Challenges in food system development for deep space missions

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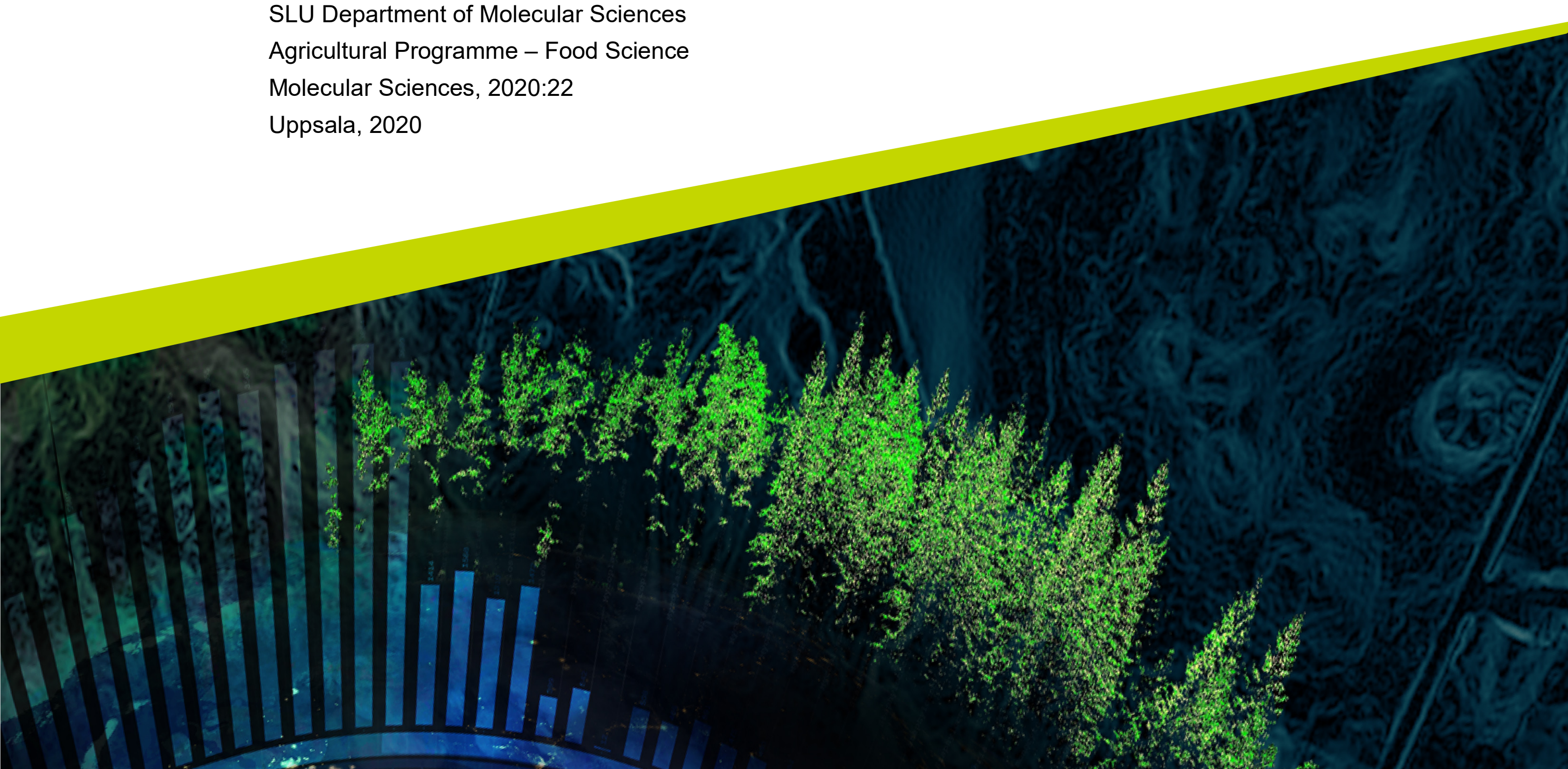

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Abstract

With a reinvigoration of space travel, space agencies around the world collaborate to land the first woman and the next man on the moon by 2024, establish a moonbase with a constant human lunar presence by 2028 and bring humans to Mars by 2030. Even though we may have the technology to bring humans to Mars, we do not have the required food systems and the food technology to sustain them. A mission to Mars will last for approximately 3 years and will be the first time humans traverse into deep space which will introduce a plethora of new challenges. First, food developers need to ensure that food sustains a 5 year shelf life in ambient temperature that can withstand the extreme environments of space such as elevated levels of radiation. Second, food developers need to consider that food serves as a countermeasure to many of the challenges of deep space missions. Nutrition plays a critical role as a countermeasure for environmental stressors such as microgravity and elevated levels of radiation which will severely affect both shelf life as well as astronauts' health. Conversely, these environmental stressors also affect nutrient stability and bioavailability. Third, food developers should not overlook the psychological aspects of food that we may take for granted in everyday life and how food may work as a countermeasure to the many psychological challenges that come with living in a confined space far away from earth, deprived of other sensorial stimulation. Furthermore, without organoleptic appeal, there is a risk that food remains uneaten, deeming the food worthless. This will result in astronauts suffering from both malnutrition and sensorial deprivation which can have a snowball effect leading to severe physiological and psychological problems. Food developers need to take all of the factors mentioned above into account, and it may be imperative with interdisciplinary studies between the areas highlighted in this review in order to achieve proper food systems for future deep space missions.

Keywords: Space food, microgravity, radiation, space food development, deep space, Mars, deep space, Space food challenges, extreme environments

Sammanfattning

För närvarande pågår ett omfattande internationellt samarbete för att upprätta en månbas med en konstant mänsklig närvaro år 2028 för att sedan landa människor på Mars år 2030. Rymdforskning har hittills främst haft som fokus att utveckla den teknik som är nödvändig för att ta människor till Mars. Andra områden såsom livsmedelsteknologi och livsmedelssystem i rymden har dessvärre hamnat på efterkälken. Det första uppdraget till Mars och den yttre rymden beräknas vara i ungefär tre år och livsmedelsforskningen står idag inför en mängd nya utmaningar som måste lösas innan detta uppdrag kan möjliggöras. Livsmedelsforskare måste bland annat kunna säkerställa att maten kommer att ha 5 års hållbarhet i rumstemperatur och därtill kan uthärda de extrema miljöerna i rymden, såsom höga nivåer av radioaktiv strålning. Mikrogravitation och förhöjda strålningsnivåer kan också komma att påverka matens hållbarhet och astronauternas hälsa. De extrema påfrestningarna som rymdmiljön utsätter den mänskliga kroppen och psyket för måste därför övervägas noggrant och här kan näring kan komma att spela en avgörande roll som motåtgärd. Utanför Jordens gravitationsnät kommer biotillgängligheten att minska och stabiliteten hos näringsämnen kommer att undermineras, vilket leder till att människans näringsupptag kommer att påverkas negativt. En annan aspekt som tidigare har varit förbisedd inom rymdforskningen är matens betydelse för den psykologiska hälsan; maten kan komma att vara astronauternas enda motåtgärd för att klara livet i ett trångt utrymme långt ifrån jorden eftersom bristen på sensorisk stimulans är påtagande under resor till yttre rymden. Om maten saknar organoleptisk tillfredsställande egenskaper är risken därtill stor att den inte förtärs och astronauterna kan sålunda riskera att bli undernärda, vilket i sin tur kan leda till allvarliga fysiologiska och psykologiska problem. I utvecklingen av rymdmat bör livsmedelsforskare därför ta hänsyn till samtliga av de ovannämnda faktorerna. Denna uppsats belyser även vikten av fler tvärvetenskapliga initiativ för att kunna utveckla lämpliga livsmedelssystem för framtida uppdrag till den yttre rymden.

Nyckelord: Rymdmat, utveckling av rymdmat, radioaktivitet, mikrogravitation, mars, utmaningar i rymden, yttre rymden, viktlöshet, extrema miljöer

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Abbreviations

ESA	European Space Agency
GCR	Galactic cosmic rays
GIT	Gastrointestinal tract
Gy	Gray
HZE	High atomic number High energy
ISS	International Space Station
MATS	Microwave-assisted thermal sterilization
MFD	Microwave freeze-drying
mSv	Millisievert
NASA	National Aeronautics and Space Administration
PATS	Pressure-assisted thermal stabilization
PSMVD	Pulse-spouted microwave vacuum drying

1. Introduction

In May 2019, the National Aeronautics and Space Administration (NASA) together with the European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), Canadian Space Agency (CSA), Australian Space Agency (ASA) and commercial spaceflight companies announced the Artemis Program, a joint mission to reinvigorate space exploration (Dunbar, 2020, Northon, 2019). The plan of this new space race is to land the first woman and the next man on the moon by 2024, establish a moon base with a constant human lunar presence by 2028 and bring humans to Mars by 2030 (Wilson 2016; Obrist et al., 2019; Cahill & Hardiman 2020; Dunbar 2020). Interplanetary missions to Mars come with a myriad of challenges and even though we may have the technology to bring humans to Mars, we do not have the required food systems or the food technology. Ultimately food is a limiting factor. The space mission to Mars is estimated to last for about 3 years, which will be the longest period of time humans have ever been to space. Moreover, it will be the first time humans have traveled beyond the moon into deep space (Cooper et al., 2011; Szocik et al., 2018). To make this mission possible, the astronauts will need access to food that can sustain a shelf life for 5 years in ambient temperature. To store food in a spaceship during 5 years poses a range of challenges. For example, aside from maintaining the food's safety, space food developers need to ensure that the food keeps its organoleptic acceptability and nutrient efficacy as well as to minimize the food's volume, mass and waste. Additionally, even if all this would be achievable on earth, it may not be so in space due to the extreme space environment with an increased exposure to radiation, which is probably the most difficult challenge. (Perchonok & Bourland, 2002; Cooper et al., 2011).

Over the last decades, space food has evolved significantly and has gone from toothpaste-like tubes to food similar to what we eat on earth. By virtue of that, no matter how much nutrients food contains, it needs to be consumed to fulfill its purpose, and in order to be consumed, food needs to have an organoleptic appeal and also be variable. Furthermore, during longer missions, it is important to consider that food is not only a source of nutrients, but it should also ensure personal and emotional well being. In other words, food plays an important role as a countermeasure to the psychological challenges that humans experience on deep space missions (Obrist et al., 2019).

Traversing into deep space, astronauts face several physiological and physical challenges as a result of increased exposure to radiation and the way microgravity affects the body. Nutrition is imperative for humans to overcome and survive the physiological and physical challenges in space. Conversely, the environmental conditions in space severely affect our metabolic processes and the body's ability to utilize nutrients. Furthermore, microgravity affects pharmacokinetics and since the research on pharmaceuticals and potential side effects in space is scarce, food is the primary source of nutrition and the most important countermeasure for these challenges (Blue et al., 2019; Antonsen, 2017).

When developing food systems for long term space missions, all of the factors mentioned above need to be taken into consideration. There is currently a need to develop sufficient processing methods to fulfill all of these demands (Jiang et al., 2019) and to do so, we need a better understanding of how food systems behave in microgravity and being exposed to constant radiation. The research is scarce and even though some studies exist on fluid behavior, colloids and heat and mass transfer in microgravity, only a fraction of those studies have been conducted on food systems (Chao et al., 2020). NASA's C-9 low g flight research aircraft is one of the few attempts that have aimed to simulate microgravity on earth. However, the time of microgravity is too short for certain systems to reach equilibrium and the experiments will therefore not grant enough insight to provide accurate data (Spanier et al., 2007; Wagenborg, 2008; Chao et al., 2020). There are similar issues with studies of the human physiology and psyche. One of the weaknesses with space research is the limitation of participants in the studies. Due to ethical reasons we cannot study humans in the more demanding deep space scenarios here on earth since it would demand a person to be confined in a low stimulus room in bedrest for long periods of time while being exposed to high amounts of ionized radiation and High atomic number High energy (HZE) particles (Szocik et al., 2018). Some ground analogues such as long duration head-down-tilt bed rest have provided some insight to the physiological effects of microgravity such as fluid shifts and bone loss, but lack the synergic effects with radiation and psychological issues (Smith & Zwart, 2008a; Hargens & Vico, 2016).

This review has provided a brief introduction to the research conducted on the challenges that relate to the development of food systems for long term missions into deep space. The review has indicated that food is more than a functional source of energy in isolated environments. Thus, to develop food systems for deep space missions, it is necessary to take several factors into consideration, which demands more interdisciplinary studies.

2. Method

This study has been conducted as a literary review and a compilation of articles on disparate areas, all deemed as relevant to the development of space food. The study is divided in thematic chapters that will help highlight and uncover the research field of space food development on a meta-level. The thematic divisions aim to identify the research gaps in space food development and to clarify the challenges that need to be met. The data has been gathered from databases such as PubMed, Google Scholar, Primo and Web of Science as well as NASA Technical Reports Server (NTRS) and journals such as Acta Astronautica and Advances in Space Research. Examples of keywords and phrases used in the search are ‘’Space food systems’’ ‘’Nutritional biochemistry space’’ ‘’Space radiation’’ ‘’Physiology space travel’’ ‘’Fluid systems microgravity’’ ‘’Microgravity physiology’’ ‘’microgravity food systems’’ ‘’Food processing space missions’’ ‘’Fluid shifts microgravity’’ ‘’Bioregenerative Food Systems’’ ‘’Pharmaceuticals microgravity’’ ‘’Colloids microgravity’’ ‘’Foam microgravity’’ ‘’Rheology microgravity’’ ‘’Colloidal crystallization microgravity’’ etc.

3. Significance of organoleptic qualities

Regardless of how much nutrients food contains, it must be eaten to fulfill its purpose. The chemical senses such as taste, ortho- and retronasal contribute significantly to the sensory effects of food choice, appetite and intake. Taste works as a macronutrient sensing system and along with texture, it determines the duration of oral exposure, whereas the smell triggers a priming process and induces the appetite (Boesveldt & de Graaf, 2017). This makes flavor the most important determinant of quality (Bourland, 1993; Mestres et al., 2000). This became apparent during the Mercury missions (1961 to 1963) where the food served all of the nutritional requirements, but it had some objectionable features; the crew could neither see nor smell the food since it was served in tubes similar to toothpaste tubes. The astronauts did not eat all of the food provided, simply due to the lack of organoleptic appeal and they became malnourished.

There were similar problems with bite sized cubes that contained a high calorie mixture of protein, fat, sugar and nuts. Although similar to fruit and nut bars, the cubes did not have a familiar mouth feel and taste and many remained uneaten. Aside from the tubes and the bars, the crew were provided with freeze dried powders that were difficult to rehydrate and crumbs from the food risked fouling instruments. The food systems went through further development during the Gemini missions (1965 to 1966) and more focus was directed towards the packaging to ensure maximum safety. This quality assurance process was the start of the Hazard Analysis and Critical Control Points (HACCP) system. However, even though more focus was aimed at the food systems, the crew continued to eat food in tubes and energy dense cubes. Even though the food was acceptable in ground based tests, it did not meet the requirements in space and the decrease in acceptability led to weight loss and malnutrition of the astronauts. It was first in the Apollo missions (1968 to 1972) that the malnourishment was taken into account. The crew members did not want to eat due to the low palatability of their diet, a menu fatigue, and a lack of stimuli that was an effect of confined environments (Olabi et al., 2002; Perchonok & Bourland, 2002; Perchonok et al., 2012; Jiang et al., 2019; Cahill & Hardiman, 2020). With this acknowledgement, the food system on the later Apollo missions deviated from tubed food and were developed further. These were the first missions to have thermostabilized and irradiated foods as well as hot water which made rehydrating food easier. Around this time, the crew started to use open container food with utensils which provided the astronauts with an eating experience that was reminiscent of earth. However, despite all of the improvements to the food systems, the astronauts still did not consume the proper amount of nutrients and much of the food was left uneaten. It became more apparent that the food systems needed to develop further with a greater focus on palatable and familiar tasting food (Smith et al., 1971; Perchonok & Bourland, 2002; Olabi et al., 2002; Perchonok et al., 2012).

On shorter missions, such as the ones mentioned above, the palatable attribute of food remains secondary. However, on a longer mission, food becomes more than just a functional source of nutrients. Aside from the sensorial qualities such as taste, texture, smell, freshness and variation, food needs to fulfill emotional, social and environmental aspects, which all relates to the basic human psychological and biological needs (Szocik et al., 2018; Obrist et al., 2019). Traversing into deep space, astronauts have to deal with various psychological challenges that cause a high level of stress, which in turn may alter their physiology. To live in a confined space with limited habitation volume, reduced habitational quality and environment as well as absence of fresh air are all aspects that affect the human psychological health negatively. In addition to these basic needs, astronauts may face reduced sensory stimulation and boredom due to strictly regulated work and rest schedules, and delays in communication with earth and the absence of loved ones may all reflect upon the psyche of the crew (Gabriel et al., 2012) Another important factor to consider is that Mars missions will be the first time humans have to deal with the "earth out of view'' phenomenon. This separation from earth may lead to an extreme pathological separation anxiety, which in turn could trigger an out of control existential crisis that may lead to a self destructive behavior that can damage the crew and spacecraft (Szocik et al., 2018; Gabriel et al., 2012). There is a synergic effect between the physiological and psychological health, if one is deficient, the other suffers. Szocik et al. (2018) mention that these synergic effects are magnified by environments different to the ones where we evolved, and to minimize the mismatches between space and earth, it is imperative to accommodate the fundamental human needs to reduce the disruptions of the genome, epigenome and psyche. Therefore, it is important to consider the effects of food as a countermeasure to these psychological stressors. As previously mentioned, when researchers design food for space missions, they should consider aspects of food that are otherwise overlooked. For instance, the emotional aspects of food can be used as a reminiscent of life back on earth, where food is commonly used as comfort. The social concept of food should also be taken into consideration, since sharing a meal with someone or making food a shared social experience have positive psychological aspects (Obrist et al., 2019). Several studies have highlighted the importance of food in isolated environments and the function food has to build morale in isolated micro societies where dining is one of the few social events during the day that encourages communication. Journals from over 100 polar expeditions have been analyzed and out of all the categories mentioned, food was one of the most important ones that had the most positive entries. The expedition members viewed food as a compensation for living and working in the harsh environments (Milon et al., 1996; Stuster et al., 2000; Olabi et al., 2002; Szocik et al., 2018).

To design palatable food for space missions is, as concluded above, imperative for astronauts positive psychological health. Nevertheless, the design may pose a severe challenge, since food that is deemed to be acceptable in ground based tests may still come to taste different in space (Perchonok & Bourland, 2002; Perchonok et al., 2012). The reason behind this challenge is the microgravity and its effects on the chemical senses and the chemosensory perception of food. When exposed to microgravity, bodily fluids shift from the lower part of the body to the upper part, which causes facial edema and in turn congests the nasal passages. Thus, the microgravity reduces the olfactory components of food, which is comparable with the symptoms we experience during a cold. This results in a loss of direct smell as well as a part of the retronasal stimulation, which is important for certain perceptions of sensorial qualities. For instance, orange juice tastes sweet because the aroma of the orange increases the perception of sweetness retronasally. With a reduction of retronasal stimulation, it would taste bland or sour (Vickers et al., 2001; Olabi et al., 2002). Space radiation may also affect astronauts taste and odor receptors. Studies of cancer patients have shown that patients that have been exposed to 8 to 30 Gray (Gy) had a decreased perception of sweet and sour. On shorter missions in space and on the International space station (ISS), the astronauts will not be exposed to these levels of radiation, but for future Mars missions, the prolonged and high exposure to radiation needs to be taken into consideration (Sato & Kamata, 1984; White & Averner, 2001; Olabi et al., 2002). Furthermore, these factors may be synergic with other factors such as the high oxygen concentration and the lowered atmospheric pressure of the spacecraft as well as the low stimulus of the surrounding environment, all of which may have a deprivation effect on sensorial information and cause changes in the taste threshold. Psychological factors such as stress may also increase the buffer capacity of the saliva as well as the lipophilic carrier proteins which increase bitterness and reduce the aftertaste and intensity of sourness (Nakagawa et al., 1996; Wang et al., 2015). Using flavor enhancers may not fully mitigate these complications. Some enhancers, such as ethyl maltol, trigger a retronasal olfactory sensation which is often confused with sweetness and would therefore not have the desired effect in space (Bingham et al., 1990; Ni et al., 2005). Viscosity also affects flavor perception, since an increase in viscosity will decrease the intensity of sweetness and delay the burning effects of e.g. capsaicin. Different hydrocolloids have different effects on flavor and on how they behave during oral shear stress. Xanthan gum has a lower oral shear stress than hydroxypropylmethyl cellulose (HPMC) or guar gum and due to its shear thinning behavior, it has better flavor release properties. Proper texture adjustments to eliminate or reduce any decreased chemosensory perceptions of food should be considered when designing space food. Although, since storage volume is scarce, food will be overcompressed which may have effects on the texture and other properties (Olabi et al., 2002; Hollowood et al., 2002; Cook et al., 2003; Ferry et al., 2006).

The significance of the organoleptic appeal and the social and environmental aspects of food will become more apparent when living in a confined space, deprived of other sensorial stimulation. When designing food for deep space missions, it is important to consider that food is more than a functional source of nutrients and the many psychological aspects of food that may be taken for granted in everyday life should not be overlooked.

4. Physical and Physiological challenges and nutritional countermeasures

4.1. Physical Challenges

When astronauts traverse into deep space, they will be exposed to a multitude of environmental challenges unique to space, such as microgravity and elevated levels of radiation. In addition to the new technological challenges for food development, the environment poses a great risk for astronauts' physical health.

4.1.1. Radiation

Radiation is one of the main environmental concerns for deep space missions, since radiation affects both human health and n food stability. On missions into deep space, astronauts leave the earth's protective magnetosphere, and their exposure to radiation will increase greatly, in particular their exposure to ionized radiation. There are three main sources of radiation to consider. First, the Van Allen radiation belts that encircle earth (Baker et al., 2013; Xiao et al., 2015). Second, the Solar particles (SPE) and third, the galactic cosmic rays (GCR). GCR originates from supernovas from outside of our solar system and contain mostly protons, helium ions and HZE ions which travel nearly the speed of light (Smith, Zwart & Heer, 2014). HZEs are less abundant but possess a higher ionizing and penetration power which increases the radiation damage and can create clusters of damage where a multitude of molecular bonds are broken along their path, for example rendering DNA repair more difficult (Cucinotta & Durante, 2006; Patel & Welford, 2017). Out of these, 56Fe is one of the most important isotopes to consider due to its high linear energy transfer of 100 megaelectronvolt (MeV) to 10 gigaelectronvolt (GeV) per nucleon and is therefore difficult to shield against (Gridley & Pecaut, 2016; Raber et al., 2015; Delp et al., 2016; Mehta & Bhayani, 2017; Cucinotta et al., 2020). To put things in perspective, on earth, which consists mostly of α-, β-, and γ-rays, the average annual dose of radiation is about 3.6 millisievert (mSv) and in low earth orbit, the average annual dose is 50 mSv. On the travel to Mars, astronauts will instead be exposed to 1-3 mSv a day, and during a three year Mars mission, the exposure is estimated to be around 1100-2000 mSv which equals approximately 12 000 chest x-rays (Cucinotta & Durante, 2006; Johnson et al., 1993; Lloyd, 2017).

Radiation has either a direct damage to DNA or an indirect damage to biological systems, since radiation creates free radicals that are highly reactive and cause oxidative damage to biomolecules (Fang, 2002). In turn, this may lead to increased carcinogenesis, cataracts, circulatory diseases, changes in epigenetic methylation, damage to the central nervous system (CNS) cognitive detriments, acute radiation sickness, gastrointestinal tract (GIT) and other degenerative diseases (Moeller et al., 2017; Cucinotta & Durante, 2006; Demontis et al., 2017; Naqvi & Kim, 2019; Cucinotta et al., 2020; Nelson et al., 2016). The damage to the GIT can remodel the tissue and alter the motility and structure of the gut, causing gastrointestinal perforations and adhesions. These deleterious changes alter the normal function of the gut and can have a severe impact on nutrient uptake and cause deficiency-associated diseases (Cahill & Hardiman, 2020). Aside from the physiological effects, radiation has a deleterious impact on food itself by inducing lipid peroxidation, protein oxidation, decreasing antioxidants and other nutrients as well as their bioavailability. Furthermore, radiation impacts the color and texture of certain foods and can thereby greatly reduce shelf life. Consequently, radiation decreases the overall nutrient content in food, its bioavailability and its impact on nutrient uptake in the GIT, makes radiation a severe challenge for space food developers to provide astronauts with sufficient nutrition. Radiation also has different mechanisms depending on its source; for example, there is an uncertainty regarding HZE particles and their biological effects on both food and the human body as well as potential countermeasures to these effects (Gandolph et al., 2007; Zwart et al., 2009; Huff & Simonsen, 2016; Lloyd., 2017).

4.1.2. Fluid shifts

Under the conditions of terrestrial gravity, the constant hydrostatic pressure of the human vascular system is called the hydrostatically indifferent point (HIP) of the body where, in a vertical position the hydrostatic pressure is located above the HIP and is either negative or close to zero. In microgravity, there is an absence of the hydrostatic pressure gradient which results in a redistribution of blood and extracellular fluids towards the head and chest area. This causes alterations in the nervous and the endocrine systems as well as in the baroreceptor which encumbers the body's function to maintain blood pressure (Demontis et al., 2017; Nagatomo et al., 2014). There is also a decrease in oncotic pressure from intravascular to the extravascular space due to a rapid decrease of circulating albumin which facilitates the decrease in extracellular fluid volume and an increase in plasma volume (Smith, Zwart & Heer, 2014; Smith & Zwart, 2008a). These factors may also affect renal activity and renal hemodynamics as well as the excretory function. The change in hemodynamics and a lower pressure in the renal artery, leads to a greater release of renin affecting the renin angiotensin aldosterone system and increases the secretion of antidiuretic hormone which controls the amount of fluid reabsorbed by kidneys. This will in turn lead to an increase of glomerular filtration and natriuresis which leads to diuresis and dehydration, even though bodily fluid volume remains unchanged (Smith, Zwart & Heer, 2014; Smith & Zwart, 2008b; Williams et al,. 2009; Demontis et al,. 2017; Noskov, 2013; Kramer et al., 2001; Doty & Seagrave, 2000). Aside from a loss of leg volume, diuresis and a puffy face, the shift of fluids and alteration of blood pressure may impede the delivery of oxygen and nutrients to individual cells greatly affecting bioavailability of nutrients (Nagatomo et al., 2014). Another effect of the puffy face, or facial edema, is that it congests the nasal passages and reduces olfactory components of food which results in a loss of direct smell and retronasal stimulation which is important for certain perceptions of sensorial qualities (Vickers et al., 2001; Olabi et al., 2002)

4.2. Physiological Challenges

Our knowledge of the human physiology in space is restricted to short term missions in low earth orbit, and due to the extreme environment, even short term space missions require careful preparations in order to meet the physiological needs or to reduce the deleterious impact it may cause. During long term missions in deep space, we can assume that these physiological challenges become more apparent, not only because of the prolonged duration, the lack of gravity and the increased radiation in deep space, but also because of the psychological impacts that come with a low stimulus environment and "earth out of view phenomenon''(Kanas & Manzey, 2008). Furthermore, the epigenetic and genetic mismatches to the terrestrial environment and the human adaptability to the deep-space environment may become a new physiological challenge (Szocik et al., 2018). The physiological effects of deep space and microgravity are many and they include a disrupted calcium homeostasis which affects muscle atrophy and causes bone demineralization. There is a redistribution and homeostasis of fluids, changes in protein utilization, metabolic acidosis, impaired cardiovascular function and red blood cell loss. There are also changes in the gastrointestinal motility, immune system dysregulation and issues with the circadian rhythm. Furthermore, there are changes in gene expression and signal transduction as well as an impaired DNA repair mechanism which leads to an increase in double strand breaks, chromosome aberrations and mutations in the micronucleus. (Szocik et al., 2018; Olabi et al., 2002; Crucian, 2002; Cahill & Hardiman, 2020; Williams et al., 2009; Moreno-Villanueva et al., 2017; Hughes-Fulford, 2001). The role of nutrition as a countermeasure for these physiological changes during extended space flight missions will be of paramount importance in order to ensure crew health (Lane et al., 2013; Smith et al., 2019; Heer et al., 2020). Aside from the physiological concerns, the food needs to be able to withstand long-term storage and radiation induced oxidation over time which poses a challenge regarding nutrient stability (Smith & Zwart 2008b).

4.2.1. Bone Loss

Exposure to microgravity and radiation results in an early onset osteoporosis, increased skeletal fragility, general bone loss and altered calcium homeostasis as well as bone demineralization which in turn leads to an increased risk of kidney stones (Arfat et al., 2020; Burkhart et al., 2020; Smith et al,. 2014). Although the exact mechanism behind bone loss is not completely understood (Coulombe et al,. 2020, Arfat et al,. 2020), similarities between microgravity along with physical inactivity has been found with hibernating animals (Arfat et al,. 2020). In space, there is an increase in bone resorbing osteoclasts and an inhibition of bone forming osteoblasts differentiation along with radiation induced apoptosis of osteocytes. This has shown to result in a loss of calcium and bone minerals, which alters the endocrine metabolic regulation of calcium and general mineral homeostasis which in turn decreases the gastrointestinal absorption of calcium (Smith et al., 2014, Smith & Heer, 2002; Willey et al., 2011; Tahimic et al., 2017; Coulombe et al,. 2020). Along with a lower production of calcitriol due to a an inadequate UV exposure and impaired endocrine function, astronauts are expected to have a general loss of bone mineral density and general bone loss which exceeds the annual 1% loss in post-menopausal osteoporotic women (Axpe et al,. 2020; Doty & Seagrave 2000, Arfat et al,. 2020) Exercise and an increased intake of vitamin D has been implemented as a countermeasure, but it has not fully mitigated the problem (Lane et al,. 2013; Smith & Zwart, 2008b; Smith et al,. 2012). These findings has indicated that the regulation of bone physiology is a complicated harmonic interaction between mechanical and nonmechanical factors, all of which need to be considered when designing effective countermeasures (Ziambaras et al,. 2005)

4.2.2. Immune system

The immune system is particularly sensitive to radiation (Plante et al., 2019) and in synergy with a myriad of different stressors such as microgravity, constant fluid shifts, circadian shifts and isolation, deep space can have adverse effects on the immune system and reduce the adaptive immune system and sometimes enhance the innate immune system as well as alter the interaction between them (Crucian et al., 2018) Crewmembers who have been aboard the ISS for six months have demonstrated a reduction of T cells, Natural Killer cell function, dysregulations in cytokine production and changes in the distribution and function of leukocytes (Gridley & Pecaut, 2016; Crucian et al., 2018; Mehta et al., 2018; Plante et al., 2019). Such immunosuppression has been documented to reactivate latent herpes viruses such as the Varicella Zoster Virus, the Epstein-Barr virus and the Cytomegalovirus. Although the reactivation of these viruses has mostly been asymptomatic during short term, low orbit missions, it is probable that the symptoms of these viruses can become relatively severe and more frequent when humans are exposed to the elements of deep space (Mehta et al., 2013; Plante et al., 2019)

4.3. Nutritional countermeasures

Like any other exploration journey throughout history, space flights rely on adequate nutrition for their success and food plays an essential role in mitigating the physiological effects of the extra terrestrial environment. With an increased duration of space missions, nutrition not only has to meet the requirements for optimal health and energy, but it also has to become an important factor overarching the physiological adaptation to the extreme space environment (Smith & Zwart, 2008a). Understanding the underlying mechanisms the space environment has on the human physiology as well as the counteracting role of nutrients will be necessary to maintain the astronaut's health and ameliorate the deleterious physiological effects of the space environment. Since the research on drug delivery, stability and potential side effects of pharmaceuticals in microgravity is scarce, food is the only source of nutrition during space travel (Blue et al., 2019; Antonsen, 2017).

Studies have shown that certain vitamins and compounds, especially those with antioxidant properties, such as L-selenomethionine, ascorbic acid, α-tocopherol succinate alpha-lipoic acid and N-acetyl cysteine, can reduce the DNA damage caused by radiation and oxidative stress (Wambi et al., 2009; Davis et al., 2010; Schreurs et al., 2016; Cahill & Hardiman, 2020). Also, the production of reactive oxygen and nitrogen radicals disrupts redox signaling and in turn, the metabolic processes that impact the body’s ability to utilize energy and nutrients. This underlines the importance of an antioxidant dense diet even before being exposed to radiation (Cahill & Hardiman, 2020). Antioxidants not only protect the body from spontaneous oxidation reactions, but protect the food itself from oxidative degradation (Zwart et al., 2009). Therefore, food developers should consider including compounds such as phytic acid, ethylenediaminetetraacetic acid as well as polyphenols that can protect the antioxidants themselves. These compounds can sequester metal ions, and prevent them from regenerating hydroxyl radicals, thereby taking the load off antioxidant compounds (Morello et al., 2002).

Research has indicated that an increased intake of vitamin D, calcium, phosphate and exercise is not enough to mitigate bone resorption and to counteract vitamin D insufficiency and a negative calcium balance. Studies showed that an omega-3 fatty acids prevent osteoclastogenesis and decrease inflammation by the inhibition of proinflammatory eicosanoids through the inactivation of nuclear factor kappa B, a complex of proteins regulating DNA transcription and cellular responses to stress (Lane et al,. 2013; Smith & Zwart, 2008a; Smith et al,. 2012; 2014; Zwart et al., 2010). Omega-3 fatty acids as well as several micronutrients such as beta-carotene, folic acid, cobalamin, vitamin C, riboflavin, selenium, iron and zinc along with arginine, glutamine, have immunomodulatory actions. Along with probiotics this can help to improve the intestines immunologic barrier (Cena et al., 2003). It has also been suggested that an intake of alkaline potassium salts may counteract metabolic acidosis and mitigate the snowball effect it has, such as osteoclast formation and other physiological issues (Thompson et al., 2000; Heer et al., 2015; Cahill & Hardiman, 2020)

There are many nutritional countermeasures to the physiological issues related to space travel and a highly acceptable and nutritious diet will be important for their efficacy. However, it is difficult to sustain a vitamin and nutrient stability in space due to the elevated radiation, the long term storage of foods in ambient temperature and the food processing that is required.

5. Current processing methods

When developing food systems for long duration space flights, aside from minimizing mass, volume and waste, food needs to be variable, maintain organoleptic acceptability, and have a shelf life that extends up to five years without refrigeration. During that time the food has to keep its nutritional efficacy and palatability, where each category is a limiting factor in shelf life stability (Perchonok & Bourland, 2002). It is also important to consider extraterrestrial environmental conditions such as extreme temperatures, extreme radiation and weightlessness, all of which affects heat and mass transfer as well as fluid behaviour (Fu & Nelson, 1994). These environmental effects on food and how they may isomerise or oxidise fatty acids, vitamins and amino acids have barely been tested (Schroeder, 2018). To sustain a crew with food for five years without replenishment, there is a need to optimize food processing technologies (Cooper & Douglas 2015). For now, the food system is only appropriate for missions that last six months to a year, and only a few foods sustain palatability after three years. To develop processing systems is a balancing act between development of nutritious, safe, and acceptable food and an efficient use of mass, volume, waste management, water recovery, biomass production, air recovery, thermal control systems, power, and crew time (Perchonok & Bourland, 2002; Perchonok, 2014; Jiang et al., 2019).

5.1. Thermostabilized foods

In thermostabilization, or the retort process, heat is used to impede microbial growth and enzyme activity. This process is similar to canning, but instead of cans, the food is packed in lighter, more flexible aluminium retort pouches. The characteristics of thermostabilized foods is somewhat similar to common food in terms of shape and taste. They contain the normal amount of water but with an increased viscosity to reduce the microgravital influence, which reduces their palatability (Jiang et al., 2019) However, there are still certain physical and chemical changes that may occur after the thermostabilization. Heat accelerates the breakdown of proteins, amino acids and other nitrous compounds that increase the concentration of ammonia (Chia et al., 1983). Heat also speeds up vitamin degradation and causes non enzymatic browning (Olivas et al., 2002). Catauro & Perchonok (2012) investigated the shelf life of thermostabilized foods and found that the results varied with only a limited amount of products that could maintain their quality for up to five years at ambient storage conditions. They concluded that in order to support a longer duration mission, there is a need for reformulations of the actual food products as well as non-thermal processing technologies (Catauro & Perchonok, 2012). Alternatives such as microwave-assisted thermal sterilization (MATS) and pressure-assisted thermal stabilization (PATS) have also been evaluated but few advantages were found. MATS products have proven to have a more overall acceptable texture and color. However, the vitamin stability of the food did not improve. The reason for this is that space food requires packaging with an impenetrable barrier to protect the foods from oxygen and moisture. The non metallic protective packaging film required to use in the MATS process did not provide an adequate oxygen barrier and therefore, it resulted in accelerated vitamin degradation (Cooper & Douglas, 2015). PATS is a combination of high pressure processing and thermal processing and has an overall better effect on fruit compared to the retort process, where a five year shelf life of fruit could be achieved but it may affect meat color and exacerbate biochemical reactions which leads to an indirect nutrient destruction (Dhawan et al., 2014; Cooper & Douglas, 2015; Zhang et al., 2016, Jiang et al., 2019)

5.2. Irradiation

To use ionized radiation by either radioactive isotopes or accelerated electrons from γ-ray, β-ray or X-ray is an effective method to destroy any microorganism that may be present in food. Irradiation disrupts the normal cellular functions by directly damaging the DNA and/or RNA helix or indirectly damaging proteins by creating water free radicals in the form of hydrated electrons, hydrogen atoms or hydroxyl radicals. These radicals will in turn lead to changes in the protein structure such as deamination, disulphide linkage reduction, decarboxylation, oxidation of sulfhydryl group, peptide chain cleavage, aggregation and modification of amino acid moieties (Kuan et al., 2013). The sensitivity to irradiation varies between pathogens and the state that they are in. If a pathogen is starving, in a vegetative state, or subjected to heat stress, osmotic stress or alkali stress, it may show some resistance to irradiation, affecting the radiation dose required to inactivate 90% of the microbal population, i.e. their D10 value (Khan et al., 2017). The benefit of irradiation is that the food maintains its structure and flavor and has minimal effect on food quality. In presence of its natural protectors, lipids are not sensitive to radiation-induced peroxidation for up to 10 kGy. A similar threshold was found for proteins and carbohydrates. As for vitamins with high radiation sensitivity (Vitamin

A, Vitamin C, Vitamin E and Thiamin (B1), radiation doses should not exceed 1 kGy to prevent their loss due to generated free radicals (Thayer, 1990; Lacroix & Ouattara, 2000; Prakash et al, 2019; Pedreschi & Mariotti-Celis, 2020). To meet the requirements for space diets, irradiation sometimes needs to exceed 40 kGy, which limits the foodstuff that is processed this way to meats and poultry which does not contain the same radiosensitive nutrients as other foods (Khan et al., 2017; Pedreschi & Mariotti-Celis, 2020). However, such a high dose of irradiation may however induce changes in the sensory characteristics as a result from sulfur-containing volatiles and lipid oxidation byproducts (Brewer 2009; Song et al., 2009).

5.3. Freeze Drying

Freeze drying, a method also known as lyophilization or cryodesiccation is a method used to dehydrate food materials by first pre-freezing the wet product followed by sublimation of the frozen solvents under vacuum conditions and finally the residual bound water is desorbed from the material matrix to create a low density porous dried particle structure without changing the cellular structure, or the nutritional and sensorial qualities (Zhang et al., 2017; Nastaj & Witkiewicz, 2009; Jiang et al., 2019) On account of these advantages along with the low weight and easy storage, many freeze dried and rehydratable foods are currently used in space. They are especially advantageous on shuttles since shuttle fuel cells are powered by hydrogen and oxygen that leave water as a byproduct (Bourland, 1993; Jiang et al., 2019; Cahill & Hardiman, 2020).

The Italian Space Agency developed a freeze dried yogurt, a rich source of both calcium and probiotics and found that the addition of sucrose reduced the mortality of *L. delbrueckii* subsp. *bulgaricus* and *S. thermophilus* when exposed to freeze drying (Venir et al., 2007) Since freeze drying has a high energy and production cost relative to the yield, it is often combined with other processing methods such as irradiation or microwave freeze-drying (MFD). MFD can heat materials by volume which would solve the difficulty of heat transfer during regular freeze frying. However, MDF has a non-uniform distribution of the microwave field in the drying cavity which in turn leads to a nonuniform distribution of temperature and under certain conditions, heat and mass transfer may interfere with each other and the change in microwave power can cause the temperature to rise quickly. This will create a catastrophic phenomenon that creates an uncontrollable positive feedback called the Thermal Runaway (Vriezinga et al,. 2002; Duan et al,. 2007) To solve this problem pulse-spouted microwave vacuum drying (PSMVD) which alters the location of the materials in the drying cavity during drying, is being tested (Jiang et al., 2013).

6. Alternate food systems

The current processing methods do not provide a 5 year shelf life for most foods, and even though MATS and PATS have shown some promises, they may still exacerbate certain biochemical reactions that can lead to indirect nutrient loss or organoleptic qualities. Moreover, with the current systems it will be difficult to attain a decent eating experience for the crew as these processing methods may limit the taste and variety of the food (Cooper et al., 2017; Jiang et al., 2019). Therefore, there may be a need for alternative food systems to use alongside the current processing methods (Perchonok et al., 2012).

6.1. Bioregenerative Food Systems

The current food systems only have the capacity to sustain a crew for six months up to one year and are not adequate for long duration missions. As an alternative to prepackaged food, in 1978, NASA began to develop Controlled Ecological Life Support Systems, a project that aims to produce crops *in situ* in order to achieve self-sufficiency of food for space missions with longer durations (Averner & Maurice 1990; Cooper et al., 2011). Aside from reducing the mass and storage of pre-packed food, bioregenerative systems revitalize air and fresh water to provide the shuttle with a breathable atmosphere. Furthermore, these systems can provide a central recycling system for crew waste materials which would take a load off current systems where oxygen is generated by the electrolysis of water and CO_2 is removed by in the Carbon Dioxide Removal Assembly, by scrubbing the CO_2 with lithium hydroxide (LiOH) to create water and solid lithium carbonate (Li_2CO_3) (Reysa et al., 2004; Yamashita et al., 2009; Matty, 2010). Another advantage of a bioregenerative system is horticultural therapy and biophilia. Studies conducted in hospitals have indicated that patients with windows overlooking a garden or the presence of plants have faster recovery rates. These studies showed that plants have a stress reducing effect and have been linked to a lower systolic blood pressure, heart rate, lower pain ratings, anxiety as well as elevated levels of natural killer cells, resulting in immune enhancing functions (Ulrich 1983; Söderback et al., 2004; Park & Mattson 2008; Li et al., 2008; Szocik et al., 2018).

Compared to processed food, fresh produce is more nutrient dense since some nutrients such as vitamin C and phenolic acid are heat sensitive and degrade during processing. However, processing results in an increased bioavailability of carotenoids and some polyphenolic compounds. This allows the crew to optimize nutrient intake for each foodstuff as well as personalizing the menu to accommodate their individual preferences, resulting in a more fresh and variable menu with a higher acceptability (de Graaf et al., 2005; Perchonok et al., 2012).

Bioregenerative systems may, however, be more appropriate for lunar and mars bases rather than on board space crafts. The infrastructure required for a working system has to be large enough to provide a suitable atmosphere and enough food, which in turn requires more power, mass and volume compared to pre-packed food systems (Salisbury 1999). Moreover, a crop system would demand the crew members to function as farmers, stockroom managers, cooks and health inspectors which, aside from taking too much time from their primary responsibilities, would require the crewmembers to possess these extra skills (Perchonok et al., 2012). The biogenerative systems would also introduce the enhanced risk of microbial contamination, since it has been found that microgravity makes some bacteria to better handle stressors such as pH, osmolarity and temperature. Furthermore, it has been found that microgravity influences virulence in some Gram-negative bacteria, enhancing their pathogenicity (Rosenzweig et al., 2010; Sheet et al., 2020). Another concern is the risk of crop failure, which is likely to occur if one considers that plants are highly sensitive to gravity and that even if plants would grow, they cannot complete their life cycle due to the need for an accelerating force at some point during their development, which on earth is provided by gravity (Salisbury 1999; Monje et al., 2003) This further underlies the importance of sustainable processing methods, since in the event of a crop failure, the crew will rely on a pre-packaged back up food system (Perchonok et al., 2012).

Despite these hurdles, as the infrastructure and crop selection develops, bioregenerative food is expected to become an important addition to the current food systems for the crew (Cooper et al., 2017).

6.2. 3D Printing

With 3D printing, food can be made in flight which would alleviate packaging and processing concerns as nutrients, proteins, lipids, carbohydrates can be stored in powder, puree, liquid or aqueous solution dispersions in the ink cartridges. The macronutrient stocks will be fed to the printer during the production of food. At the printhead, the food will be combined with water or oil and texture modifiers, to later be extruded and shaped into desired structures layer by layer (Liu et al., 2017). This way, food can also be personalized and cater to different people's needs in terms of lifestyle and appetite, and in addition, this method can more easily record and save health information about individuals, i.e., it can tailor timely adjustments to meet the crews energy and nutritional needs (Yang et al., 2017; Jiang et al., 2019). Although some food printing technologies are available, the 3D printing technology for food is nascent; printing precision and accuracy still needs to be perfected. For that to be achieved we need a better understanding of food material and its rheological properties even in normal gravity. (Sun et al., 2015; Lipton et al., 2015; Liu et al., 2017; 2018; Jiang et al., 2019). Fluid behaviour in microgravity has been studied, but very few studies have been conducted on food materials. Many of these studies have been conducted on board NASA's C-9 low g flight research aircraft where the time of microgravity is too short for fluids to reach equilibrium (Spanier et al., 2007; Wagenborg, 2008; Chao et al., 2020).

7. Microgravity and food properties

Physics in microgravity differ from terrestrial gravity in some main respects: Hydrostatic pressure, buoyancy, potential energy, natural convection and sedimentation all rely on gravity to exist. One significant example of this is boiling water, which requires gravity for a homogenous distribution of heat. Here, buoyancy induced flow causes lighter, less dense fluids to rise upwards, such as steam bubbles, and more dense cooler water flows downwards. In microgravity, the gas bubble size increases, their velocity decreases and they coalesce, forming a big gas bubble close to the heat source resulting in film boiling, leaving the surrounding water cooler (Chao et al., 2020).

Viscosity is also affected, mainly due to an increase in the radial dimension of liquid bridges which leads to an increase in the viscous force. Foams have been found to stabilize in microgravity and even dense water foams, close to the jamming transition limit have been found to be stable (Caps et al., 2014a). Gravity drains the foam of excess liquid, this is normally counterbalanced by a vertical capillary-pressure gradient in stable foams. Without gravity, excess liquid does not drain, leaving only the capillary forces which causes film thinning on the plateau borders of different cross sections due to capillary suction (Saint-Jalmes et al., 2007). However, since spheres in microgravity will take on a dendritic morphological structure, causing the bubble surfaces to become partly rigid, this capillary drainage is slowed. Since hydrostatic pressure does not exist in microgravity, there is little to no Laplace pressure causing the bubbles to coalesce and coarse the foam (Vandewalle et al., 2011). There have been studies on the action of various anti-foaming agents in microgravity. It was shown that anti-foaming agents were inefficient and did not have time to rupture any films during the foaming process. Since the space between the bubbles is large relative to their size, the bridging-dewetting mechanism does not work, deeming the anti-foaming agents inefficient even after foam formation. This may cause problems if foams are not wanted and accidentally produced. At the same time, the foam stability creates new opportunities to create foams impossible to create on earth and may aid in food foam stability (Caps et al., 2014b).

Gravity also plays an essential role for colloidal particles and influences the way they interact, sediment as well as the formation and structure for colloidal crystals as they are weakly bound (Zhu et al., 1997). Colloidal crystals in microgravity have shown to form hexagonal close-packed planes and subsequently formed a dendritic crystal growth, whereas in the influence of gravity they form face centered cubic packing and as the crystals settles it sediments and the shear viscous stress in the fluid causes the dendritic structures to shear (Russel et al., 1997; Wagenborg, 2008) Colloidal systems on earth fail to crystallize completely and remain in a glassy state whereas in microgravity the crystals become ordered and nucleation is relatively fast and also occurs at various locations in the fluids. Although the effects this has on food systems has yet to be studied, this may have consequences for nutrient delivery as well as the rheological and organoleptic properties of the food (Zhu et al., 1997; Gast & Russel, 1998; Dickinson, 2015; Chao et al., 2020)

Not much research has been conducted on the physical properties of food systems in microgravity. It is however of high importance to achieve a deeper understanding in the subject in order to develop functioning food systems for future space travels.

8. Summary and Conclusion

A lot has happened regarding food systems in space over the last 60 years. However, most of the research has been driven to develop food for the crew on board the ISS (Obrist et al., 2019). With a reinvigoration of space travel and new plans to go beyond the low earth orbit and the moon into deep space and to Mars, a plethora of new challenges regarding the development of food systems for these missions has been introduced. Before we can send humans into a confined environment for a long period of time, deprived of sensorial stimulation, it is essential to take basic human needs into account and what role food plays for the psychological well being. Furthermore, it is important to consider how food may work as a countermeasure to other psychological stressors as well as how it can countermeasure the physiological effects of deep space. It is highly relevant to understand these effects and the underlying mechanisms in order to better design the diet and the nutritional composition of the food.

One of the main challenges will be to develop a variety of palatable foods with a shelf life for up to 5 years that can withstand the hazards of deep space. Alternative methods and techniques, such as 3D printing and bioregenerative systems, show certain promises and remind us that food systems are not restricted to pre-packed foods. However, in order to achieve acceptable food systems, it is necessary to get a deeper understanding of the space environment and its effect on the properties of food. The space food research field, which includes all of the topics mentioned in this thesis, is scarce and finding relevant papers have proven to be a challenge. This review has pointed out the need of more interdisciplinary measures that can solve the challenges that space food developers currently face. The research regarding microgravity's effect on food properties is exiguous and somewhat scattered. Most of the research conducted on fluid systems and the rheological properties in microgravity have understandably been focused on rocket fuel dynamics and similar areas. To achieve technologies such as 3D printing, to be able to cook in microgravity

or even in hypogravity on other planets, it is essential to get a better understanding of the properties of food systems in microgravity. This research also allows to get a better understanding of the underlying mechanisms of for example fluid behavior and without the interfering physical forces on earth, be able to observe intermediates masked by these forces (Chao et al., 2020).

Similarly, the need to develop processing methods that are able to keep nutrient efficacy/bioavailability and organoleptic acceptance for a long period of time may not only be relevant for space travel, but could also be applicable to areas such as isolated research expeditions on earth, military purposes and crisis management. As is the understanding of possible nutritional countermeasures for physiological stress.

This study has addressed a fraction of the complexities related to food and space travel and there are still many unsolved areas and limitations. Topics such as packaging materials, even though partly excluded here, are relevant in order to achieve sufficient shelf life of foods. To be able to achieve proper food systems for future deep space missions, further research needs to be conducted and it may be imperative with interdisciplinary studies between the areas highlighted in this review.

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