The Future is Fresh: Creating a Fresh Crop System for Extended Space Flight

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Abstract

With the horizon of space travel set for humans landing on Mars, the duration of flights could last as long as five years. As with any space shuttle, the success of the mission can only be carried as far as the fuel will allow. This concept is no different for food. Crew members depend on a stimulating, nutritious food source to sustain the team for the entirety of their time in space. Individuals who choose to work in such extreme conditions have indicated they would be positively impacted by the availability of fresh produce and the option to cultivate their food. Initial research with the Vegetable Production System, Veggie, aboard the International Space Station (ISS) is testing the feasibility of a fresh crop system in microgravity conditions. Though the current production system on the ISS does lay the groundwork for variety and palatability for fresh food production, there is still more to consider before humans can grow and meet proper nutritional and energy intakes for long-duration, manned missions. Scientists, such as those working on Astro Garden ™, are quickly innovating and developing ways to sustainably and efficiently cultivate crops in microgravity conditions. Other factors, such as preservation and food safety, still require further research to make fresh food in space a reliable source of nutrients.

1. Introduction

As space travel duration increases, so does the necessity for sustainable food sources in space flight. With a race to explore habitation on Mars, human shuttle duration could last as long as 5 years. According to research by Taylor et al., 2020[1], scientists estimate a six-member crew on a three-year mission to Mars will need 1.8kg of food per person per day. There is a launch cost of around $15,000/kg. This totals about $180 million just to feed the crew members. To support the realization of lengthy missions, scientists are working to find ways to extend the shelf life of current space foods or develop capabilities to grow fresh food sources in flight. Currently, the main target of research is salad crops. These crops, such as lettuce, tomatoes, and carrots, can be used in the early stages of lunar or planetary visits. With the addition of fresh crops, the space menu will provide more texture and color apart from the freeze-dried concoctions astronauts are known to consume. A variety of foods can help increase psychological well-being, which is equally as important as nutrition in space flight [2]. To bring this ideation of science and biology to reality, there is preliminary research being conducted aboard the International Space Station (ISS) to assess the feasibility of fresh produce in space.

Solving the issue of providing astronauts with feasible, nutritious food is not a new concept for space programs throughout the world. Project Mercury, started in 1958, pioneered the way for the development of food in space. Crew members tested the impact of chewing, drinking, and swallowing foods in zero-gravity conditions with foods such as "bite-sized cubes, freeze-dried cubes, and semi-liquids in aluminum toothpaste-type tubes" [3]. The consistency and preparation of the food were unappetizing and problematic for astronauts. Because of this, scientists developed bite-sized, freeze-dried cubes that rehydrated with saliva. Researchers also looked at innovating packaging for the materials to keep the food quality fresh and lightweight. By the time the 1965 Gemini Project launched, scientists had made massive improvements by way of packaging and rehydrating food sources. This mission now contained foods like grape and orange drinks, cinnamon sprinkled toast, fruit cocktail, chocolate, turkey, and soups.[3] The more palatable the food evolved, the more the astronauts were willing to eat. This became a major issue as science pushed mission duration timelines and human capability in space. A culmination of research and development as laid out by previous space flights such as the Gemini and Project Mercury mission have greatly influenced the food science achieved today. Astronauts crave a taste of home and variety, and with technology developing at a rapid pace, the possibilities can only go as far as the energy source allows.

2. Effects on adequate energy intake in microgravity conditions

Deep space missions have become a scientific plausibility. Humans need food to survive, and the need for fresh, nutritious, and good-tasting food, is evolving. The palatability and variety of food selection are extremely important. Some may wonder, why can't astronauts just take nutrient supplements to sustain their missions? While it is important to consume essential nutrients for optimum functionality, the appearance, taste, and texture of the food presented to individuals are just as necessary. The body's goal is to "maintain food intake so it meets the body's needs for energy, repair, growth, etc. It is now apparent that taste and smell receptors are part of this regulatory process." [4] Nutritional status in humans is controlled by feelings of hunger of satiety as food is eaten and broken down. Taylor et al. [4] suggest there is more than just hunger that drives the mechanism for controlling food consumption. The research suggests food consumption can be divided into two phases: food intake and food uptake. [1] While eating, chemosensory receptors interpret signals as a flavor and regulate the uptake of nutrients from the gut. If the food that is presented does not offer an enticing flavor or aroma, the product is rejected by our senses "presumably to avoid toxic compounds or spoilt foods that may contain food poisoning organisms" [4] In microgravity, there are some factors that could potentially be affecting the way crew members perceive flavor. This could ultimately be the culprit for low calorie consumption among those in space. These properties are laid out in Figure 1 below.

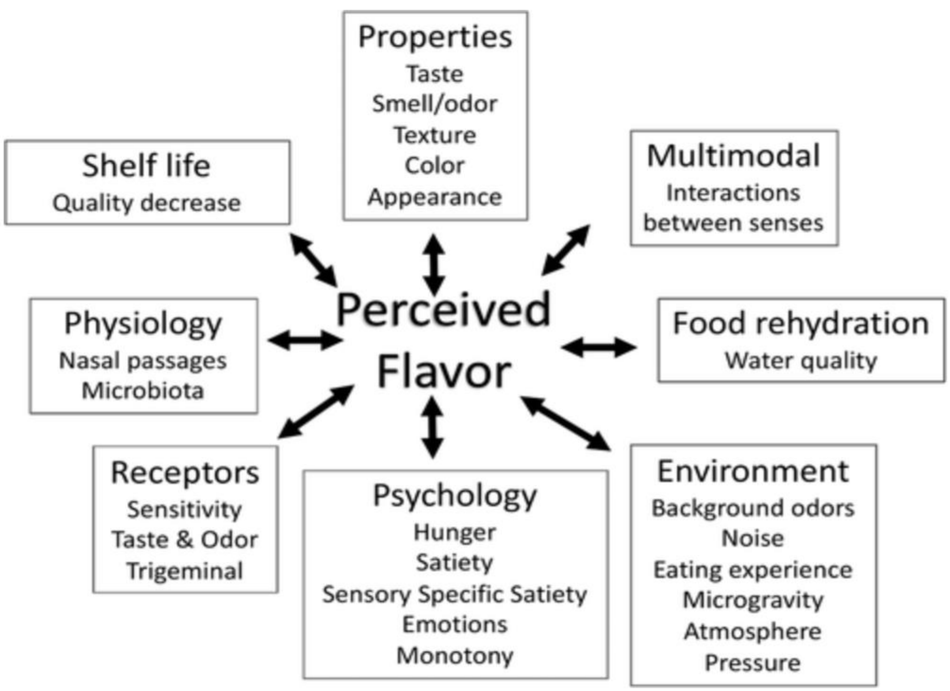

Figure 1: Factors that have the potential to affect the flavor perception of foods in space [1]

Important factors to consider when looking to alter the current food system include properties (sensory influence), multimodal interactions, psychology, and shelf life. Sensory properties of food and how they are perceived by crew members in space are shown to have some impact on how much and what food astronauts eat. There is a great effort by scientists to provide the crew with a variety of foods and textures. Even with the efforts, astronauts report having a shift in food preferences during space flight. [1] Multisensory flavor perception details how foods interact with one another and how that is ultimately perceived by the senses.

The degradation of food may produce an off-putting odor or background note in the product. This could jeopardize the palatability and the way the body consumes the product as a whole. The factors that drive psychology behind astronaut food consumption are still relatively unclear. From an Earth perspective, emotions such as stress or general mood can sometimes play a pivotal factor in how much food is consumed. Broadly speaking, providing astronauts the ability to grow their food selection could generate a certain emotional response in the individual and promote feelings of satisfaction when eating. This could, in turn, drive the individual to eat more. Lastly, the shelf life can have an overall effect on the direct quality of the food product. Though scientists can preserve the safety of food for years-long duration missions, it is almost impossible to stop chemical changes in the food. This can alter the characteristics of the product such as color, smell, and general appearance. [1]

Along with analyzing the palatability of food products and how space can affect key components of product conception, the food that is grown has to not only prevent essential nutrient deficiencies but also optimize the food system to promote health and performance. Analyzing results from a study of 15 U.S. ISS crew members, the average energy intake of the crew was 74% of what the World Health Organization recommends.[5] This is less of a concern for short-term missions, but as the duration of space flight increases, "chronic inadequate energy intake could lead to weight loss over an extended period, along with possible accelerated muscle and bone loss" [5] To combat the degradation of the mental and physical well-being of crew members in space flight, scientists are pioneering small-scale inflight food growth and are providing the basis for what will be the future of food grown in space. Astronauts require appealing and fresh food, like everyone on earth, to be able to maintain their appetite and, ultimately, their health. When in microgravity conditions, this becomes increasingly more important.

To better quantify crew members' needs and desires regarding fresh produce, a study was conducted with the former and present crew of Neumayer Stations. These German research stations are location in Antarctica in the Atka Bay on the Ekström Ice Shelf and were built to research ocean and atmospheric data crucial to observing climate change. Individuals who work at the Neumayer Stations undergo similar emotional and physical challenges as those who live and eat in space due to the long, isolated periods in a desolate location with high reliance on technology and minimal resupply missions. The conducted study looked further into food acceptability and possible psychological benefits of having a plant production system for crew members in isolated conditions. The research consisted of 107 former and present crew members from three different stations: Georg-von-Neumayer (1982-1992), Neumayer II (1993-2009), and Neumayer III (2009-present).[6] These members were surveyed with a series of standardized questions. Respondents were asked if the availability of fresh produce grown at the station would have improved their overall wellbeing, presented with candidates of produce choices for growth, and asked which produce variety they ranked as most important for growing. According to the study conducted by Mauerer et al. (2016) that surveyed individuals who work in the Neumayer Station III, a remote research facility supporting the EDEN ISS, 85% of those who worked there in the long, winter darkness indicated the availability of fresh fruit, vegetables, and herbs grown at the station would have improved their overall well-being.[6] Data from the study suggests "61% of respondents rates the 'Pleasure of fresh fruit and vegetable consumption' as more important and 'Positive psychological benefit' was rated as most important by 21%" [6] It is evident the accessibility to fresh produce for those in isolated conditions will greatly improve the overall well-being of crew members.

Respondents were also asked what fruit or vegetables they missed most during their stay in the stations. They were given the options of tomato, strawberry, bell pepper, cucumber, and the option to fill in their own answer. 77% of participants chose tomato as the fruit they missed most and added options like apples, banana, carrots, potatoes, and citrus.[6] Crew members were also asked what leafy greens they missed most as well. They could choose either leaf lettuce, green lettuce, arugula, or iceberg lettuce. Participants also had an option to submit a different answer than the ones provided. 56.8% of respondents missed leaf lettuce the most, followed closely by green lettuce at 51.1%. Lastly, crew members were asked to indicate which herbs and condiments they missed most in their isolated stay. 73% said basil was the most missed followed by 64% chives and 45% parsley. Of these three categories of food, 71.6% of respondents said they missed fruits and vegetables the most, as indicated in Figure 2 below.[6]

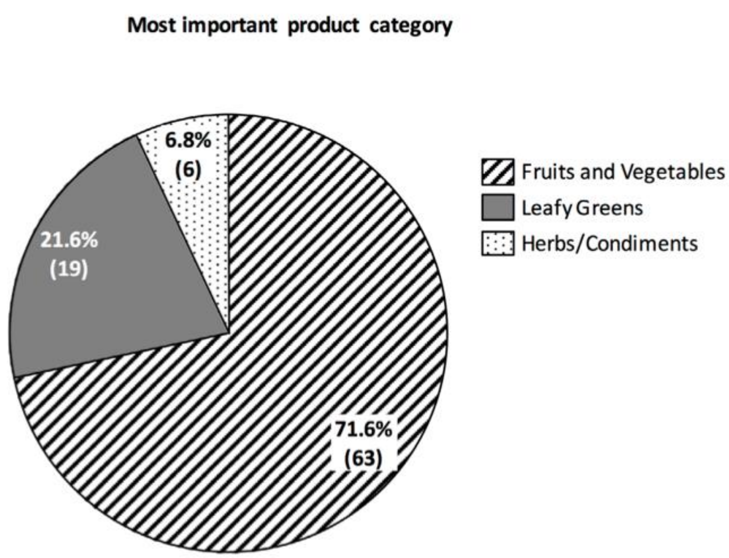

Figure 2: Most important product category [6]

To round out the research, the crew were asked to answer if they would have volunteered to care for and cultivate crops in their free time. Even with little free time, 84% of the crew said they would have volunteered to care for plants. [6] The demand to have a rewarding project that promotes team comradery and not only benefits the senses but also increases mental and physical well-being is high for individuals in such an isolated environment.

3. Fresh crop growth in the International Space Station

The National Aeronautics and Space Administration (NASA) is running an experiment that began in 2014 with a Vegetable Production System, Veggie, to test the viability of plant growth in space to combat the growing need for progressive food sources as space travel duration increases. Veggie's purpose is to help scientists observe plant growth in microgravity conditions while examining the effects of fresh food on the astronauts' diets, happiness, and well-being. NASA payload scientist for Veggie, Gioia Massa, details the device as "an internal growing area of 11.5 inches wide by 14.5 inches deep, making it the largest plant growth chamber for space to date."[7] The current space garden has room for six plants that grow in a "pillow" made with Teflon-coated black Kevlar and a Nomex bottom filled with calcined clay-based growth media and fertilizer. The seeds are maintained with a controlled-release fertilizer and water. Veggie uses a wicking system in the pillow to maintain the water source to the plants and keeps the seeds secured in place with guar gum as a "glue." [7] The light source for the produce comes from a LED panel with red, blue, and green color. Because plants reflect the majority green light and use red and blue wavelengths, the Veggie system is known to glow a magenta pink. [7]

The first food crop grown in space with the use of Veggie, VEG-01A, was by astronaut Steve Swanson in 2014. He grew red romaine lettuce for 33 days. When selecting what crops to grow on the ISS, it is important to consider the food that will positively supplement the current space diet. Research has shown essential human nutrients are not consumed or are easily degraded over time in the pre-packaged foods that are consumed by astronauts in the space station. This problem can be solved with the supplementation of fresh salad crops that will provide important antioxidants and phytochemicals from whole foods [8] Ultimately, red romaine was chosen based on the food's "reliable germination, rapid growth, attractiveness, low native microbial levels, palatability, and antioxidants" [7] Of the six seeds planted, three germinated and grew. The crew cites the 50% success rate to watering issues aboard the ISS. Half of the red romaine was harvested for consumption and half was frozen and returned to earth for analysis. The samples returned from the flight were screened for E. coli, S. aureus, Salmonella sp., with negative results. The total yeast and mold counts were below the upper limits, except for flight plant C, which was the largest sampled plant. Those bacteria and fungi that were isolated from the product samples were found to be typical microbes found on the ISS. From these results, the first food grown on the ISS posed no health threat to the crew aboard the Space Shuttle.

Following the relative success of specimen VEG-01A, the red romaine, scientists began analyzing a different variety of plants. VEG-01C, Zinnias, was the first flowering plant to be grown in the Veggie project. This is important for researching the prospect of growing flowering fruits in space. The subsequent trials involved VEG-03 A, B, C, which targeted research on "cut-and-come-again" harvesting. This method involves harvesting the older, outer leaves of the plant and leaving the center of the plant to continue to send new leaves. Scientists also experimented with 'Tokyo Bekana,' a Chinese cabbage. This plant grew but had a negative response to the high CO2 levels on the Space Station, which led to more extensive testing of crop samples before choosing them for growth prospects in space. [7]

At the launch of VEG-03 D, E, F, there was a second Veggie habitat sent up to the ISS to provide for more continuous cut-and-come-again harvesting. Following these studies, even more crops were sent up into orbit. VEG-03 G, H, I focused on the combined growth of crops such as Red Russian Kale, Dragon Lettuce, Wasabi Mustard, Extra Dwarf Pak Choy, and 'Outredgeous' lettuce. In this trial, varying water needs among the plants was a cause for decreased crop growth when grown in combination. The current project growing on the ISS as of May 2020 involves research in the study of impacts of red to blue to green light. With this test, scientists will also be researching the "nutrient composition, organoleptic appeal, and microbial food safety with additional assessments of crew behavioral health." [7] In the future, the crew is looking to add cooking capabilities on the ISS to supplement more calories into their salad crop diet with foods like white potato and sweet potato.

The research that has been conducted is crucial for determining the viability of germinating plants in space systems. With the success of crop growth, scientists are now seeking improvements to the small-scale Veggie system and the possibility of scaling up for years-long missions. To provide astronauts with adequate energy and nutrient sources, methods of production will have to be sustainable for crew members to navigate the cultivation of plants and within mission constraints by weight, safety, and cost.

4. Astro Garden ™ and the potential for large-scale crop production

Current research is searching for a method of irrigation and nutrient delivery system that will satisfy all discussed requirements. Scientists from the Sierra Nevada Corporation (SNC) [9] have been developing an aeroponic system called Astro Garden ™. The goal of this system is to provide a large-scale growing system that eliminates the need for rooting media, which presents an opportunity to reduce mass requirements. In aeroponics, the roots are exposed to air and a nutrient solution is applied directly to the root. According to the study by Moffatt et al., "aeroponics can function the same in 1-g as it does in microgravity for nutrient delivery; because of the relative droplet size (50 microns) and the velocity at which the droplet is discharged, the inherent momentum of the particle overcomes the effect of gravity acting on the particle mass." [9] Research is still ongoing in Phase 2 of Astro Garden ™ to help close the loop on their existing system. There are two distinct zones within the system, a root zone and a shoot zone. This prevents the LED lights from reaching the root zone, while also allowing sprayed nutrients to stay within the roots. The lighting used in the system is comprised of a single, multi-channel panel distributed with red, white, and blue LEDs. Another component of the system is a Water Processing Module. This helps to mix and recover used water for plant use. Water that is nutrient depleted is pumped back to the mixing tank, and humid air is recovered and sent to the Water Capture Device. These devices are the main source of pumping nutrients to the root zone. [9] Researchers for the Astro Garden TM. are hoping to test the systems in extended microgravity conditions aboard the ISS to better understand how this may affect the current nutrient delivery and recovery techniques.

5. Selection of crops for space application

After establishing how to effectively grow plants in space, scientists will need to narrow down exactly what plants will be able to grow and thrive in the variable conditions of space. Focusing on a study in the Future Exploration Greenhouse (FEG), scientists Dueck et al. [10] outline the relative importance of the main aspects and underlying criteria for crop selection for the FEG. The FEG has a larger cultivation area than other growth chambers, such as the International Standard Payload Rack (ISPR), with a focus on maximum fresh food production and a continuous daily flow of fresh food. The FEG has been modeled for the Neumayer Stations as mentioned previously. Initial data is based on the decision to exclude plants that do not meet criteria such as edible, ready-to-eat, or plant size. The results for the most important criteria for FEG are listed below in Figure 3.

Table 1: Importance of main aspects and underlying criteria for crop selection for FEG [10]

Main aspect		Criteria within each Main aspect					
		Yield		Cultivation		Quality	
Yield	100:100	Light use efficiency	100:100	Handling time	100:100	Taste	100:100
Cultivation	70:30	Space/time efficiency	55:45	Disease resistance	50:50	Appearance	55:45
Quality	80:20	Harvest index	70:30	Spread harvest	50:50	Texture	50:50
				Shelf life	95:5	Pungency	95:5

*ranking: yield (100:100) > cultivation (70:30) > quality (80:20)

Yield was listed as the most important aspect of growth in FEG, as noted by the continuous goal of fresh food production (100:100). This was followed by cultivation (70:30) and quality (80:20). [10] Under yields, light efficiency was listed as the most important factor for production. The main priority for light availability is making sure there is the proper utilization of the light spectrum and intensity. When a plant is provided the proper level of light, this also influences quality increasing compounds such as phenolic compounds, ascorbic acid, and anthocyanins. [10] Within cultivation, handling time, such as pollination, pruning, and harvesting, is stated as the most important factor. Scientists want the food that is grown to have the shortest, easiest, and most sustainable plant cycle as possible. Table 2 below scores produce based on best to cultivate and worst.

Table 2: Ranking of selected crops to be cultivated in the FEG[10]

Crop	Score	Crop	Score
Lettuce	48.8	Spinach	14.6
Cucumber	37.9	Swiss chard	11.9
Dwarf tomato	26.9	Bell pepper	10.8
Chives	26.3	Red mustard	8.0
Tomato	26.3	Coriander	7.9
Strawberry	17.3	Water cress	6.7
Radish	16.9	Basil	2.9
Parsley	14.7		

Based on the factors mentioned in Table 2 above, lettuce is the number one crop listed in Figure 4 as it has an extremely short plant growth cycle. Crops such as cucumber, bell pepper, and tomato are high on the list due to the yields each plant can produce per cycle, making it efficient for continuous fresh crop production. [10]

6. Preservation of fresh food products

After scaling-up the growth of food products, it will need to be stored. Food preservation is an ongoing issue when it comes to fresh crop growth in space. With eyes on the horizon set to Mars, the food will need at least five years of storage, and packing a refrigerator or freezer on board is easier said than done. Currently, fresh foods are loaded onto the Space Shuttle less than 24 hours before launch. The shelf life of these products is a fraction of what is needed for the future of extended space missions. The fresh foods "must be eaten within the first week of flight. Carrots and celery sticks are the most perishable items in the fresh food locker, and they must be eaten within the first 2 days of flight" [11]

The food that is stored is not refrigerated and shares a space with electrical equipment, which is around 85 to 90F. Any extra weight carried on the Shuttle must be added into mission volume, mass, and power constraints. As recent as September 2020, scientists are working to solve the issue of food preservation in space. The Freezer Refrigerator Incubator Device for Gallery and Experimentation (FRIDGE) by BioServe Space Technologies [12] is undergoing initial tests and validations. The device can range in a temperature setting of 5.0 to 118.4F and about the size of a microwave.[12] Robby Aaron, a student working on the project details, "there are no rotating parts, no fans…a normal fridge is also hot in the back. We can't have that in space. Warm air doesn't rise in microgravity; it stays stationary and can cause things to overheat. ISS has a water-cooling system that will be tapped into to directly dump the waste heat and keep the system cool" [12] The first two prototypes were sent on the NG-14 resupply mission on September 7. Scientists are hoping experiments and devices such as the one developed by BioServe Space Technologies will help to pave the way for the long-term preservation of fresh food in space.

There are also spaceflight requirements to consider with any equipment on board such as microgravity, cabin pressure changes, and radiation. Scaling up will also require detailed attention to factors such as food safety. Food grown in the shuttle will need preliminary microbial testing and cleaning parameters that limit waste streams into the air, water, and existing waste systems. The system must use minimal resources such as mass, volume, crew time, water, power, and equipment when implemented onboard. The food production system must be easy to use and grow quickly in mission for the crew. Veggie may provide the basis for variety, nutrition, and palatability, but many other factors need to be developed before humans are ready for full-scale crop production in space to be able to properly supplement the crew's nutritional needs.[13]

7. Food safety in space

Preserving the safety of the food grown onboard a spacecraft is just as important as the capabilities to grow, cook, and store the products of the system. Though the microbial tests from the Veggie experiment came back with a clean bill of safety, there is still a serious concern for the introduction and development of opportunistic pathogens in crop production. A study published in December 2020 by Kim and Rhee aimed to quantify the safety of scenarios such as cross-contamination from spacecraft involved the environment and the crew. [16] Because 90% of the water on the International Space Station is recycled [16], there is potential for bacterial contamination in the food system due to the nature of a closed environment. Currently, there is a monitoring system to track acceptable limits of bacteria and fungi in the air, surfaces, and water of the ISS. [16] Even with extensive efforts before space flight begins to control the microbial population growth, microorganisms have still been shown to grow, and an acceptability standard was established to further support the monitoring process, as shown in Table 3 below.

Table 3: Limits for microbial counts from the air, surface, and potable water of the ISS [16]

Category	Microorganism	Acceptability limit	
		Before flight	**During flight**
Air	Total bacteria	300 CFU/m^3	1000 CFU/m^3
	Total fungi	50 CFU/m^3	100 CFU/m^3
Surface	Total bacteria	500 CFU/100 cm^2	10,000 CFU/100 cm^2
	Total fungi	10 CFU/100 cm^2	100 CFU/100 cm^2
Water (potable)	Total bacteria	50 CFU/ml	50 CFU/ml
	Coliform	ND/100 ml	ND/100 ml

ND, none detected.

Since monitoring was started with the Mir space station in 1986, 95% of samples from the air were below the maximum limit {16}, with the most prevalent species identified as *Staphylococcus* and *Bacillus* spp. The dominant fungal species were identified as *Penicillium* and *Aspergillus. [16]* When sampling surfaces, touchpoints and biofilm formation are the greatest concerns. Data from the Mars Odyssey Orbiter and China's spacecraft showed no bacterial or fungal contamination over the allowed limit. The dominant bacteria and fungus were the same as what was prevalent for the air samples. [16] The safety of the water system is a vital factor for any mission success. According to scientists Kim and Rhee, "there were 16 cases of in-flight water samples for which bacterial contamination levels were above the limit of 100 CFU/100ml." [14] There also was an instance where the water used for preparing food on the ISS was contaminated at a level of 5100 CFU/100 ml. [16] The most prevalent organisms in the water system were reported as *Ralstonia pickettii* and *Burkholderia multivoras.* One case on the Mir space station showed the growth of *Legionella* from the condensate samples. [16] This species of bacteria can cause severe illness and even death and poses an extreme threat to the environment of space flight. Sampling crew members for microbes have also shown data of opportunistic pathogens such as *S. aureus, Klebsiella pneumoniae, P. aeruginosa*, and some Enterobacteriaceae. Though microorganisms are still able to grow in space and there has been no reported evidence of gastrointestinal diseases by foodborne pathogens in crew members, it is a potential possibility moving forward. [16] The water source, found to house many arrays of microorganisms, is a vital source for crop production and success. There will have to be extensive food safety parameters in place to ensure the fresh food that is grown will be a source of nutrients and not disease.

8. Conclusion

Fresh crop production is possible in space as evidenced by the growth achieved by Veggie on the ISS. The capabilities of growing fresh food in space will have positive effects on crew members' mental and physical well-being as the appearance and nutrition content of food has a strong correlation to the amount consumed. Though the current production habitat, Veggie, does lay the groundwork for variety and palatability for fresh food production, there is still more to consider before humans can grow and meet proper nutritional and energy intakes during long-duration, manned missions. Scientists, such as those working on Astro Garden ^{TM,} are quickly innovating and developing ways to sustainably and efficiently cultivate crops in microgravity conditions. Technology will need to develop preservation systems that are within mission constraints to store the food that is not eaten right away, and the research done by those at BioServe Space Technologies is a great start to effective cold storage onboard a spacecraft. Food safety parameters will have to be implemented for the food that is grown, as the reproduction of microorganisms is a possibility in microgravity. Cooking capabilities will greatly expand options and provide the opportunity for the growth of higher-calorie foods, such as potatoes. Food science in space is developing beyond freeze-dried formulations, and the future of food in space—is fresh.

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