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Edible Ideas / Recipes

Cheese, bread, and beverages: formulating fermentable foods in the final frontier

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Abstract

Access and variety of food in space is limited. Sustainable space habitation and exploration necessitates the supply of food. Fermentation processes can create a variety of space-suitable products that address the challenges of synthesis, resource availability and nutrient restriction presented by the space environment. Bread, cheese, and beverages could all be sustainably produced in space using modified fermentation techniques, appropriate for reduced convection environments. While able to be consumed separately, when combined, these components may form a delicious and nutritious “space brunch” or further, a signature “Cheesy AstroDough”.

Keywords

fermentation, microgravity, *in situ* resource utilisation, process, engineering

Introduction

Food, fuel, and waste account for many critical products that must be managed for the success of self-sustaining human settlement. It is widely accepted that extra-terrestrial settlements must engage *in situ* resource utilization to create sustainable resource cycles. The fermentation process allows for the conversion of biomass, waste or otherwise, to edible products which may have higher preservation, nutritional content and health benefits (Dimidi *et al.*, 2019; Şanlier *et al.*, 2019; Sharma *et al.*, 2020).

The advent of utilizing plants specifically cultivated for space application attracts the process engineer to conceptualise applications for plant-based products. Further value can be added to plant-based products at low energy investment by harnessing fermentation processes.

In the context of this special issue “Space Cook Challenge”, the opportunities for increasingly

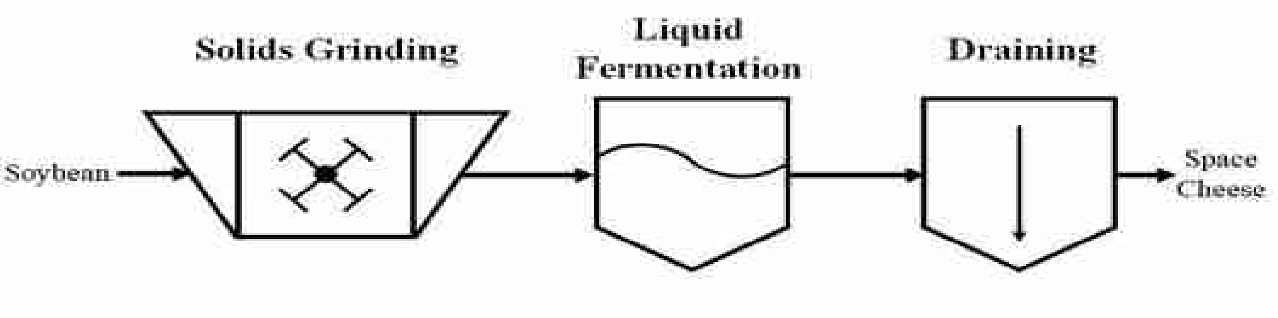

Figure 1. Diagram of simple material flow for the production of space-cheese alternative highlighting the gravity-dependent processing steps which are then most likely to be influenced by the reduced convection of the space environment.

diverse and flavourful food and beverages produced by fermentation generate a particular interest. The formulation, processing, and health benefits of a number of fermented, terrestrial, plant-based products have been collated by Gosken *et al.* (2023). Building on this work, potential candidates for space food will be investigated and a resulting dish will be proposed by discussing potential feedstock, processing requirements or considerations, and nutritional value. Additionally, the authors aim to spark a curiosity within the reader for the potential of fermentable products in space.

Cheese

It is possible to produce cheese analogues entirely using plant based ingredients (Kamath *et al.*, 2022). In general, plant-based cheese analogues (PBCAs) require polysaccharides to form a three-dimensional network to entrap fluids and other ingredients; proteins to fulfill a number of physiochemical and functional properties; and fats to determine formation and texture as well as sensory and nutritional quality (Grossmann and McClements, 2021).
Obtaining cow's milk in space is not easy. Plant-based milk alternative products have been used on Earth as an alternative to its bovine form for consumers who have allergy, lactose intolerance, concerns about calorie density, or a preference for veganism. In nutritional comparison between feedstock for alternative milks - including coconut, rice, and almond - soy is the most similar to dairy milk (Vanga and Raghavan, 2018), making it an attractive basis for a space-cheese alternative. Yet, it is reported to have a "beany" flavour and may trigger an allergic reaction in some individuals.
In 2002, DuPont scientists in collaboration with NASA demonstrated that soybeans could be grown as a crop in space (DuPont, 2003). Twenty years later, students at Purdue University found promising results for the growth of soybeans in both Lunar and Martian simulants (Ellison, 2022). Soy beverage is often described as having an undesirable "beany", flavour. This can largely be attributed to aldehydes and other volatiles which could be reduced or eliminated with reductase activity present in lactic fermentation (Blagden and Gilliland, 2005). This fermentation is pivotal in the formation of major flavour and consistency compounds in dairy cheese. Outcomes of lactic fermentation of plant-based alternatives to milk have been well documented, but further understanding how carbohydrates and proteins, specific to plant-based feed, function as substrates for proteolytic and glycolytic systems are needed (Harper *et al.*, 2022).
By comparing to terrestrial processes, the production of a simple and tasty space-cheese alternative can be proposed. Feedstock of soybeans are first ground and filtered to a liquid. This is inoculated with lactic acid bacteria,

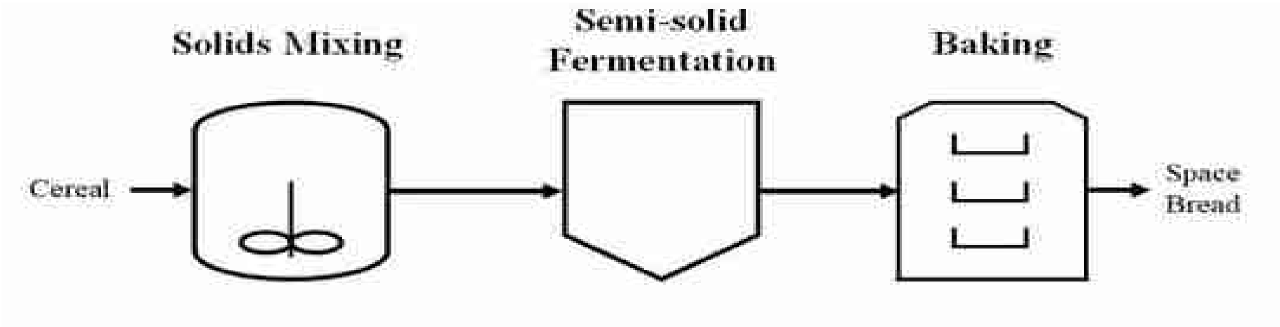

Figure 2. Diagram of simple material flow for the production of space-bread highlighting the gravity-dependent processing steps which are then most likely to be influenced by the reduced convection of the space environment.

fermenting the liquid to a curd which can then be drained, brined and matured to a space-cheese alternative.

Figure 1 shows a simplified version of a terrestrial process outlined by Li *et al. (*2020) by which a space-cheese alternative could reasonably be formed. The flavour and consistency of fermented products can vary significantly with slight changes in the process. In conjunction with changes in fluid mixing, settling, and convective phenomena due to a reduction in gravitational acceleration, a space-cheese alternative is likely to have an altered flavour profile and consistency.

Detailed information about the production process for PBCAs would require further developments in astrochemical engineering. Understanding differences, like the impact of a reduced convection environment, in the production process between space-cheese alternative and its terrestrial counterpart will allow for comprehensive flavour and texture profiling.

Not all PBCAs require fermentation to form curd. Tapioca and corn starches have potential to be inexpensive and protein rich alternatives to dairy cheese (Mattice and Marangoni, 2020). However in investigations where fermented products underwent sensory analysis, the fermented products were considered more likable than unfermented products, but not as likable as dairy cheese itself (Harper *et al.,* 2022).

Further research regarding the nutritional and sensory characteristics, as well as the production process, may yield a suitable space-cheese alternative along with improvements in the terrestrial analogue and open the potential in variety for both.

Bread

Cereals are the most widely grown crops on Earth and a staple food which should be considered for space. Cereals occupy an important nutritional position; being good sources of carbohydrates, dietary fibres, essential fatty acids, proteins, and micronutrients (Laskowski *et al.*, 2019). Bread is one possible cereal derivative which can be beneficially tweaked by the baker to the needs of the consumer - under the presumption of successful off-world cereal harvest.

Biofortification of bread may help compensate for nutritional deficiencies in space. Carotenoids, which have antioxidant properties and some of which are precursors to vitamin A, as well as lutein and zeaxanthin, are not synthesized by the human body (Eggersdorfer and Wyss, 2018). These nutrients must be sourced through food or taken as a supplement. Padhy *et al. (2022)* successfully biofortified wheat to enrich the carotenoid content. As carotenoids are natural pigments, enriching their content may enhance the colour of the dough. Space foods, especially breads, could be further dyed and colour coded to represent micronutrients with which they are enriched.

A simple production makes bread an appealing contender as a space food. The most common breads are made from a combination of flour, water, and raising agent, typically yeasts. Alternative to yeasts, lactic acid bacteria are used as the raising agent in sourdoughs (Arora *et al.*, 2021). The biocatalyst ferments the reducing sugars into flavour and texture compounds as well as carbon dioxide (CO_2) which causes the "raise". Applied to an extra-terrestrial context, the behaviour of the CO_2 bubbles in space-dough may differ to the terrestrial due to reduced convective force in the reduced gravity environment. The concentration and size of CO_2 bubbles contribute to both the volume of the bread, as well as the porosity and structure of the crumb (Rathnayake *et al.*, 2018). As bubble characteristics are gravity dependent, an altered bubble size and distribution throughout a dough fermented in space will likely give the resulting space-bread product a consistency or texture different to the same product made in terrestrial conditions. While the recipe is relatively simple, baking in space is not. Terrestrial baking is reliant on convective heat and mass transfer. A reduction in gravitational acceleration decreases convective forces, thereby possibly decreasing the efficacy of conventional unit operations.

In 2021, as part of NASA's Deep Space Food Challenge, Hersh and her colleagues pioneered a modified fluorinated ethylene propylene bag, commonly used for handling of blood products, to a "bread bag" containing dry ingredients from Earth which then, in space, could be injected with water, mixed by astronauts, allowed to rise, and then be baked into a loaf (Shellhouse, 2021). This method favours microgravity environments where gravity dependent processes such as mixing, pouring and settling are cumbersome.

For larger scale planetary operations, a more conventional terrestrial baking approach should be adequate. Lunar or Martian cereal grain harvests could be processed to flour on-site, and their dry ingredients sealed in "bread bags" for microgravity missions and resupply to dependent habitats. For the heat transfer component of baking, NASA is exploring a "Zero-G" oven which uses electrical elements, similar to a terrestrial toaster, and designed for specific use in the microgravity environment aboard the *International Space Station* (ISS) (NASA, 2019). Although baking has been achieved on the ISS, the food cannot be consumed by its inhabitants because of hazards presented by crumbs.

The signature crumb of most breads presents a significant issue for space flight. In 1965, a corned beef sandwich was infamously smuggled on board *Gemini III* (Anderson, 2022). The breadcrumbs present a hazard both for the astronauts and delicate equipment. A new age space-bread, at least for microgravity conditions, needs to be effectively "crumb-less". Crumbs are formed during heating of the dough and come from both the crust and the matrix of the bread. Heating the bread dough causes gelatinization of the starch, amino-carbonyl reactions, state change of glutenin and gliadin, and pyrolysis of proteins (Gasparre and Rosell, 2023; Dos Santos Conceição *et al.,* 2024). Together, these chemical processes contribute to the structure, texture and flavour of the bread. Decreasing the heat during the baking process would then logically decrease the quantity of crumb. In 2005, the food company Hovis demonstrated this by releasing crust-free loaves of bread, claiming a lower baking temperature to prevent its outside from hardening as the explanation (Manchester Evening News, 2005).

The tendency of the bread to break and form crumb, as well as the size of the crumb particle, are also dependent on the formation and structure of the bread matrix. The susceptibility of bread matrix to crumbing - bread hardness - is a function of porosity (Demirkesen *et al.*, 2014). The porosity of the loaf is itself a function of the CO_2 production and diffusion throughout the dough (Rathnayake *et al.,* 2018), and the production and distribution of CO_2 are a function of the fermentation process parameters and present convective forces – both of which would likely differ to terrestrial counterparts when convective forces are reduced because of a reduction in gravity. Experimental work with ovens for zero-g have reported bread having a

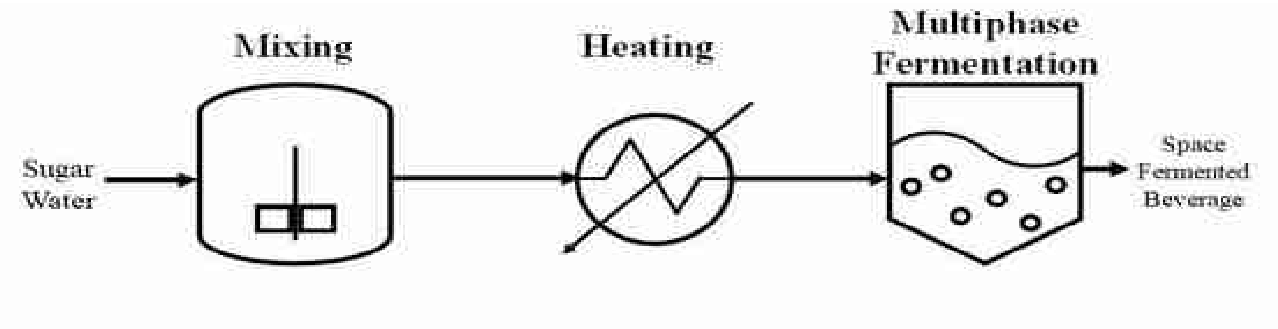

Figure 3. Diagram of simple material flow for the production of space-fermented beverages highlighting the gravity-dependent processing steps which are then most likely to be influenced by the reduced convection of the space environment.

different, fluffier texture which may be indicative of higher porosity (Nelson, 2017). A space-baker might counteract porosity by adjusting ratios of flour and water, or possibly the addition of stabilizing and fortification agents to close or fill pore space.

Bread pores could be filled with space-cheese alternative to create a space Pão de Queijo (cheese bread). Cheese bread is a traditional baked good from the state of Minas Gerais, Brazil (Corado *et al.*, 2017). Most producers of cheese bread follow a similar method where starch is scalded with water, vegetable oil, or milk, the dough is kneaded with eggs, cheese is added, and the mixture is baked (Clareto e*t al.*, 2006). Increasing the percentage of ricotta in the preparation of cheese bread resulted in a softer product with a thinner crust as well as reduced gumminess, fracturability and chewiness (Pereira *et al.*, 2010). Altering the consistency of the dough with the addition of cheese combines constituent ingredients to make a space-dish while also aiming to reduce the tendency to crumb by filling some pore space. The space-sourced feedstock and process parameters will affect the formulation of the food and therefore influence the texture and flavour profile of this dish. To differentiate from its terrestrial counterparts and due to its predictably lower porosity, this dish could stand alone as “Cheesy AstroDough”.

Development of a modified “crumb-less” recipe, biofortified harvestable space grain, and understanding of CO_2 bubble size, formation and distribution, could mean nutritional and tasty space-bread, and a “Cheesy AstroDough” dish are closer than they seem.

Beverages

Both alcoholic and non-alcoholic beverages serve an important role in the future of space travel relating to tourism and nutrition respectively. In general, starter cultures of microorganisms ferment reducing sugars in liquid into flavour and nutritional compounds along with CO_2 (Maicas, 2020). Substrate composition, process conditions, as well as strain and concentration of microorganisms, are major variables predicted to be affected by the reduced convection induced by a decrease in gravity from the space environment. The flavour and texture profiles of fermented beverages can be adjusted by targeting different steps of the fermentation process.

Kombucha and kefir are examples of popular terrestrial beverages which are enhanced through fermentation to provide antioxidant and anticancer properties (Chong *et al.*, 2023). Kefir feedstock is typically animal milk-making it unsuitable as a space-beverage. However, terrestrial plant-based alternatives have been created (Uruc *et al.*, 2022) which could make space-kefir a reality. Kombucha can be made from a wide variety of plant products but is traditionally fermented from tea (de Miranda *et* *al.*, 2022). A symbiotic culture of bacteria and yeast (SCOBY) converts sucrose to ethanol, organic acids, and CO_2. Ethanol is then fermented further to acetaldehyde and acetic acid. Terrestrially, factors which influence the flavour and nutrient profile of kombucha include composition of the SCOBY and substrate, fermentation temperature, time, and oxygen concentration (Dimidi *et al.*, 2019).

Each of these factors may be influenced by the space environment in addition to effects on the microbial substrate or dynamics of the fermentation because a reduction in gravitational acceleration reduces the presence of convective forces thereby impacting the extracellular substrate environment. As a result, space-kombucha is likely to have an altered taste and mouthfeel which is difficult to predict without replicating the fermentation conditions.

Alcoholic beverages, such as beer and wine, have applications in space tourism, like how passengers on an international flight may enjoy a drink during their journey or a complimentary bottle is provided at a hotel stay. The increase in commercial flights to space, with plans for eventual space-hotels, provides an opening to develop these terrestrial luxuries off-world. Space-grown grains and fruits could serve as the wort and juice substrates for space-made beers and wines. There are many factors to the fermentation process - itself oversimplified prior in Figure 3 - which would need investigation and optimization to create a desirable space-brew. In the same manner as kombucha, the result would be intrinsically space specific.

Beverages for space are likely to have flavour profiles differing from the same products made under terrestrial conditions because of alterations in gravity-dependent processes utilized in their formation. For a bioprocess, change in gravitational acceleration will predictably affect the system as it is likely to alter the behaviour of fluid particle mechanics, transport phenomena and kinetics (Wuest *et al.,* 2017). The ability for the microbe to interact with its extracellular environment to exchange nutrients and waste as well as any stresses experienced, or changes to secondary metabolite production, could each impact the flavour profile of the product if they were to impact the growth or fermentation kinetics of the organism. The distribution and size of CO_2 bubbles could also adjust the mouthfeel of the beverage from the terrestrial counterpart if the reduction in gravity predictably alters the process. The extent to which the gravity vector may alter the flavour and texture of fermented beverages -through an assumed reduction in convective forces- would be needed to improve the prediction of product characteristics.

Conclusion

Fermentation provides a pathway to create consumable products with higher preservation, nutritional content, and health benefits in space. Fermentation also adds value to the resource cycle of plant-based products procured from space agriculture as a low energy investment process.

Sustainable extra-terrestrial exploration and habitation necessitates innovations in production of closed resource products *in situ*. A brunch type dish, “Cheesy AstroDough”, with fermented constituent cheese, bread, and separate beverage, is a potentially appealing and nutritious option for space farers. Plant-based cheese alternatives are presented as possible sources of protein; bread as a rich carbohydrate source; both of which can be further fortified with additional, specific nutrients. Beverages both alcoholic and non-alcoholic are included as attractive options for commercial voyages to space and to provide variation in nutritional sources respectively.

When compared to its terrestrial counterpart, space-cheese alternative may have an adjusted formation and texture due to its plant-based feedstock, as well as changes in the fermentation and maturation stages because of decreased convective forces. Space bread is likely to vary in colour based on its nutrient enrichment. It will likely also have a texture and consistency different to the terrestrial counterpart due to unknown changes in CO_2 distribution throughout the dough, and the requirement for the bread to be "crumb-less". Fermented beverages are likely to have flavour profiles and mouthfeels particular to the space environment due to a reduction in the gravity vector assumedly reducing convective forces present during the fermentation process. Expanding the scope beyond food security and diversity, investigation into fermentation processes in space creates potential for a multitude of other prospects including medicines, waste managemen,t and fuel synthesis.

Further research should endeavour to quantify feedstock amounts and ratios for these foods to cater to the demands of the space environment and specific nutritional needs. Knowledge regarding production processes and feedstock supply is also necessary. A better understanding of how the reduced presence of convective force in the space environment would affect production is important. This knowledge will help to predict flavour and texture profiles as well as provide a springboard for the development of safety protocols for the process. With such advancements, space travellers will be able to prepare and enjoy delicious food on their journeys.

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