPSE. Veggie was launched to the International Space Station (ISS) in 2014 (Ehrlich et al. 2017). Vegetable crops for consideration include carrots, tomatoes, lettuce, radish, spinach, chard, cabbage, and onion (Perchonok et al. 2002). A series of tests including color and moisture were carried out and sensory evaluation was carried out to compare the results with those of ground crops. Massa and Gioia (2016b) conducted a series of studies, which initially included red romaine lettuce and zinnia, while Chinese cabbage and tomatoes are as follow.

The scientists suggest that in order to ensure the health of the astronauts, sufficient animal proteins should be ingested, and the metabolism in the process of obtaining animal proteins can be combined with the material circulation in the closed system. Therefore, various countries have carried out a variety of research on the breeding of animals in space. Since fish and amphibians have a short life cycle, they are ideal space food. Currently, the fish selected for research mainly include carp, rainbow trout, tilapia and swordtail fish, etc. (CNR 2018). European countries and Japan have studied sea urchins, snails and salamanders. However, these animals are sensitive to feeding conditions, especially living water conditions, so space feeding is still in the experimental research stage.

Chinese researchers are taking a different approach, proposing insects as candidates for life support systems. Previous experiments have shown that large animals, such as cows and sheep, are not ideal. Because in the confined and narrow space, lonely experimenters develop feelings in the animals they feed every day, and if they end up eating their fellow animals that accompany and feed each other day after day for survival, there will be strong psychological swings (CNR 2018).

Silkworm is first selected and expected to be a good choice rich in animal protein during astronaut interstellar travel (Cui and Yu 2006). By the same weight, the protein content of silkworm chrysalis is much higher than that of eggs. Five to six silkworm chrysalis are equivalent to one egg's nutrition, and the amino acid content of silkworm chrysalis is several times higher than that of pork, mutton, eggs and milk. Silkworm protein also has the characteristics of short harvest time, only a month. Silkworms do not need water or produce waste water. While space can't provide silkworms with mulberry leaves, their staple food, researchers have found that they can use lettuce as an alternative to silkworms (Cui and Yu 2006). In 2014, China's first Bioregenerative Life Support System (BLSS), Moon Palace No.1, successfully introduced mealworms into BLSS for the first time. As an important link in the Moon Palace No.1, mealworms can not only provide abundant edible protein for crews, but also degrade some wastes in the cabin, thus accelerating the material circulation. The dry weight protein content of the mealworm that feeds on plant waste is up to 76.14%, which is much higher than that of the mealworm that feeds on traditional feed. Its dry fat content is as low as 6.44%, much lower than other animals (Lunar-Palace-No.1 2017). The mealworm is sometimes eaten fried, which tastes like French fries. It can be sometimes fried and dried into powder and mixed with flour to make steamed bread and steamed buns (CNR 2018).

In all, as national space agency missions expand from short-term manned space to international space stations and long-term space exploration, the space food system has to evolve. The increasing autonomy of these tasks requires moving away from complete reliance on shipped prepackaged food systems and requires staff to demonstrate increased reliance on bioregenerative food systems. In addition, the development of new light weight and durable space equipment, such as food heating and refrigeration equipment, or machinery for processing, should also be carry out.

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