Modelling of Space Crop Dishes for Optimal Nutrient Delivery to Astronauts and on Earth

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Abstract

Future long-term human exploration of space will need supply of resources for astronauts, including fresh food from space farms. This means it is necessary to identify combinations of crops that can be successfully grown together, and which provide a balanced and palatable diet for astronauts. We used numerical optimization to identify such combinations, using macro and micro nutritional content as constraints, while optimizing water load needed for crop farming. The food constraints considered were based on the recommendations of National Aeronautics and Space Administration (NASA), considering up to 36 nutrients and 102 crops. We evaluated ten scenarios ('space dishes') for daily full-nutrient supply to one astronaut, with four scenarios being vegetarian (crops only) and six being omnivorous (crops and meat). Each scenario was analyzed for capability of plant growth, including required planting area and crop growth time and productivity; from the viewpoint of optimizing performance in space. As plants contain both edible and inedible parts and require fertilizer input, respective circularity assessments were made determining the waste generation, degree of recyclability, and overall mass processed; using three common metrics of the Circular Economy. The space dish identified as optimal was prepared as a salad, to allow judgement on the palatability, i.e., the 'space food acceptance', by a small psychology test at a space agency research center (NASA). These assessments are essential steps towards feasibility in long-term human space missions, for example to Mars.

Introduction

Space food and farming

The provision of food is a long-term and fundamental strategic subject for human life support and well-being. This is particularly important for the future of long-term space missions, in which timescales and payload requirements prohibit the transport of sufficient food. There remains a critical need to identify the best material and design of cultivation systems to maximize outputs and system circularity, while combatting the harsh environment and plant stressors, including space cosmic rays, vacuum, and microgravity [1].

For long-term space missions, the food supply required is large and its effective management will need considerable effort [3]. For example, a male astronaut needs about 1.2 kg food per day [4], and the cost of replenishment by external supply is extremely high. In the current space mission, six different classes of food are available for astronauts on the International Space Station, ISS: thermostabilized food, rehydratable food, intermediate moisture food, natural form food, irradiated food, and fresh food [5]. Space production of food would enable long-term missions with a lower food payload. However, this would come with increased water payload need. Water recycling has been a prime issue for sustainability on spaceflights, as reported previously [6]. Solutions for water recycling on the ISS have been developed [7] yet are an important consideration for any space farming solution.

Several plants have been cultivated in space over recent decades. Crops such as wheat, soybeans, lettuce, peppers, tomatoes, and strawberries are suitable for growing in space [8]. Whereas, red romaine lettuce, Chinese cabbage, mizuna mustard, kale, pak choi, and other leaf crops have also been planted in space experiments [9]. However, this list is not exhaustive, nor does it constitute a potentially nutritiously complete diet.

Nutrients for astronauts

Nutrients are substances that need to be ingested from food to maintain all life activities including reproduction, growth development and survival of the human body [10]. Macronutrients, including carbohydrates, lipids and proteins, supply energy are key requirements [11]. Micronutrients, including vitamins and minerals, are responsible for a range of physiological function, and are generally required in smaller amounts [11]. Recommended requirements have been reported for each nutrient (Table 1) [3]. In general, all macronutrients are a source of energy [12]. Some minerals, including potassium (K), magnesium (Mg), and calcium (Ca), are required in larger quantities, while other micronutrients are only needed in trace amounts.

However, the nutritional requirements of astronauts are different from those on Earth because of the stresses placed on the human body in space conditions [13]. For example, the human body faces stressors including vibration, noise, weightlessness, cosmic radiation, high vacuum, circadian rhythm changes, drastic temperature changes, overloaded psychology and work pressure [14]. These factors may lead to astronaut cardiovascular system dysfunction, motion sickness in spaceflight, and structural and functional changes in bones and muscles [15]. Studies have shown that nutritional deficiencies and other adverse factors can be counteracted by adopting an effective dietary approach [16]. For example, during spaceflight, bone loss in the legs of astronauts is severe. Several nutrients are important for bone health, especially Ca and vitamin D, and thus optimal requirements are higher for astronauts [17]. Against this backdrop, the aim of this study is to identify combinations of crops that could be grown on a long-term space mission, such as a trip to Mars that would provide a balanced diet for the astronauts. This study is specifically guided by a report on dietary requirements for long-duration missions [3], co-authored by NASA researchers, recommending a space nutrition mixture for a male astronaut (Table 1). The nutritional requirements of astronauts are established by the World Health Organization (WHO) based on the daily requirements of people on Earth combined with additional stressors [18].

Table 1 *Macro- and micronutrient recommended intake for adult male astronauts (AMA) (space, [3]) and on Earth (WHO, [18]).*

	Intake Requirements for AMA	Recommended Dietary Allowances or Adequate Intakes (*) for Earth Adult Man	Units
Carbohydrate	337.5	130	g/d
Fat	105	52	g/d
Protein	101.25	58	g/d
Calories	2700	2000	Kcal/d
Fiber	10	38*	g/d
Histidine	0.78	0.62	g/d
Isoleucine	1.55	0.78	g/d
Leucine	3.03	1.09	g/d
Lysine	2.33	0.94	g/d
Methionine	0.78	1.01	g/d
Phenylalanine	1.94	1.09	g/d
Threonine	1.17	0.55	g/d
Tryptophan	0.31	0.27	g/d
Valine	2.02	0.78	g/d
Calcium (Ca)	1200	1000	mg/d
Iron (Fe)	8	8	mg/d
Magnesium (Mg)	420	420	mg/d
Phosphorus (P)	945	700	mg/d
Potassium (K)	4700	3400*	mg/d
Sodium (Na)	1500	1500*	mg/d
Zinc (Zn)	11	11	mg/d
Copper (Cu)	0.5	0.9	mg/d
Manganese (Mn)	2.3	2.3*	mg/d
Selenium (Se)	55	55	µg/d
Vitamin A	700	900	µg/d
Vitamin B1	1.2	1.2	mg/d
Vitamin B2	1.3	1.3	mg/d
Vitamin B3	21.6	16	mg/d
Vitamin B5	6.75	5*	mg/d
Vitamin B6	1.7	1.3	mg/d
Vitamin B9	400	400	µg/d

Vitamin B12	2.4	2.4	μg/d
Vitamin C	90	90	mg/d
Vitamin D	25	15	μg/d
Vitamin E	15	15	mg/d
Vitamin K	120	120*	μg/d

The recommended intake for carbohydrates and proteins proposed for astronauts is more than twice that for a person on Earth. In addition, a macronutrient composition of 15% proteins, 30% fats, and 55% carbohydrates was taken as minimum [19]. The recommended intake of essential amino acids for Earth adult males and astronauts is calculated assuming a body weight of 78 kg. Some differences are observed in the minerals and vitamins, e.g. including for K, Cu, and vitamin B_3.

Animal source food provides a higher concentration of many nutrients, including protein, Fe, Zn, and vitamin B12 [20]; a purely vegetarian diet might lead to large needs of food intake [21]. Therefore, this study considers both vegetarian (plant-only) diets and diets supplemented by animal source food. Animal source food are available on the ISS because it can be stabilized for some time and stored. Thus, including animal source food is plausible for short-term space travel. For long-term travel, there is little research on how to include animal source food products in the astronauts' diet. Laboratory-grown meat could be an option, and space aquaculture has been reported for growing fish in space and using their droppings as fertilizer for plants [22]. A number of tree crops have also been considered, including olives, chestnuts, dates, citrus etc. While these are generally recognized to be unsuited for space growth, we nonetheless include these because developing space conditions for arboriculture is a legitimate research topic, and because we intend to co-valorise our results on Earth.

This study has been designed to aid the selection of fresh and renewable agricultural products, as food source of astronauts, grown and produced in the space environment. The optimal astronaut food mix is determined by numerical optimization, involving several types of system constraints, including maximal food intake, caloric uptake, and space farming needs (planting area, fertilizer consumption, and circularity.

Methodology

Data sources

All food nutrient composition data were collected from the U.S. Department of Agriculture (USDA) [23]. Data on nutrient requirements for macronutrients and essential amino acids for adult males and adult females were obtained from the dietary reference intakes published by the Food and Nutrition Board of the National Academies of Sciences, Engineering and Medicine [24]. Astronaut nutrition requirement data were retrieved from Cooper et al. [3]. The amount of water required to produce a given weight of crop is obtained from HEALabel [25].

Numerical optimization

Linear programming

We employ the widely used linear programming (LP) procedure. LP solves problems of the following form:

$$\min_{x} c^T x$$

Such that

$$A_{ub}x \leqslant b_{ub}$$

$$-A_{ub}x \geqslant -b_{lb}$$

$$\sum x = b_{eq}$$

where x is a vector of decision variables (here, the weight of each food); c is a vector of linear objective function coefficients (here, water requirement of each food, produce 1 kg food/L water); b_{ub}, b_{lb} and b_{eq} are vectors comprising constraints (here, maximum nutritional requirements, minimum nutritional requirements and daily food consumption of astronauts, respectively); and A_{ub} is the matrix of different nutrients for each crop.

The three different types of data collected are substituted into the formula, with the amount of each food considered as the decision variables. The sum of the amount of water needed to produce all food represents the objective function to be minimized, whilst the astronaut requirements for each nutrient are considered as constraints.

LP was implemented using linprog from the Scipy (v1.6.2) library. This implementation required the problem to be formulated as a minimization problem and the inequalities to be expressed as an equal to or less than.

Scenarios

Ten different scenarios were assessed using the method described above by considering modifications to LP problem constraints. Ten scenarios were defined to supply macro and micro nutrients, with additional consideration of fiber content and food consumption (i.e. to account for portion sizes; maximum weight of food consumed). An overview of the details of each Scenario are given in Table 2. Scenarios 1-4 represent a vegetarian only diet and consider 44 crops in total and differ in terms of how many constraints are imposed with regards to amino acid, mineral and vitamin requirements as well as total food intake. Scenarios 5-10 include 6 additional animal-derived items including beef, chicken spread, trout, salmon, tuna fish, and clams [34], whilst scenario 8 increased number of foods from 50 to 102. Scenarios 9 and 10 change crop constraints based on the previous scenario. Some of these crops are not traditionally considered for space production and it may hold potential in the future. Within each of these scenarios, the amount of nutrient constraint is also different.

Scenario 1 represents a base case with a minimal, yet essential inventory of nutrients, excluding fiber or consideration of total food intake (mass). It considers all macro- and micro-nutrients and amino acids, yet restricts consideration of vitamin A, B12, and D as payload supplement due to low requirements and difficulty in obtaining vitamin B12 in vegetarian diets. Scenario 2 is similar to scenario 1, with a restriction on total food mass at 1.2 kg per day based on the amount of food a male astronaut eats each day during a space mission [4], whilst Scenario 3 assumes phosphorus, Na, Cu, Se and vitamins B12, E, and K are taken as payload. Compared with scenario 1, scenario 4 removes the sodium constraint and adds a food intake constraint. Scenario 5 is the same as scenario 2, but includes vitamin B_{12}. 16 nutrients have been found particularly important for human health on Earth and in space and include protein, calcium, iron, vitamin A, vitamin C, thiamine, riboflavin, vitamin B12, folic acid, vitamin D, vitamin E, magnesium, potassium, zinc, fiber and pantothenic acid [3]. Those 16 nutrients were considered in scenario 6 for computer modelling, and subsets of these 16 for all other scenarios. Scenario 7 faces all constraints given in scenarios 1-6, meaning it is the most advanced inventory considered. Scenarios 8-10 do not consider essential amino acid and minor vitamin restrictions due to missing data for additional crops.

Table 2 *Constraints included in the ten scenarios for the optimization modelling for nutritionally complete space food.*

		Nutrition constraints considered						
Scenario	**Number of crops**	**Calories (2700 – 3700 kcal)**	**Macro-nutrients**	**Amino acids**	**Minerals (Ca; Fe; Mg; P; K; Na; Zn; Cu; Mn; Se)**	**Vitamins (A, B_1, B_2, B_3, B_5, B_6, B_9, B_{12}, C, D, E, K)**	**Fiber**	**Food intake per weight (1.2 kg/d)**
1	44	√	√	√(9)	√(10)	√ (9), exclude: A; B12; D	-	-
2	44	√	√	√(9)	√(10)	√ (9), exclude: A; B12; D	-	√
3	44	√	√	-	√ (6) exclude: P; Na; Cu; Se	√ (6), exclude: A; B6; B12; D; E; K	-	√
4	44	√	√	√(9)	√(9) exclude: Na	√ (9), exclude: A; B12; D	-	√
5	50	√	√	√(9)	√(10)	√(10), exclude: A; D	-	√
6	50	√	√	-	√ (5) exclude: P; Na; Cu; Mn; Se.	√(9), exclude: B3; B6; K	√	-
7	50	√	√	√(9)	√(10)	√(12)	√	√
8	102	√	√	-	√(10)	√ (9), exclude: A; B12; D;	-	√
9	100	√	√	-	√(10)	√ (9), exclude: A; B12; D;	-	√
10	99	√	√	-	√(10)	√ (9), exclude: A; B12; D;	-	√

In addition, we considered a recent astronaut nutrient recommendation released by NASA in

2020 [49], given for an adult male (age: 40 years old; weight: 70 kg; height: 1.75 m) example, Based on this, three additional calculations were performed (Scenarios 11, 12 & 13). This is given in the Supplementary Material, yet not included in the paper core, as we like to refer to a peer-reviewed paper mainly rather than to a web release. Scenario 11 considered 102 types of food, while scenarios 12 and 13 were optimized for vegetarian scenarios, considering 44 and 96 crops, respectively.

Circularity metrics

The circularity metrics recommended by the Ellen MacArthur Foundation (EMF) were used for the circularity assessment of the ten scenarios. It is based on three principles: eliminating waste and pollution, recycling products and materials, and regenerating nature [26]. In this study, EMF calculations were made on the material mass, the share of non-renewable material relative to reusable or recyclable material, and the mass of non-recyclable waste associated with each scenario. In addition, a normalized circular EMF metric associated with recovery was calculated.

Psychological method

Following optimality, the palatability and acceptance of the proposed space scenarios were assessed. The psychology test was conducted by the College University New York and reported "The Harmonic Psychology of a Space Salad"; human uses of space products pose ethical issues, as e.g. raised in NASA ethics [27]. The food psychology study was made on the backdrop of color psychology, meaning the harmonic appearance of the food product. Colors are placed next to each other on the color wheel, comprising concepts of 'Analogous Colors' [28], different in shades of the same pigment (e.g. light blue, blue, dark blue), 'Monochromatic Colors' [29], and 'Split-Complementary Relationship', choosing one color and finding its opposite [29]. A second backdrop is the concept 'Eating As A Family', fostering interactions with crew mates and personality types when living in tight quarters in the void of space. Meals bring palatability to the individual human satisfaction and emotional unity to a community, associated with celebrating life.

Results and Discussion

Hierarchy of nutrition optimization under food and digestion constraints

We have developed a hierarchy of constraints as an aid to space farming design, and in order to frame our computational analysis. Figure 1 provides a holistic summary of constraints considered for space food growth and nutrition. It also shows the hierarchy of the constraints. The initial ('must-meet') request is the provision of all life-essential nutrients in sufficient amount. The caloric value is of equal importance, relating to the health of astronauts and affecting the body weight. In this study, must-meet requests are solved by computational modelling.

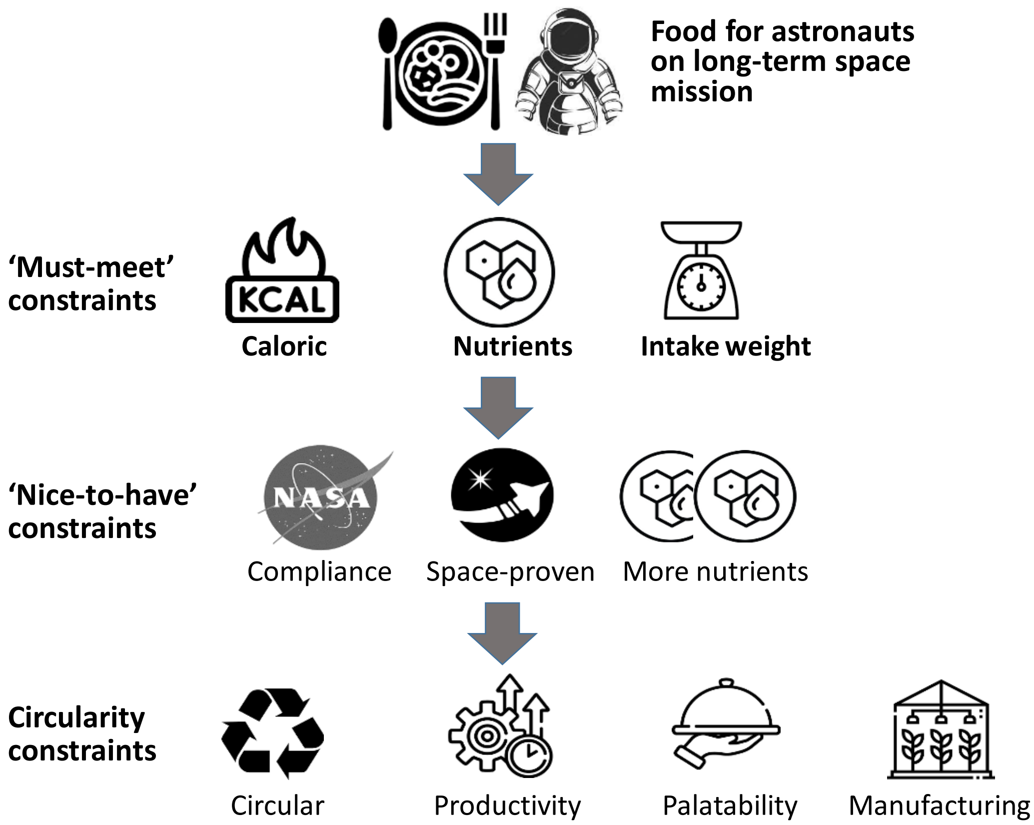


Fig. 1 *Constraint levels for space food. Considered in this study is the first ('Must-meet') and third ('Circularity') level.*

'Nice-to-have' constraints refer to current technological issues that may be overcome in future and are therefore not as stringent as the former human-survival related issues – we considered only the "more nutrients" constraint in this study. A space agricultural technology, for example, needs to be at hand. Planting experiences of crops in space (ISS) and simulated space environments guide the practicability and robustness. A too large farm area will be technically demanding, meaning plants with fast growth rates are generally preferred. Not all nutrients need to come from space-grown crops, and addition (as payload) especially for micronutrients is an option. That may also help to keep the weight of the digested food in space to a level similar or lower to that on Earth. Eating more in space is not an option, as per digestion issues outlined above.

Manufacturing capability, food consumption experience and sustainability must be met. This includes meeting targets of productivity, palatability (sensorics), and circularity. While these targets are ‘must-have’, this study puts them on third level, as the complexity is large, when solving a three-level hierarchy problem, especially seen that on the third level hardly any full-functional technical solutions are available. In this study, must-meet requests are solved by mathematical modelling– we considered “circular, productivity, and palatability” constraints in this study..

For future constraint setting, experiments might be considered that demonstrated ‘positive stress’ (Eustress) under the harsh space conditions, promoting growth or nutrient yield, rather than perceiving these only as ‘blockers’ [2]. Stress-induced chromosomal aberrations can be utilized for fast the mutation of biological genetic characteristics for breeding of new varieties [30]. The bred seeds have high yield, high quality, disease resistance, stress resistance, and wide adaptability. For example, "Hangjiao 1 pepper", made by aerospace breeding, has a vitamin C content of 234 mg, which is about 183% greater than in ordinary peppers. ‘Space 5 wheat’ has good taste, and its yield exceeds traditional varieties by more than 10%. The flowering period of "Space marigold" has been extended to 9 months [31]. Space planting also helps create a sustainable environment, as plants can be used to recycle wastewater and generate oxygen [32] and create a biophilic design promoting well-being [33].

<u>Credible food combinations identified from optimization under the ten scenarios</u>

The optimized crop types and weights for each of the scenarios is given in Table 3. In terms of the total weight of food, scenarios 1 and 6 largely exceed others, by a factor two or greater than the recommended daily food consumption of astronauts (1.2 kg/day). A major part is sweet potatoes at 1280 g and 1460 g, respectively.

Table 3 *Identified optimal crop combinations for ten modelled scenarios (unit: g/day). No results are presented for Scenario 2 as no feasible solution was found.*

			Scenarios							
	Nutrient sources	**1**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Vegetable	Soybean	75	55	63	-	-	-	-	-	-
	Poppy	120	173	155	36	-	35	-	36	34
	Barley	18	254	223	365	-	357	-	-	198
	Garlic	-	-	-	91	-	115	-	-	-
	Chard	616	-	-	-	-	-	-	-	-
	Kale	-	74	79	36	-	28	61	93	93
	Peanuts	76	30	25	-	-	-	-	-	-
	Broccoli	-	-	-	-	53	-	33	-	-
	Spinach	-	-	-	94	15	96	-	-	-
	Sweet Potato	1280	527	642	-	1460	-	-	-	-
	Sunflower	-	-	18	25	13	26	-	16	18
	Quinoa	-	-	-	-	-	-	361	294	265
	Flax	-	-	-	-	-	-	223	-	-
	Figs	-	-	-	-	-	-	104	-	-
	Maize	-	-	-	-	-	-	-	173	-
Animal	Beef	-	-	-	-	-	-	21	20	9
	Chicken spread	-	-	-	309	164	302	-	65	114
	Trout	-	-	-	133	709	155	-	504	469
	Salmon	-	-	-	-	-	-	130	-	-

Clams	-	-	-	111	521	88	267	-	-
Total food weight	2185	1113	1205	1200	2935	1202	1200	1201	1200

*Wheat, rice, pea and other 79 crops are also considered, but those crops did not assign any amount in any of the scenario.

Scenario 1 – full-scale inventory of nutrient constraints

The crops of scenario 1 meet the minimum nutritional and caloric requirements of male astronauts, the latter being 2700 kcal to 3700 kcal. This is achieved by a food mix (g day^{-1}) of soybean (75), poppy (120), barley (18), chard (616), peanut (76), and sweet potato (1280). However, this is achieved with a total food intake far exceeding that which is feasible (2185 g day^{-1}), highlighting the need to constrain this variable. Sweet potatoes and chard together account for 87% of the weight (Figure 2a). While questionable for its large weight, the results shows that sweet potatoes can meet most of the astronauts' requirements for nutrients.

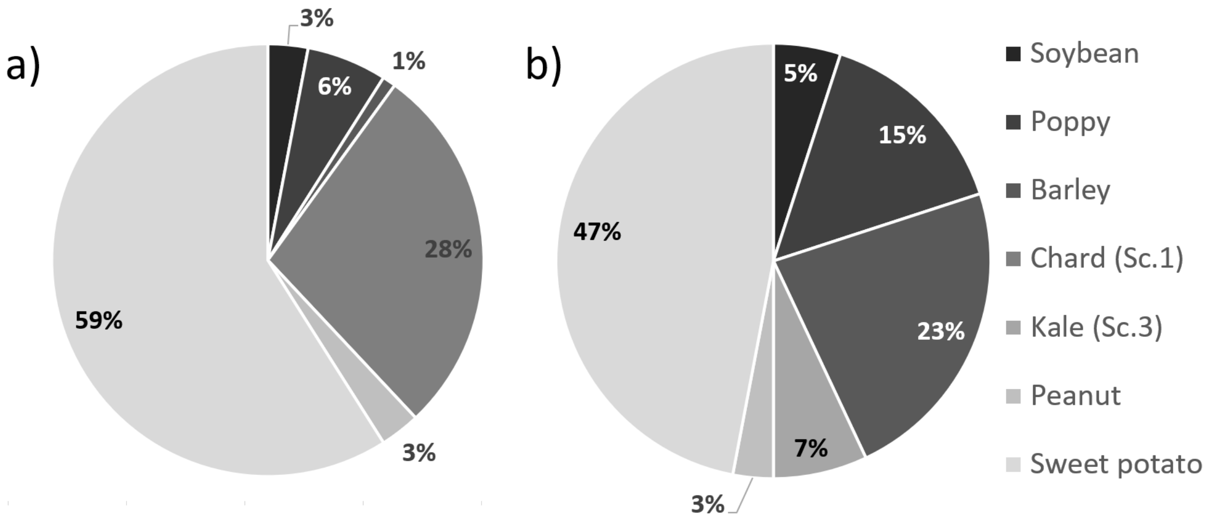


Fig. 2 *Full-vegetarian scenarios 1 and 3; (a) and (b) – modelled optimal crop combination to satisfy constraints as given in Table 2. (Vegetables clockwise ordered)*

Scenario 2 – full-scale inventory of nutrient and other constraints

Scenario 2 expanded the number of nutrients considered to include total food mass, an identified need from scenario 1. However no feasible solution was found for this expanded set of constraints. This suggests that the minimum daily requirements of astronauts cannot be met and thus a fully vegetarian diet is not feasible. Accordingly, with the first modelling of this study we learned about setting the boundaries for the inventory large enough to generate a result from large data and many constraints. Yet, we also learned limitations when making the inventory too large, e.g. the simulation fail in predicting an acceptable daily food intake (per weight). This learning has been used to better set constraints for modelling of scenarios 3-10. In the inventory of subsequent simulations, the number of nutrients considered as constraints was reduced and a larger choice of crops were considered (increased degrees of freedom). This justified because some micronutrients, especially vitamins, are required in only small amounts (micrograms), whereas crops or food in general weight a lot more. Therefore, vitamins may provide a preferential target for supply by payload.

Scenario 3 – reduced-scale inventory of nutrient constraints

This solution including the minimum requirements of 15 macro- and micro-nutrients, the caloric requirement of 2700 kcal to 3700 kcal, and within the maximal food weight of 1.2 kg day^{-1}. The resulting crop mix (g day^{-1}) consists: 55 of soybean, 173 of poppy, 254 of barley, 74 of kale, 30 of peanut, 527 of sweet potato. Sweet potatoes account for 47%, which is a more realistic weight relative to scenario 1 (Figure 2b).

The improved performance of scenario 3 compared to 1 demonstrates that exclusion of some micronutrients results in valid computation results, and supply these as payload (e.g. *via* tablets) can help in achieving better 'must-have' targets. This indicates that the space food strategy should include consideration of payload supplements for low intake micronutrients, thus requiring further studies into the viability of these supplements during long-term missions.

Scenario 4 – reduced-scale inventory of nutrient constraints, with targeted exclusion

It meets all three 'must-haves' (Figure 1), and the food weight intake is similar to that of scenario 3. The resulting crop mix (g day^{-1}) includes: 63 of soybean, 155 of poppy, 223 of barley, 79 of kale, 25 of peanut, 642 of sweet potato, and 18 of sunflower. In this scenario, sweet potatoes account for more than half of the total (Figure 3a). External supplementation of Sodium allows variations in the food mixture by addition of sunflower seeds, e.g., for improved palatability. As opposed to supplementation and thus the extra payload it entails, Sodium could be made circular through recovery from wastewater or other strategies.

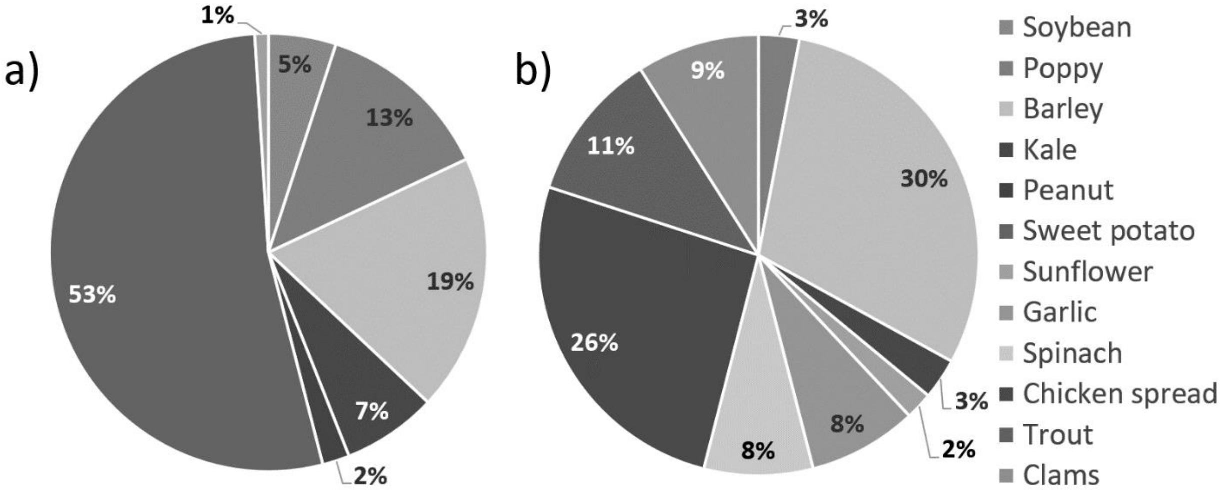


Fig. 3 *Full-vegetarian scenario 4 and meat-added scenario 5, (a) and (b) – modelled optimal crop combination to satisfy constraints as given in Table 2. (Items clockwise ordered)*

Scenario 5 – large-scale inventory of nutrient constraints, within an omnivorous diet

The combined crop-animal food is a more complex, diverse mixture as for scenarios 1-4, and includes poppy, barley, garlic, kale, spinach, sunflower, chicken spread, trout, and clams. Their amounts (g day^{-1}) are 36, 365, 91, 36, 94, 25, 309, 133 and 111, respectively. The main food in the scenario 5 comes from barley and chicken spread, accounting for 30% and 26% (Figure 3b). Three must-haves are met in scenario 5.

Scenario 6 – Reduced-scale inventory of nutrient constraints, with animal products

Fibre, vitamin A and D were added as additional constraints in scenario 6. This scenario was inspired by the official space nutrition mixture consisting of 16 essential nutrients, including protein, Ca, Fe, vitamin A, vitamin C, vitamin B1, vitamin B2, vitamin B5, vitamin B9, vitamin B12, vitamin D, vitamin E, Mg, K, Zn, and fiber [3]. The provided food mixture (g day^{-1}) consists: 53 of broccoli, 15 of spinach, 1460 of sweet potato, 13 of sunflower, 164 of chicken spread, 709 of trout, and 521 of clams. Sweet potatoes accounted for half of the total food weight, meat is almost half the weight. (Figure 4a).

However, this scenario indicates that including too many constraints may not be a viable option. Here, the total food mass was more than twice the constraint used for scenarios 2-5 thus indicating that payload addition would still be required even if an omnivorous diet was feasible.

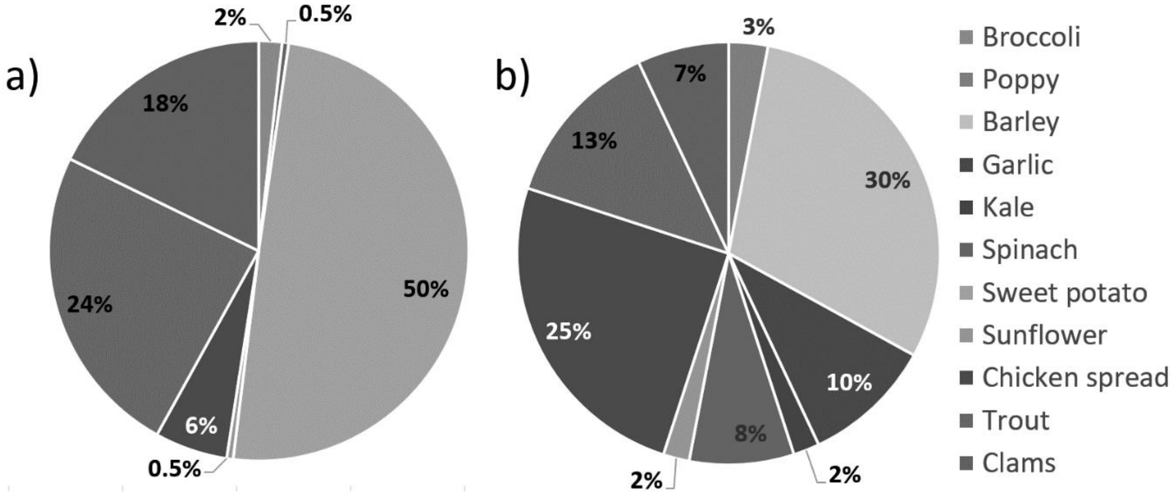


Fig. 4 *Meat-added scenarios 6 and 7, (a) and (b) – modelled optimal crop combination to satisfy constraints as given in Table 2. (Items clockwise ordered)*

Scenario 7 – Full-scale inventory of nutrient constraints, with animal products

A scenario encompassing all three must haves combined with 34 (macro- and micro-) nutrients, calories and fiber are considered as 'full-scale'. This resulted in a suggested food mix of poppy, barley, garlic, kale, spinach, sunflower, chicken spread, trout, and clams. Their amounts (g day^{-1}) are 35, 357, 115, 28, 96, 26, 302, 155 and 88, respectively. The food distribution results in are similar to those in scenario 5 (Figure 3b & 4b), indicating that inclusion of fibre and the exclusion of a two vitamins (A, D) does not greatly impact the results. Thus the addition of animal source food products can complement micronutrient provision, and solve deficiencies in nutrient constraints. The inclusion of animal products therefore more constraints to be considered with a reduced impact on overall food mass.

Scenario 8 – reduced-scale inventory of nutrient constraints, with animal products and amino acids, but with exclusion of three vitamins

Scenario 8 performed optimization with increased number of crops from 50 to 102, without considering vitamins A, D, and B12 due to missing data for these additional crops. The proposed food mix (g day^{-1}) is 61 of kale, 33 of broccoli, 21 of beef, 130 of salmon, 267 of clams, 361 of quinoa, 223 of flax, and 104 of figs. Although flax and figs are currently unsuited for space growth, we include these because development of conditions for growing large plants or trees in space is a valid research topic, and could be justified if such crops are deemed essential for long-term space travel. However, to account for the inability to cultivate these crops, they were removed for scenario 9.

Scenario 9 – reduced-scale inventory of nutrient constraints, with animal products and amino acids, three vitamins exclusion

Scenario 9 is an optimization of the results of scenario 8, removing flax and figs from the crop pool. The resultant mix is poppy, kale, sunflower, beef, chicken spread, trout, quinoa, and maize. Their amounts (g day^{-1}) are 36, 93, 16, 20, 65, 504, 294 and 173, respectively. Whilst maize may also not be suitable for planting due to space constraints; the development of dwarf maize varieties suitable for space growth is a more feasible solution than the cultivation of figs, for example, with additional benefits for Earth-bound crops.

Scenario 10 – reduced-scale inventory of nutrient constraints, with animal products and amino acids, three vitamins exclusion

In scenario 10, flax, figs and maize were removed from crop mix as per analysis of scenarios 8 and 9, but with the same constraints imposed. This resulted in a food mix containing poppy, barley, kale, sunflower, beef, chicken spread, trout, and quinoa 265. Their amounts (g day^{-1}) are 34, 18, 93, 183, 9, 114, 469 and 265, respectively.

The share of animal food source-based contributions to the diverse nutrients amounts to *ca.* 35-45%, with the rest of the food being of vegetable origin. Nutrients distribution are provided on Figure 5. While scenario 5, contains only about a third of animal-based food, scenarios 6 - 10 reach *ca.* two third animal-based food share for fat and protein nutrients. The vitamin content is low as this is mainly provided by the vegetable food. While carbohydrates are mainly supplied by vegetables, fat and protein are provided by animal sources. In scenarios 5 and 7 the vegetable sources are the most prominent, while scenarios 6 and 9 show the contrary.

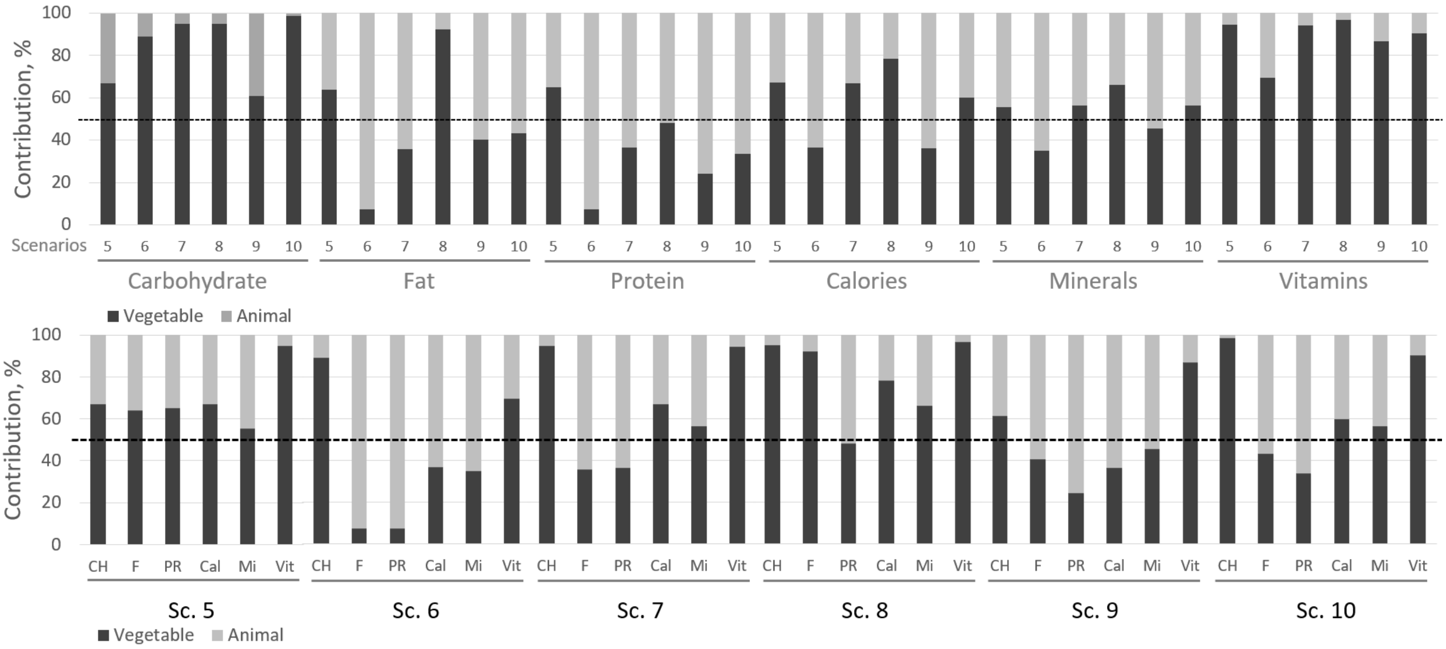


Fig. 5 *Share of vegetables and animal food source-based contributions to the diverse nutrients for Scenarios 5, 6, 7, 8, 9, 10. (Sc. Scenario, CH carbohydrate, F fat, PR protein, Cal*

Calories, Mi minerals, Vit vitamins)

Planting performance for modelled scenarios of crop composition

Whilst the above scenarios consider the combination of food combinations required to meet human health requirements, space farm design must also consider other constraints relating to achieving the plant growth and products required. For example, relevant planting performance parameters need to be considered for a space farm due to the necessary compactness, i.e. size limitations, of a space farm. These include the speed of plant growth, and thus the time it takes to achieve yield, planting area (assuming a space-equivalent LED-lighted production of an Earth glasshouse), and the amount of fertilizers needed to support crop growth.

Plant performance parameters for the crop combination proposed in scenario 1 are given in Table 4 including the time until harvest, and the nutrients required (nitrogen, phosphorus, potassium). The harvest time of all crops is within 50 to 100 days. The total planting area is *ca.* 154 m^2, which suits the size of a space habitat and potentially also of a large spacecraft. For example, ISS is 109 meters long, and assuming a width of about 4 meters, total area is approximately 400 m^2. This is approximately similar to the size of a Boeing 747 airplane. Thus for the combination of crops in Scenario 1, planting area would take 1/3 of the whole space. Whilst this could be feasible, a further reduction in size could still be necessary.

Table 4 *Yield, planting area, harvest time and fertilizer macronutrients (N-nitrogen, P-phosphorous, K-potassium) required by crops; microntrients are not considered here.*

Crop	**Daily demand (g) – Scenario 1**	**Crop yield (kg/ha)**	**Time-to-harvest (day)**	**Total planting area (m^2/astr)**	**N (g/day·astr)**	**P (g/day·astr)**	**K (g/day·astr)**
Soybean	75	2620	50	14.31	28.63	57.25	28.63
Poppy	120	1742	85	58.55	351.32	351.32	351.32
Barley	18	2380	90	6.81	40.84	20.42	13.61
Chard	616	64500	50	4.78	52.53	42.98	47.75
Peanut	76	2088	100	36.40	283.91	32.76	98.28
Sweet potato	1280	38500	100	33.25	149.61	299.22	448.83

*astr = astronaut

The distribution of planted area for the combination of crops given in the scenarios 1, 3, and 4 is given in Figure 6. Sweet potato requires only a small area for cultivation, while contributing substantially to the nutrient provision. On the flip side, the planting area of poppy is around a third of the total, whereas the crop itself makes only a minor nutrient contribution. Thus secondary-hierarchy constraints (Figure 1) such as the planting area can revise the ranking of crop diet solutions, as determined by the first hierarchy constraints.

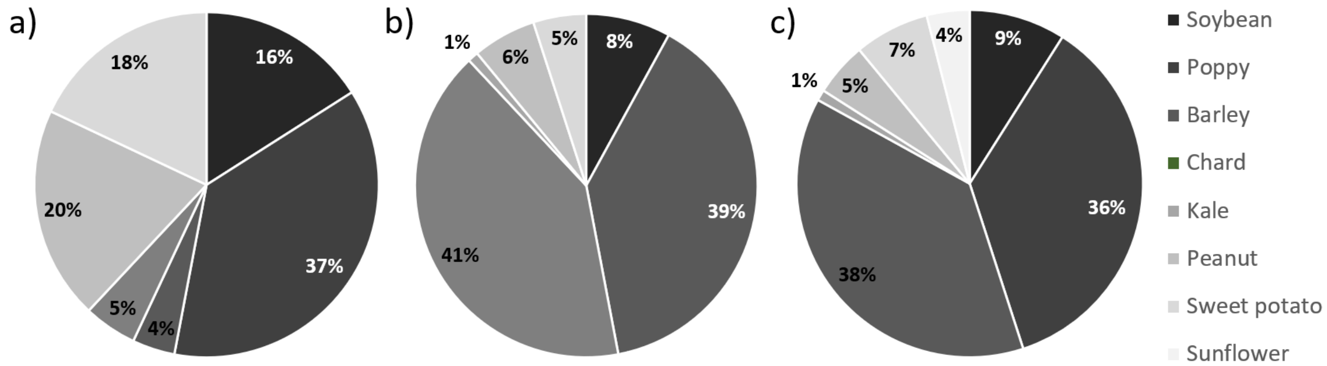
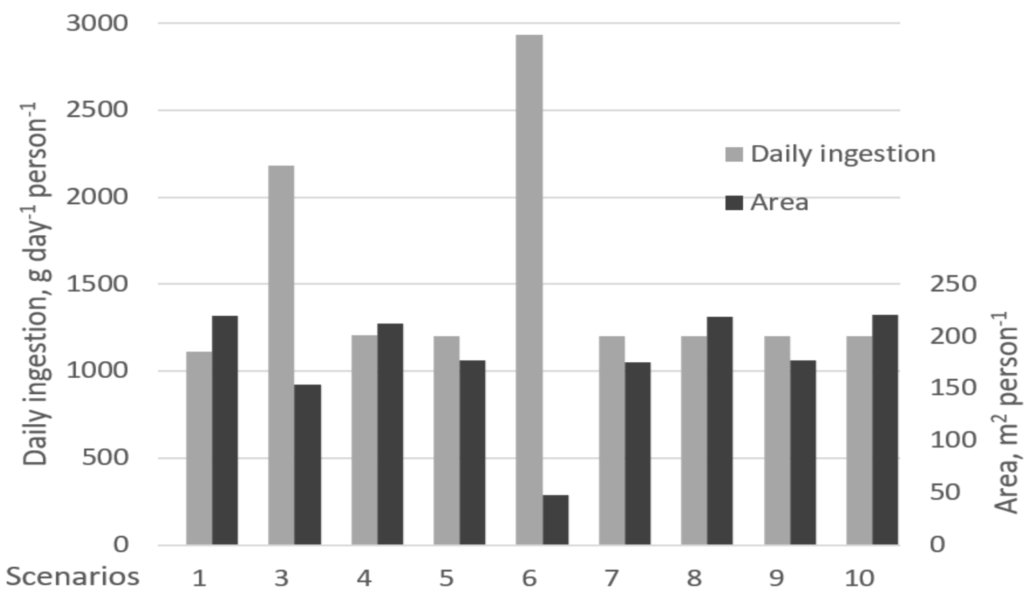


Fig. 6 *Full-vegetarian scenarios 1, 3 and 4, (a), (b) and (c) – planting area distribution, a secondary constraint for crop choice. (Items clockwise ordered)*

The planting area of sweet potatoes for scenarios 3 and 4 is small, although these account for largely for nutrition supply, as said. Barley and poppy account over 70% of the planting area. Kale requires smallest area, and other crops take a similar proportion of the planted area.

Figure 7a (grey) shows the daily vegetarian weight intake of astronauts for all scenarios, meaning any meat (e.g. chicken spread, trout and clams) are not included. In scenarios 5 and 10, plant-based food accounts for half of the total. The efficiency of constraint-targeted modelling is evident, when comparing scenario 1 without food weight constraint with scenarios 3 and 4 having food weight constraint. The latter are below the threshold for astronauts of 1.2 kg of food per day.

a)



b)

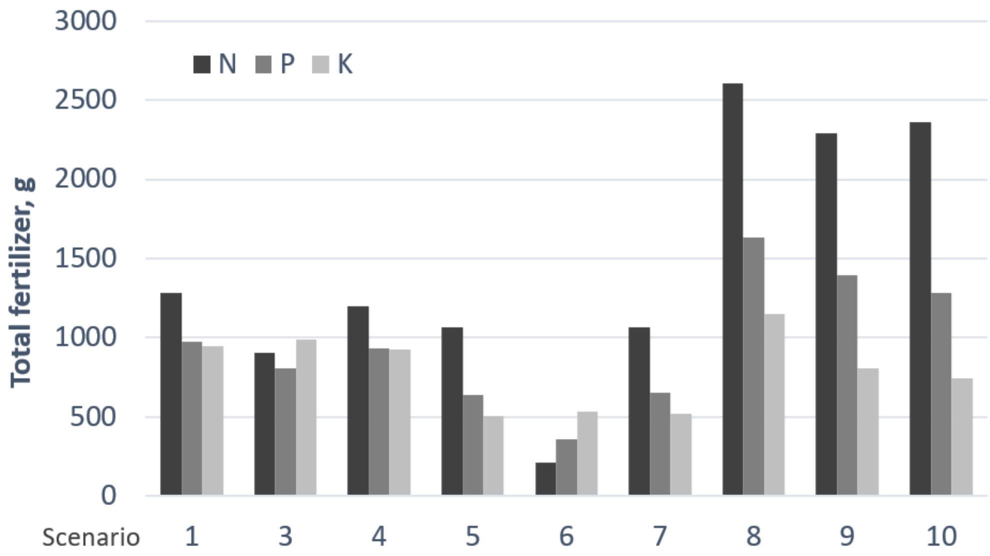
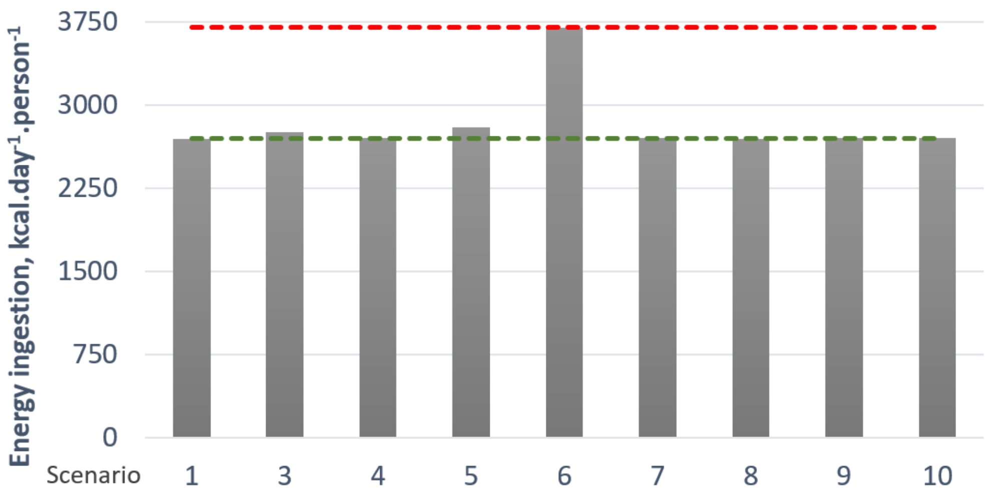


Fig. 7 *(a) Total food intake (weight) per astronaut and day; planting area, and (c) fertilizer usage for all scenarios.*

Figure 7a (black) demonstrates that no correlation is given between the weight of the crop combination and the planting area. The scenario-1 planting area is similar to that for scenarios 3 and 4, whereas the respective food weight is double. This provides a promising approach for applying crop content optimization by breeding and genetic modification. In contrast, the animal-supported diets in scenarios 5 and 7-10 require large planting areas, while needing much less plant-based food. Scenario 6 has low planting area but prohibitively high daily intake of food. In addition, the storage of meat also requires a large space for long-term space missions. Scenario 3 has lowest planting area and was favored from the previous analysis.

The vegetarian diets in scenarios 1, 3, and 4, have largely similar total fertilizer (N, P, K) requirements (Figure 7b). Similar to the planting area requirements, whilst fertilizer input is relatively lower in the omnivorous scenarios (5-7), the fertilizer demand is still relatively high considering the reduced input by plants. Within this simulation, scenario 6 represents a complex optimization, to check if reduced planting area and inputs can be achieved.

a)



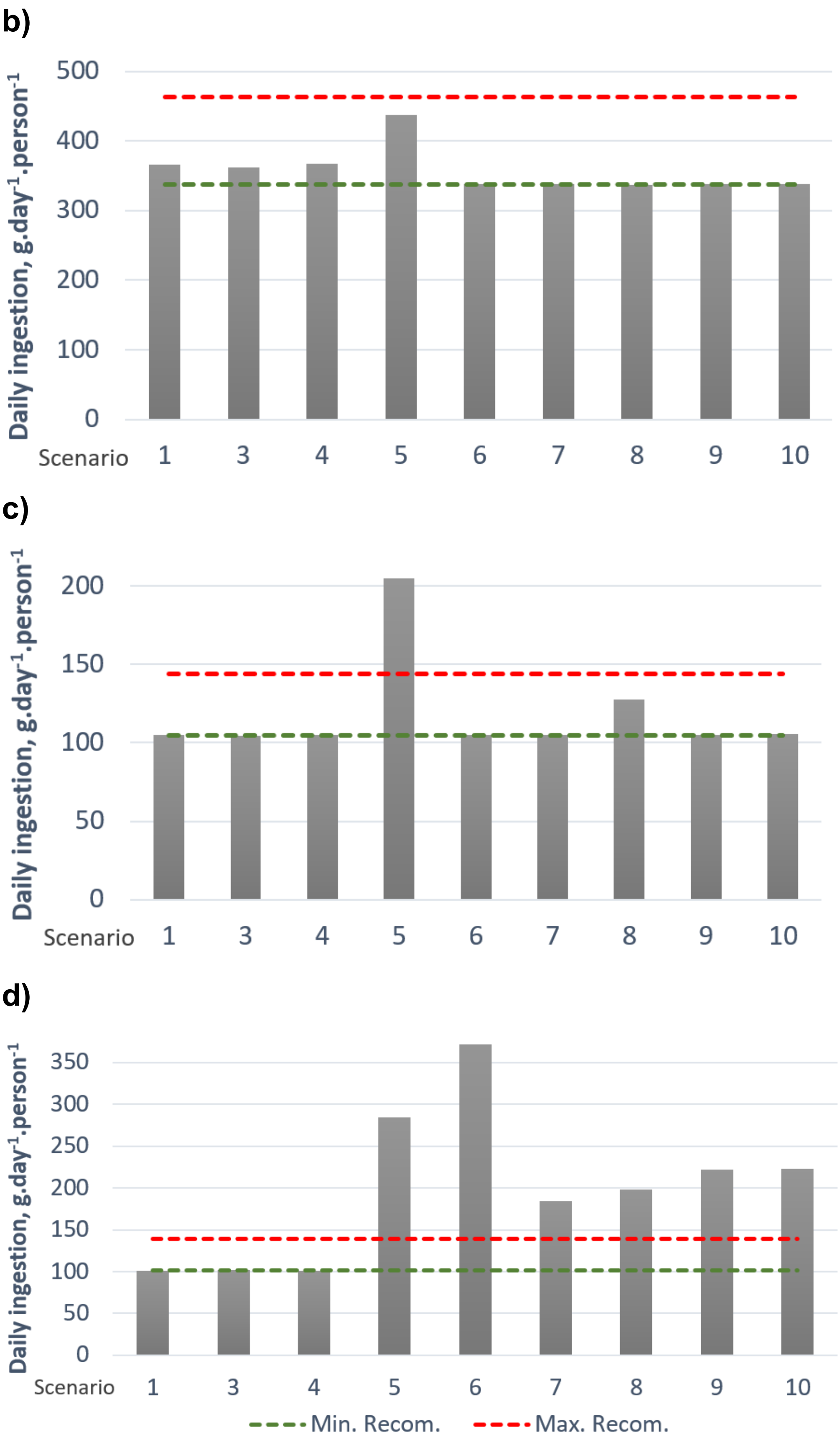
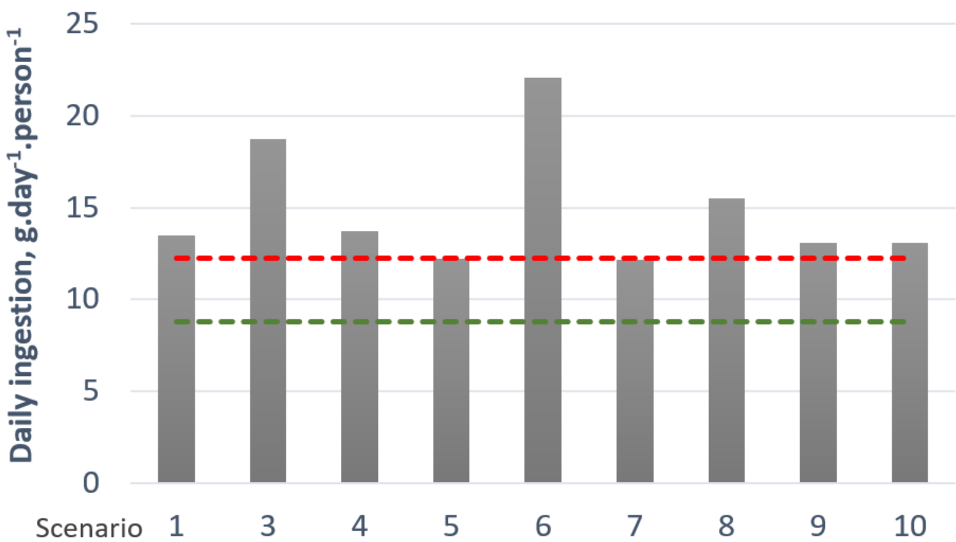


Fig. 8 *(a) Caloric intake, (b) amount of carbohydrates, (c) amount of fats, and (d) amount of proteins, per astronaut and day for all scenarios.*

Concerning the caloric intake, all scenarios meet a male astronauts' requirements, as decisive for any nutritionally complete diet (Figure 8a). The vegetarian scenarios 1, 3 and 4 provide the astronauts with carbohydrate intake above the minimum requirement, while most of the meat-based scenarios just meet the minimum level of carbohydrate intake, scenario 5 provide the most carbohydrates intake, exceeding the minimum requirements (Figure 8b). All scenarios provide sufficient fat intake for the astronaut, whereas scenario 5 provide almost twice as much fat intake as the other scenarios, Figure 8c. The protein provided by the vegetarian scenarios meet the minimum intake requirement, while the meat-based scenarios far exceeded the maximum protein intake requirement, Figure 8d.
The meat-based scenarios 5 and 7 provide maximum levels of minerals, whereas both the vegetarian and other meat scenarios far exceeded the maximum levels of mineral intakes (Figure 9a). However, vegetarian scenarios 3 and 6 provide vitamin quantities above the maximum level (Figure 9b). For example, the amount of vitamin B1 was 3.5 times the minimum requirement, and the intake of B2, B6, and B9 was also about 1.5 times the minimum requirement. Excessive intake of B vitamins can lead to some side effects, however, these are generally caused by dietary supplements rather than food [35].

a)



b)

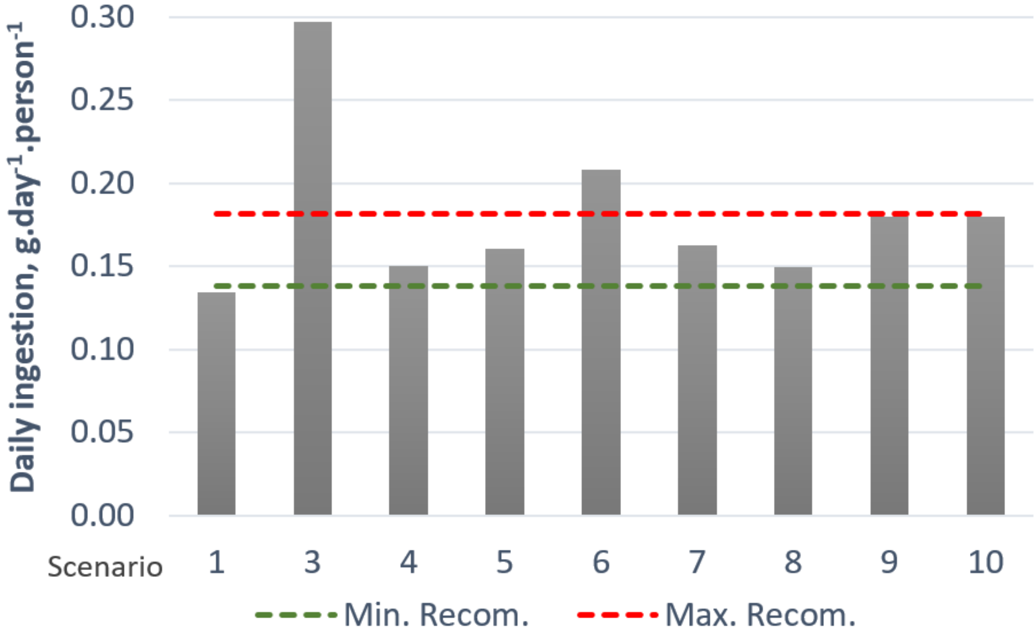


Fig. 9 *(a) Amount of minerals, and (b) amount of vitamins, per astronaut and day for all scenarios.*

3.5 Circularity assessment of scenarios

A key parameter in circularity assessments is waste generation. This is, in the context of this study, related to the share of edible and inedible parts in plants. A large share of the edible relative to the inedible part will diminish planting area. Plants have large spread in the ratio of edible to inedible parts from *ca.* 90:10 to 20:80, Table 5. Inedible parts include all biomass which it is not consumed, as reported in the literature ~~plant stem~~.

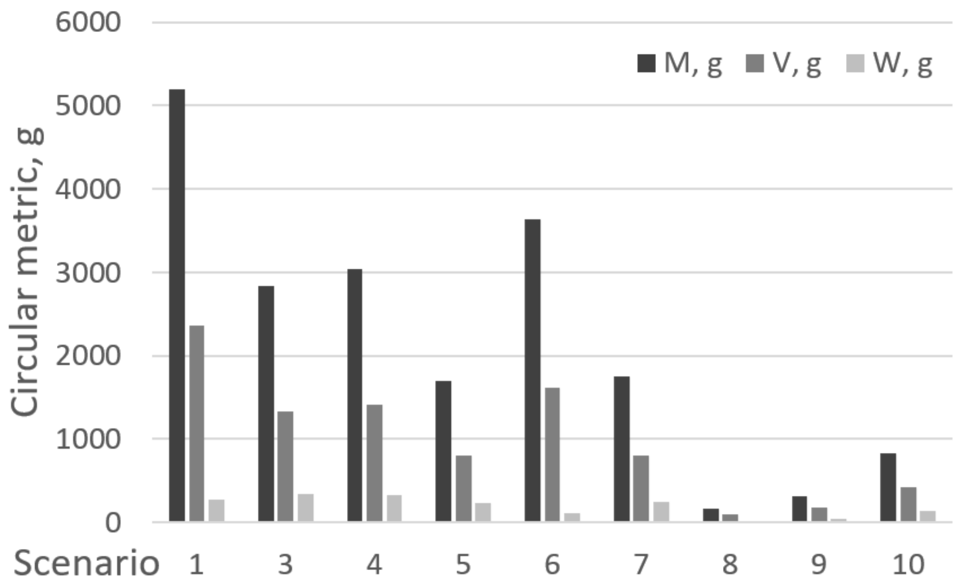
Table 5 *Edible and inedible fractions for each crop.*

	Total, g.plant^{-1}	Edible, g.plant^{-1}	%	Inedible, g.plant^{-1}	%	Refs.
Poppy	9.5	1.9	20	7.6	80	[36]
Garlic	23	6	25	18	75	[37]
Sunflower	1228	305	25	923	75	[38]
Peanut	1700	580	34	1120	66	[39]
Kale	670	322	48	348	52	[40]
Soybean	1.01	0.56	55	0.45	45	[41]
Spinach	101	60	60	40	40	[42]
Barley	818	540	66	278	34	[43]
Sweet potato	240	165	69	75	31	[44]
Wheat	1610	1440	89	170	11	[45]
Broccoli	701	630	90	71	10	[46]
Swiss chard	962	873	91	89	9	[47]

Based on this waste definition, we adapted circular metrics defined by the Ellen MacArthur Foundation (EMF), which are common to the Circular Economy literature [26]. We computed three mass-related EMF metrics (Figure 10a). The mass of materials involved (M) includes the crop edible and inedible fractions as well as the fertilizers. Of the scenarios, scenario 1 scores

the lowest, which follows the larger area requirements and intake measurements given above. The vegetarian scenarios 3 and 4 have an improved score, which is consistent with these to align to the low daily food intake threshold of 1.2 kg per day. The meat-based scenarios score even higher, as to be expected, because of the lower crop share of the food.
The share of non-renewable materials as opposed to reused or recycled materials (V) and the mass of unrecoverable waste associated with each scenario (W) are two relevant mass-related EMF metrics (Figure 10a). In terms of space missions, it is advantageous for these numbers to be as low as possible, as these determine payload and waste. V- and W-metrics follow the same trend as the M-metrics.

a)



b)

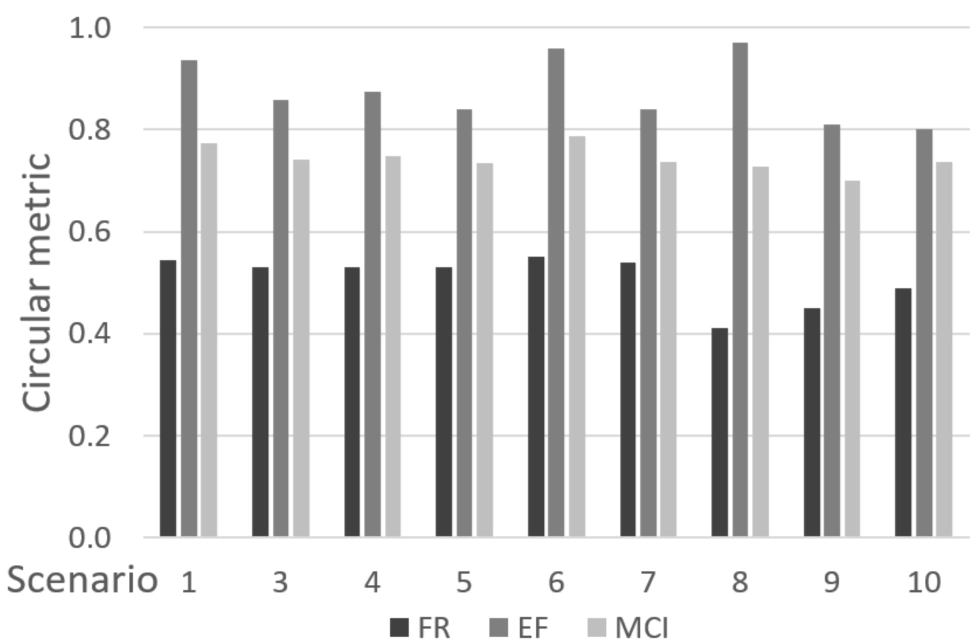


Fig. 10 *(a) Circular mass-related metrics, and (b) circular normalized metrics; for vegetable fractions in scenarios where vegetables play the key role.*

Normalised circular EMF metrics related to recyling, including the fraction of mass suitable to be recycled (F_R), the estimated efficiency of the recycled feedstock (E_F), and the materials circularity indicator (MCI) were computer, for which 1.00 defines full circularity (Figure 10b). Scenarios 1-10 achieve MCI of 0.68 and higher. That is a good achievement for our study, which represents a proof-of-concept, without process optimization. F_R, E_F, and MCI show little variation between these scenarios, and the dependency of recycling performance on crop variation is minor.

A simple way to judge circularity is provided by the ratio of input material to what is produced in the space farm. The optimal ratio of edible part produced ("production") versus edible + inedible + fertilizers (which corresponds to the metric 'M') should be in favor of production, i.e. at the top left-hand corner of Figure 11. This would constitute an ideal circular mass use. Scenario 1 has highest productivity, but it suffers from highest input demand (top right-hand corner), scoring a ratio of 0.42. Scenario 6 has 50 % less input demand with the payback of only 40 % productivity loss, scoring a ratio of 0.49, with the additional benefit of having low planting area. Scenarios 3 and 7 were favoured, having low mass input at relativelylower production output. Overall, all scenarios have similar ratios, which is understandable seeing the arguments given for Figure 11.

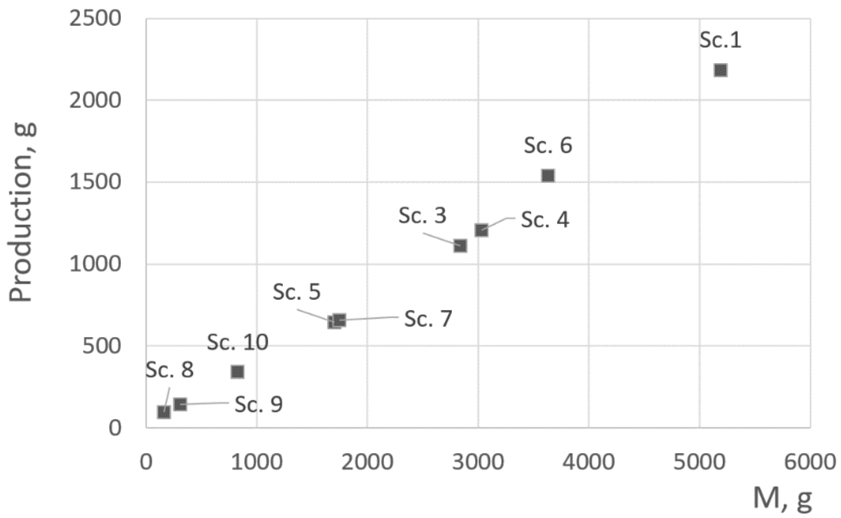


Fig. 11 *Ratio of space farm production as compared with the input materials (M) according to circularity assessment.*

<u>3.6 Food psychology study of the best crop scenario 4, 'Space Salad'</u>

Fig. 12 '*Space Salad' – for NASA food psychology study.*

As well as all factors considered previously, the optimal astronaut diet should account for psychological and social preferences of prepared meals. To this end, a food psychology study was performed using the output of Scenario 4. Soybeans, poppies, barley, kale, peanuts, and sunflowers were weighed and cut alike the same crops would be cut for an Earth salad. (By Rivera-Osorio, Space Psychology, NASA); Figure 12). Once prepared for consumption, four volunteers tasted the space salad and took notes for feedback.

The salad was a soft texture, which was achieved by boiling in the chicken broth for flavor; extending from the results of this study. It was anticipated that the dish should be palatable because of the range of textures and vibrant colors provided by the ingredients. Nuts were added to improve overall taste, whilst the poppy seeds provided texture and improved appearance of the salad. Volunteer #1 stated they loved the taste, especially the barley and sweet potatoes– also stating "wouldn't mind eating this all week as an astronaut." Volunteer #2 stated that it tasted "very sweet" and compared it to a gourmet salad. Volunteer #3 stated that the "barley was a bit dry and could have been soaked longer," but "enjoyed the sweet taste of the potatoes and freshness crunch." Volunteer #4 did not like it at first but had another bowl later. The volunteers expressed to experience energetic mood, which may help to prevent feeling lethargic when stuck in confinement of a spacecraft.

The NASA team recommended differentiation of food and food experience, including use different broths, have food premade, pre-cooked, meal planned, and salads for different health benefits. For example, diversification towards boosting immunity could lead to specialized salads such as those that are calcium rich or high protein. Recommendations indicated that the use of extra ingredients aided to improve the astronaut's taste.

Conclusions

Based on nutrition, food mass and planting area constraints as well as circularity assessment, two vegetarian food scenarios, 3 and 4, indicate the optimal solution towards astronaut diets. Although it is important to that these both require additional mineral and vitamin supplements which are expected to contribute to payload. Animal-added diets with respectively lower plant-base food, scenarios 5 and 7, also fulfilled the three 'must-meet' constraints and have potential to reduce the weight load of eating vegetarian and total food material. Yet, beyond the number of nutrients considered, overshoots in nutrient supply were observed, for example for the vitamin and minerals content of scenarios 3 and 4 that potentially could cause a health risk. A small psychology study evaluated the palatability. Whilst multiple constraints were considered within this study, these are not exhaustive. Therefore, future studies have to make more complex assessments, including glasshouse engineering, space compliance, water consumption, and more.

To prepare those complex assessment, this study imposed second-hierarchy constraints on planting capability and recycling-based circularity to provide a more comprehensive outline of a potential space farm. However, at this stage, these might overrule the first-hierarchy constraints. A broader future study, with more crops and broader assessment of mineral nutrient payload and circularity, could come to a different result. In the long term, planting and circularity constraints could be included directly into the optimization alongside the food constraints.

The simulations produce outputs with a limited number of crops, which would lead to a repetitive diet. Thus, further simulations covering a larger variety of plants, at the expense of additional water carriage, could allow variation of the daily food mixture. Cooking in space may also lead to a decrease in nutrient content which must also be accounted for in future studies. This study also indicated a lack of data concerning the nutrient contents of crops. This led to their exclusion for simulations and limited the choice of crops considered to 102. The number of plant species counted in the USDA database reaches thousands. Therefore, it would be desirable to investigate all these crops, but would again depend on the completeness of the database regarding all nutrients. Even with the limited crop choice, only one of the scenarios failed to find a solution, demonstrating that, from the viewpoint of nutrition alone, a choice of 102 crops could be sufficient, although without optimization of secondary constraints. However, in order to obtain solutions, all the vegetarian scenarios had to exclude several (maximum 10) micronutrients, under the assumption that these could be taken as payload or, in some cases, subject to mineral recycling in a circular system. Scenario 7 demonstrated that the addition of animal source food products helps to increase the complexity of micronutrients.

The simulations also raised practicality issues of food preparation and consumption. For example, scenario 7 recommends that astronauts eat 115 g of garlic every day; however, such high garlic consumption is rather undesirable. A question is also raised whether each food combination could be made into a palatable meal. Heading for real-world impact, scenario 4 was transformed into a real food product, a 'Space Salad', and tested in a space agency research center, at NASA. This confirmed palatability of the space dish and gave hints to optimize it.

Outlook

Future simulations need to consider nutrients from more diverse origins, concerning the number of crops and animal products, and also from non-food supplies. Investigations need to decipher how all those nutrient sources can be utilized, recognizing the constraints of a long-term space travel. A large increase in plant nutrients, by breeding or genetic modification, would help to meet planting and circularity constraints. Similarly, faster plant growth or higher plant yield would again improve optimal solutions.

Individual requirements for each nutrient are related to a person's characteristics, such as age, sex, physical activity level, and health. According to the National Center for Biotechnology Information, the recommended carbohydrate intake for adult men is 130 g/day and protein intake is 56 g/day. For adult women, the recommended carbohydrate intake is same,130 g/day, while the protein intake is slightly lower, 46 g/day. Any specific solution would therefore need to consider the crew composition and optimal solutions will be required based on that composition.

While animal source food is available on the ISS, little research is at hand on how to include animal source food products to the astronaut's diet for long-term travel, yet lab-grown meat could be an option [22]; see exemplarily in the literature. Supplementation in form of fortified food formulations (pills, or space drinks) is another option to supply micronutrients, instead of food, grown in space or as payload. Liquid formulations are ideal for encapsulating or

dispersing hydrophobic substances, e.g., as nanoemulsions, and are therefore good hosts, e.g., for vitamin E or vitamin K. Hydrophilic micronutrients, e.g., vitamin B, can also be added to fortified food emulsions such as energy drinks.
Finally, not all food and dishes that are acceptable on Earth, might suit space applications. Certain food products are not permitted in a space shuttle due to safety issues. For example, products that might produce crumbs such as bread are excluded, as crumbs can float around and damage equipment in a shuttle [48]. Foods that are known to produce allergies might be excluded as well. Thus, these additional restrictions must also be considered.

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