Managing Space Food Waste with Fermentation: Novel System Design Update

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Food preservation and waste management are challenges that concern astronauts living in space habitats, and for deep space travel. This research presents fermentation as a food waste management system in space. It is one of the oldest forms of food preservation, and this ancient technique can be harnessed for life-support in space in addition to its Earth-based benefits. Fermentation is the transformation of food by microorganisms, and this process can be used to help manage waste by preserving the nutritional value of fresh ingredients, repurposing food waste, and growing new food and targeted nutrients. This study will focus on the optimization of fermentation in enclosed space environments with near term benefits. A prototype for a miniaturized fermentation chamber will be developed to control and capture data on fermented food products for the purpose of waste management. The chamber will be equipped with sensors to collect environmental data including radiation, temperature, humidity, pressure, gas, Volatile Organic Compounds (VOC) and a carbon dioxide reading (CO2), and observable visual changes. Expanding on existing space-ready food technologies, it will be designed for possible future deployments and integration into the International Space Station (ISS). In addition to the hardware, we are developing new applications for space food products and novel recipes based on fermentation. A prototype for this research has already been developed and tested. In this initial experiment, a sample of miso (nutrient-rich fermented soybean paste) was sent to the ISS for a 30 days internal mission, and compared to control samples on the ground. The samples were contained in individual chambers equipped with the above listed sensors. Through this continuing experiment and an evolution of hardware platforms, we aim to learn what ecological changes may have occurred within the populations of bacterian and fungi, and to develop a standardized process and set of tools for space fermentation. This paper presents a hardware-focused recap of phase I (the initial ISS

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experiment) and describes the current prototype approach and planning status for phase II (an expanded, environmentally-controlled fermentation chamber).

Nomenclature

ATP = adenosine triphosphate
CO2 = carbon dioxide
FF = fresh food
M = intermediate moisture
ISS = International Space Station
NASA = National Aeronautics and Space Administration
NF = natural form
R = radiated
RH = rehydrated
SCOBY = symbiotic culture of bacteria and yeast
SEI = Space Exploration Initiative
T = thermostabalized
TEC = thermoelectric cooler
TRISH = Translational Research Institute for Space Health
VOC = volatile organic compounds
WRS = water recovery system

I. Introduction

To achieve sustainable food systems in closed loop life support applications such as space vehicles and habitats, we propose fermentation-based food production technology and systems. This early-stage research update highlights opportunities to bring the rich culture of Earth-based fermentation practices, such as miso,[1] garum,[2] and kimchi,[3] to space to design beneficial applications for astronauts and novel ways of managing waste. In space, fermentation could be leveraged to repurpose food waste for a closed-loop system, preserve limited fresh ingredients, diversify food selection, grow nutrients, and improve astronaut gut health. In order to support future crews on long duration deep space missions, they will require advanced space food systems to provide nourishment and improve the quality of limited fresh ingredients.[4] We are developing a novel system design for a Space Fermentation Chamber to help astronauts make safe palatable food from waste with minimal infrastructure. The chamber will optimize the fermentation process with temperature controls, an off-gassing system, sensors to capture environmental data, and a modular food storage system.

This research has direct Earth benefits as well since space is one of the best tests of sustainability, relying on closed loop systems. In terms of food, it is difficult and often impossible to grow fresh produce in space environments and there is limited access supply chains and food variability. Therefore, if the Space Fermentation Chamber proves successful in closed space habitats, it could also provide terrestrial solutions where resources are scarce.

II. Theory of Waste Streams & Applications

Waste streams are flows of specific waste, from the original source through the process of recycling, repurposing, and disposal, through various treatment processes.[5] In the International Space Station (ISS), the Water Recovery System (WRS) is an example of an effective circular economy waste stream, which collects and safely processes moisture from humans (e.g. breadth, sweat, and urine), and runoff from sinks.[6] Similarly, a fermentation system could be used to recover food. There is precedent for this, as many initiatives have emerged in the food industry to reuse waste generated in food production.[7]

Waste includes products that are suitable for consumption, but are not used due to deficiencies in the food production chain. For example, some companies take advantage of waste from bakeries to make beer. In addition to fermentation, there are other uses for foods commonly thought of as waste products, including coffee grounds which could be used as a substrate base for the cultivation of mushrooms. Discard, on the other hand, refers to parts of raw materials that are not typically considered desirable for human consumption, such as peels and pits.[8] Both waste and discard could be leveraged in space to grow new food and optimize nutrients using the gastronomic technique of fermentation.

This research presents protocols to study food waste and discard generated in space with the aim of proposing solutions for their use. In addition, it is a source of inspiration for different techniques to transform raw materials and achieve higher gastronomic value. A change in the way of understanding products is key to putting this proposal into practice. By understanding their potential, fermentation could help crews create new value for products typically disregarded for consumption. This not only means a change in the food product value chain, but a commitment to sustainability behaviours that extend into other aspects of daily life in space.

Even with the success of growing plants and fresh food in space, in the near term these will be considered "pick-and eat-crops" intended to boost crew morale, as opposed to a complete meal.[9] Fermentation is an opportunity to preserve and enhance these limited fresh ingredients. In addition, space food leftovers could be used. For example, an astronaut could create miso from leftover tortillas, kimchi from limited fresh greens needing to be preserved, or kombucha from unfinished fruit juice. Many of these materials contain carbohydrates, which can be transformed into fermentable sugars, and proteins can develop the characteristic umami taste and various aromas.[1] Other products including skins, pits, and seeds, could be used as the basis for different types of fermentation with great potential for culinary applications for flavor, nutrients, and even texture.

A lesser appreciated aspect of waste streams and sustainability is desire.[10] Humans are the driving force of sustainable practices, and need to want to use these systems. Fermentation takes a holistic approach, by offering astronauts opportunities for improvisation and customization of food, and the ability to enhance flavor.

III. Material and Methods

A. Fermentation Process

Fermentation is one of the oldest methods of food preservation and preparation. Fermentation gives food a variety of sensory attributes, such as flavors and textures, and nutritional values. In food production, fermentation is the process of transforming organic substrates such as proteins, carbohydrates, lipids or other types of organic material through the action of enzymes (biochemical catalysts), produced by different microorganisms. Thus, fermentation processes describe the transformation of complex organic molecules into simpler compounds, and chemical energy in the form of adenosine triphosphate (ATP).[11] The fermentation process includes many different reactions. One of which includes alcoholic fermentation, where the enzymes produced by yeast degrade carbohydrate molecules into ethanol and carbon dioxide. Another process is homolactic acid fermentation where the lactose molecules are transformed into lactic acid by the action of different bacteria. Lastly heterolactic fermentation, obtaining one glucose, one ethanol and one carbon dioxide molecule.[11]

Fermentation is largely impacted by the environment with temperature, humidity, and air quality being main factors. The microorganisms for fermentations are selected on the basis of their ability to produce, preserve or stabilize desirable products. Different compounds are formed by microorganisms during fermentation, including lactic acid, acetic acid, propionic acid, diacetyl, carbon dioxide, ethanol, bacteriocins, and more. These by-products can change the texture (the rheological properties), and the flavor of the food sample.[11] Together, these molecules produce another product completely different in relation to the initial substrate and generally serve to inhibit possible spoilage and pathogenic microorganisms.

B. Hardware Materials & System Design Update

1. Phase I. Sensing Natural Fermentation in Space Environments

The first phase of this project aimed to understand the natural process of fermentation in space environments by observing the natural occurrences of a sample with a sensing box without environmental controls. This was a valuable step for testing flight-ready hardware and learning what variables would need to be managed in the future to optimize the safe production of fermentation-based food products in harsh conditions.

2. Phase I. Materials & Fabrication

A closedbox was used to house and sense the environment of fermented food samples (miso), as discussed further in the Experimental Methods section. The space sample and two ground controls were contained in individual boxes equipped with sensors to collect environmental data including radiation, temperature, humidity, pressure, gas, air quality (VOC and CO2), and observable visual changes to the surface. The 9"x4"x4" box was fabricated with 3D printed ⅛" non-flamable resin. It was designed to fit inside a NanoRacks Blackbox along with five other research payloads. The miso samples were double contained inside the box, in a 6oz round wide mouth jar harnessed to the interior box side. They were sealed with a custom lid with breathable paraffin tape to allow minimal air flow (CO2 release). A pre-flight safety immersion leak test was performed.[12]

Figure 1. Close-up of ISS sensing box, equipped with sample harness, sensors, and camera. Copyright 2021 by MIT SEI.

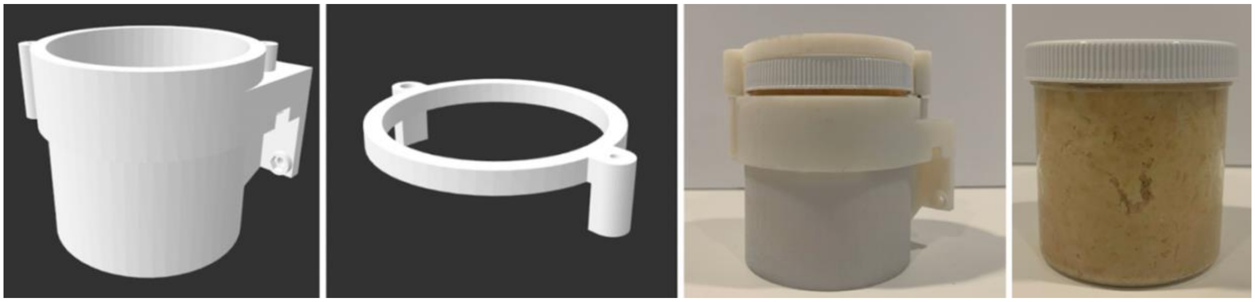

Figure 2. Left to right: rendering of sample harness; rendering of custom lid; 3D printed container harness and assembled container; and miso sample. Copyright 2021 by MIT SEI.

Table 1. List of Components:

Component
Box part A & B
Sample container
Sample holder
USB
MicroSD card 1 breakout board
MicroSD card
Arduino DUE
Camera
LED strip

Level shifter
Geiger Counter
Sensor BME680 (Temperature, Humidity, Pressure and Gas Sensor)
Sensor CCS811 (Air Quality Sensor Breakout - VOC and eCO2)
Screws
Lock nuts
24 AWG wire

3. Phase I: Power Management, Data & Downlink System

For the internal ISS mission in spring 2020, the system was powered via a USB through the Nanoracks BlackBox payload infrastructure and power line. The payload required groundmonitoring of telemetry, and used data which was stored locally on the BlackBox avionics system and downlinked from the payload to the Nanoracks console in Houston.

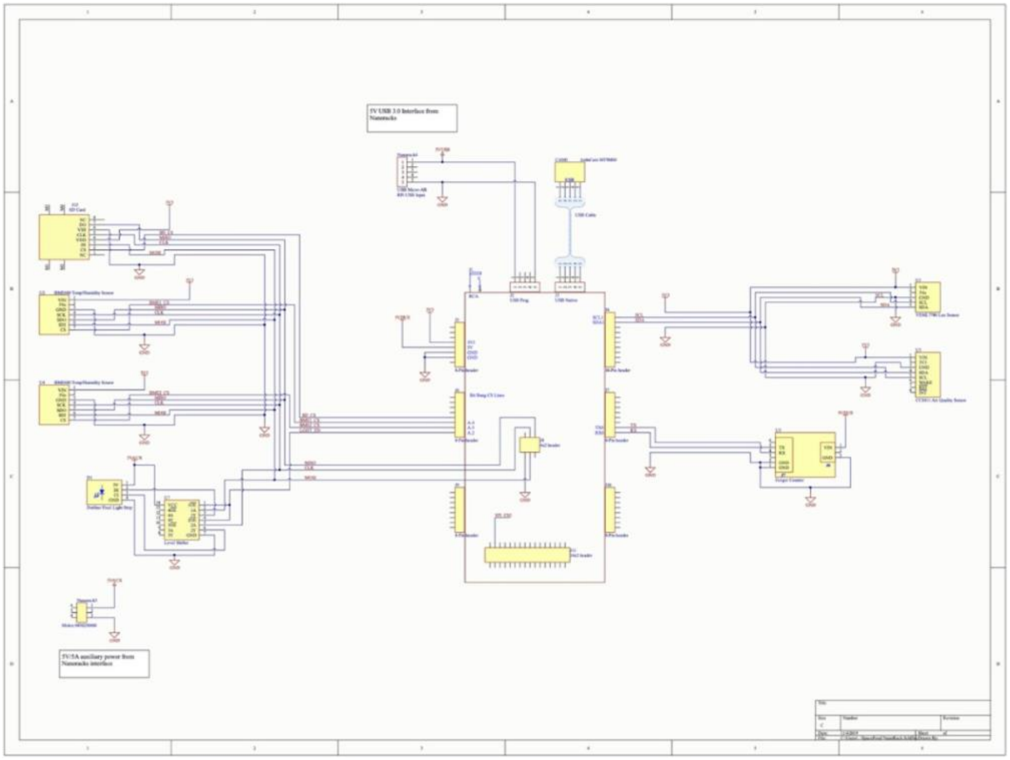

Figure 3. Phase I fermentation chamber electrical schematic for integrated sensing of the environment. Sensing system was architected around a low-cost, high-reliability Arduino DUE. Copyright 2021 by MIT SEI.

4. Phase II. Sensing & Controlling Optimized Fermentation in Space Environments

The second phase of this research is focused on the optimization of fermentation in enclosed environments (i.e. space stations and habitats), for circular economy with near term benefits. A prototype for a controlled Space Fermentation Chamber is in development to manage and capture data on fermented food products, working towards a closed-loop food system targeting food waste management. Expanding on existing space-ready food technologies, such as the Zero G Kitchen oven,[13] it will be designed for possible future deployments and integration into the ISS with Nanoracks Blackbox. The fermentation chamber will test preliminary component selection for further prototypes and validate that solid-state thermoelectric cooler (TEC) technology is workable as a temperature control technology within the space and power constraints. The ideal conditions for each fermented food vary, and we are working towards a TEC system that is controllable to a reasonable level of responsiveness and stability.

This prototype uses two identical tubs of water, one WASTE reservoir and one SAMPLE reservoir. From each, an intake and outfeed hose lead to a heat-exchange block. The blocks are mated to opposing faces of a Peltier element. Each fluid loop is driven by an impeller pump running at 12v and controlled (bang-bang, not proportionally) by a relay on the i2c bus. The TEC itself is driven by direct connection to a 12v source (initially a motor controller was in-circuit, but PWM is inefficient for driving TECs so future prototypes will just have an i2c-controllable H-bridge).Temperature probes on each of the heat-exchange blocks and in each of the reservoirs provide feedback data for the system. A Raspberry Pi 3B+ runs a customized Mycodo instance that actuates the system and records timeseries data. For this prototype, no PID or feedback-control is implemented, although it can quickly be added once TEC control via an H-bridge is set up.

Figure 4. Development of prototype of WASTE reservoir and SAMPLE reservoir for the Space Fermentation Chamber. Copyright 2021 by MIT SEI.

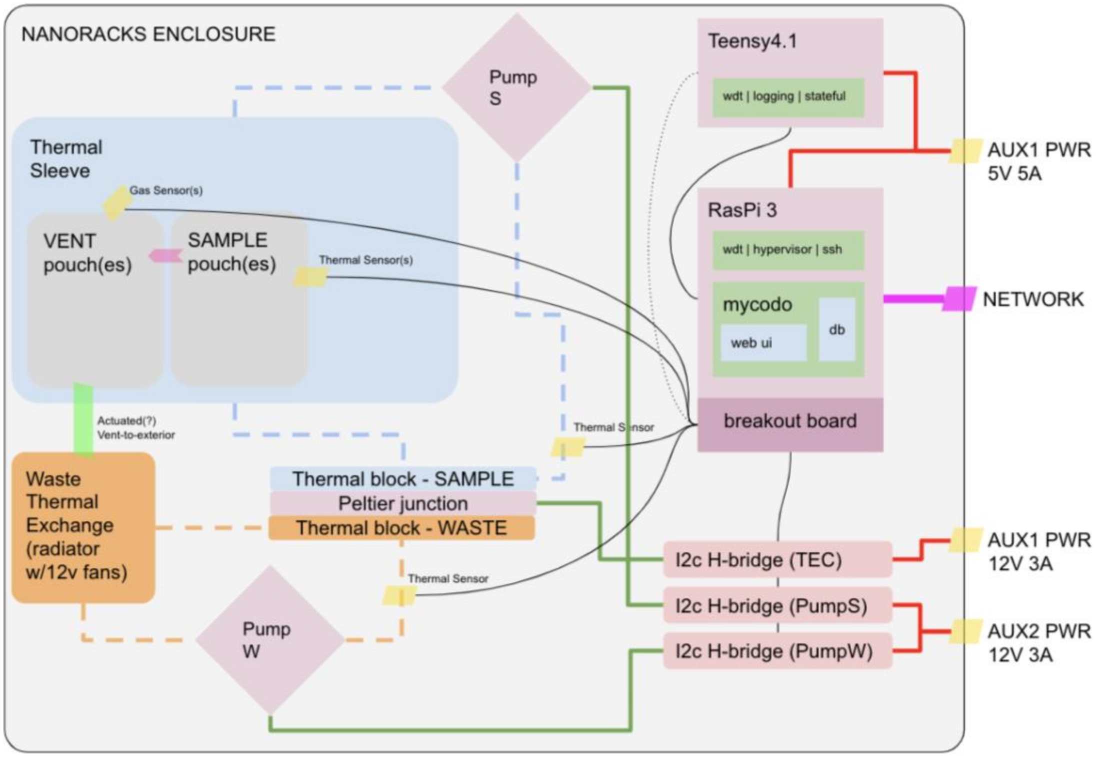

Figure 5. Space Fermentation Chamber rack system diagram. Copyright 2021 by MIT SEI.

C. Experimental Methods

1. Phase I. ISS Mission Test

In an initial experiment supported by the NASA-funded Translational Research Institute of Space Health (TRISH), a sample of miso was sent to the ISS on the SpaceX CRS-20 launch in spring 2020 for a 30 day internal mission, and compared to two control samples on the ground. Miso is a traditional Japanese seasoning, rich in nutrients and flavor, produced by fermenting soybeans with salt and kōji (the fungus Aspergillus oryzae grown on cooked rice). The samples were contained in individual chambers equipped with sensors to collect environmental data including radiation, temperature, humidity, pressure, gas, air quality (VOC and CO2), and observable visual changes to the surface. Through sequencing and analysis, we aim to learn what ecological changes may have occurred within the populations of bacteria and fungi, in addition to changes within the flavor chemistry.

We are in the process of conducting amplicon sequencing of the 16s/ITS genes, to characterise the bacterial and fungal compositions of each sample, to see whether they differ, and to analyse whether potential differences in microbiome between the samples correlate with differences in their environmental conditions. The other analysis we will conduct focuses on the flavour chemistry of the samples, to quantify the volatile and taste-active compounds, to see whether they differ, and to analyse whether potential differences might correlate with differences in their microbiomes and environmental conditions. Results from this sequencing will help inform how to monitor and control the environmental conditions of raw food materials for successful early-stage fermentation development.

2. Phase II. Next Steps Mission Design

The vision for this research is that future space habitats could be equipped with fermentation systems to manage food waste. This would involve crew support, and we are taking a phased approach to develop a rigorous flight testing platform for developing and improving the technology, system, and applications for the biological samples (i.e. raw materials and fermented food products). In Spring 2021 we are manifested to fly the Phase II prototype on a parabolic flight to test the hardware operations, fluidics, and human interaction through a series of carefully designed ConOps (Concept of Operations). Next, we propose to test the hardware and biological sample in a passive (i.e. no astronaut interaction) internal 30-day mission to the ISS. This would follow a similar protocol to the phase I ISS mission from spring 2020, and this time prioritize the environmental control system for optimizing fermentation, in addition to testing the environmental sensors. This is working towards a future astronaut interaction payload or integration into the ISS as a new food production system experiment. In terms of overall framing and experiment protocols, our fermentation module could be thought of as a similar system to the Vegetable Production System (Veggie) currently aboard the ISS.[14] The purpose is to provide an on site sustainable food source for crews, as well as opportunities for astronaut wellbeing through recreation and connection to nature.[14]

3. Phase II. Ingredients

We will focus on lactic fermented food (e.g. sauerkraut, kimchi, hot sauce) and possible other ferments (e.g. symbiotic culture of bacteria and yeast) that do not require humidity control. Lactic acid fermentation, commonly referred to as lacto-fermentation, is one of the most common and easiest methods of home preservation, where lactic acid is produced from carbohydrates by the lactic acid bacteria activity.[11] These products will however require airflow and release CO2. Customizable Space Hot Sauce for crews in the ISS will be used to build protocols and applications for fermenting in space and reducing waste. Our choice of customizable space hot sauce builds on a series of astronaut interviews conducted by the authors that strives to shape our prototype development with human-centered, direct user insights.[15, 16] We understand hot sauces, and strong-flavor foods to be favorite choices on the astronaut in-space menus. We are considering a variety of raw materials and solid waste products that could be leveraged in closed loop life support systems. This ranges from food waste from astronaut leftovers from NASA's current space food menu mainly consisting of freeze dried food, and some canned food. In addition we are exploring novel uses for food discards from underused elements of freshly grown ingredients in space habitats. Recipes and culinary applications are being developed using a combination of ingredients expanding on NASA's Classification of Space Food to architect our own taxonomy. This includes Fresh Food (FF), Intermediate Moisture (IM), Radiated (R), Natural Form (NF), Rehydratable (RH), and Thermostabalized (T).[17] Recipes include opportunities for customization with protocols for customizable crew-selected ingredients.

Table 2. Ingredient Taxonomy and Abbreviation, expanding on NASA's Classification of Space Food[17]

Ingredient	**Abbreviation**
Fresh Food	FF
Intermediate Moisture	IM
Radiated	R
Natural Form	NF
Rehydratable	RH
Thermostabalized	T
Beverages	(B)

4. Phase II Recipe I. Preparation with Solid Food Waste

Hot sauce made with base ingredients such as carrot sticks (FF) and celery sticks (FF), one of starch such as bread (FF), cornflakes (R), rice pilaf (R) or tortillas (FF). One extra flavoring is added like apple (FF), pear (IM) (T), peach (R), pineapple (T) or strawberries (R), and lastly one type of nut like almond (NF), cashews (NF), macadamia (NF) or peanut (NT). Base ingredients, one starch, one fruit and one nut are mixed with 1:1 water concentration, 4 % (w/w) of salt and 0.25, 0.50 and 1 %(w/w). To ferment for 10 days and add chile flakes and seasoning like apple cider, coffee, catsup (T) or mustard (T).

Table 3. Recipe Protocol for Custom Space Hot Sauce[17]

Base Ingredient	**Starch**	**Extra Flavoring**	**Salt**	**Custom Seasoning**

			(% of total mass)	
Carrot Sticks (FF)	Bread (FF)	Apple (FF)	4%	Apple Cider
Celery Sticks (FF)	Cornflakes (R)	Pears (IM) (T)	4%	Coffee
	Rice Pilaf (R)	Peach (R)	4%	Ketchup (T)
	Tortillas (FF)	Pineapple (T)	4%	Mustard (T)
		Strawberries (R)	4%	
		Almonds (NF)	4%	
		Cashews (NF)	4%	
		Macadamia (NF)	4%	
		Peanut (NF)	4%	

5. Phase II Recipe II. Preparation with Freeze Dried Food Waste
Kombucha is made with leftovers of tea plain (B), lemon (B), sugar (B), coffee black (B), lemonade(B), or peach-apricot drink (B), and sugar concentration at 10 ºBrix (approximately 90 g/L). The symbiotic culture of bacteria and yeast (SCOBY) is rehydrated with the infusion at room temperature in a vacuum bag. The sample is mixed and kept for 5 days for fermentation (dropping the pH until 3.5 approx.).

Table 3. Recipe Protocol for Kombucha

Base Ingredient	**Extra Flavoring**	**Sugar º BRIX**
Tea Plain (B)	Apple (FF)	10 ºBrix
Tea Lemon (B)	Pears (IM) (T)	
Tea Sugar (B)	Peach (R)	
Coffee Black (B)	Pineapple (T)	
Coffee w/Sugar (B)		
Lemonade (B)		
Peach-Apricot Drink (B)		

IV. Evaluation Protocols

The following protocols, under development by the MIT Media Lab and Alchemist teams, are intended to assess the success of the fermented food products, based on nutrition, safety standards, and palatability and will be used in future studies to assess both the chemical process and user feedback.

A. Protocol I

Three different samples of the hot sauce will be prepared following the recipe I, mixing in a vacuum bag and kept for the fermentation process in an incubator with control temperature (25 ºC) for 10 days. Each sample will be made with different concentrations of lactic acid bacteria, 0.25, 0.5 and 1% (w/w). The pH and º Brix will be measured before and after the fermentation process. The gas (CO_2) produced by the fermentation process will be measured.

B. Protocol II

Three samples will be prepared following recipe II, with different amounts of SCOBY freeze-dried previously at (pressure) for two days. After two days, the SCOBY will be kept in a vacuum bag and rehydrated with the same concentration of tea. The sugar (sucrose) concentration will be adjusted at 10ºBrix and the pH will be measured. The pH and brix will be measured every day at the same time, until the pH drops approximately to 3.8 at control temperature (25 ºC) in an incubator. The gas (CO_2) produced by the fermentation process will be measured.

C. Sensory Analysis Protocol

The sensory analysis will be conducted with 20 chefs from restaurant Alchemist, Copenhagen, Denmark, in a gender ratio of 50% males and females. All of them will be in a wide age range from 25 to 35 years old. The sensory analysis room will be kept at 25ºC and none of the consumers will have taste disorders.

The taste evaluation will be done by hedonic taste (liking), tasting two different hot sauces and kombucha samples. The first hot sauce and kombucha samples are based on space recipe protocols by the authors (listed above), and compared to traditional Earth-based recipes (similar to common off-the-shelf products). A scale from 1 (dislike extremely) to 9 (like extremely) will be used to study if there will be significant differences between the samples. Small plastic containers will be used for each sample and coded randomly.

The analysis will be carried out by the t-student test procedure for hedonic consumer data analysis[18] to identify significant differences among recipes. Statistical analysis will be performed by XLSTAT Version 2020.4.1.

As this experiment matures, and as we continue along the path towards integration of a fermentation food system on the ISS, we intend to also engage NASA Food Lab and direct astronaut testing to capture the unique sensory experience of flavor in sustained microgravity environments (noting the effect that physiological changes, due to prolonged microgravity exposure, have on taste and the sensory experience of eating).[19] [20]

V. Discussion

As space agencies prepare for a new era of space exploration, and future long duration missions to the Moon or Mars, they will need to address the complex requirement of providing crews with safe, nutritious food for survival. Not only can the Space Fermentation Chamber grow food, but it could support the ecosystem of future space stations, using recycled water and feeding CO2 back into plant growth systems. Furthermore, in order to live sustainably, crews will not be able to bring everything with them and will need to learn how to produce their own food from limited resources. These future space missions will require different types of skills and expertise. Many Earth-based research stations in remote extreme environments have agriculture technology specialists and cooks to support research staff and expeditionary crews. It is inspiring to imagine the role of a future Space Food Specialist or Metabolic Engineer who could produce nutritious and palatable food to boost morale and productivity. Most importantly this is an opportunity to design more sustainable food systems for enclosed space environments with direct Earth-benefits as well.

VI. Conclusion

This research aims to develop a closed-loop food system to repurpose food waste and discards by leveraging fermentation in space. This paper presents a system design update and a protocol plan for future work. Results from the beta test space miso experiment, including environmental data and sample sequencing analysis will be published later this year. This will reveal insights about the microbiology of the space environment, and inform future iterations of space fermentation hardware. Hardware currently under development for a controlled Space Fermentation Chamber will be tested on an upcoming parabolic test and future internal missions to the ISS.

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