Choosing crops for cultivation in space

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Future space missions require bio-regenerative life-support systems. Eating fresh food is not only a fundamental requirement for survival but also influences the psychological well-being of astronauts operating on long duration space missions. Therefore the selection of plants to be grown in space is an important issue. Part of the EDEN ISS project entails the development and application of a methodology to select suitable plants for cultivation on-board the ISS and the Neumayer III Antarctic station, a space analogue site. A methodology was developed taking physical and physiological constraints, and human well-being (quality) aspects into account. It includes a framework for the selection process, a list of relevant criteria based on plant characteristics, engineering constraints and human nutrition and psychology. It entails a scoring system to assess and weigh these criteria for each crop, in order to rank the chosen crops. Human quality aspects, such as taste, texture and appearance were related to the well-being of astronauts. Yield aspects combined crop yield and growth efficiency in time and space, while production aspects concentrated on physical constraints of the planned growth modules and the technical aspects of cultivation. The methodological framework used for the selection of plants was based on several approaches. Physical and physiological constraints determine whether or not the crop can be cultivated in space (and/or in Antarctica) and all other parameters are prioritized according to human quality aspects, yield or production aspects that were ranked according to pre-selected weighing factors. This yielded a ranking of the crops to be grown in a controlled ecological life support system. A description of the methodology and its results with a choice of crops related to the aims of the EDEN ISS project are given and will be discussed.

I. Introduction

Extended missions in space to further planetary exploration will require the development of new technologies to overcome the physical and psychological challenges of space exploration. These technologies must enable the mission crew to be self-sufficient, and will entail, among others, the production of fresh food. Fresh food is especially important for maintaining the astronauts' physical and psychological health. Since the beginning of space exploration, human life support has been one of the most important challenges since a long-term resupply from Earth is a particular challenge, and one that becomes increasingly difficult as crew size or mission duration is increased. Therefore there is need for Bio-regenerative Life-Support Systems (BLSS) that will reduce and ultimately eliminate the need for resupply of foods from Earth.

On the International Space Station (ISS) the testing of plant cultivation has focused on controlling the environment to meet the plants' needs. Bio-regenerative life support studies have shown that many traditional field crops such as wheat, soybean, potato, sweet potato, and rice can be grown effectively in plant growth chambers[1], which suggests that ready to eat crops can be successfully cultivated in space. However, when growing plants on extended missions, other requirements become increasingly important. Space travel brings about constraints not present on Earth. Space, energy, and mass will be limited onboard the spacecraft and the spaceflight environment (e.g., microgravity, reduced gravity, radiation) may create problems for plant culture and development. The number and size of plant species that can be grown at any one time on short duration missions or transit missions where space is more limited will severely limit their selection, while longer duration missions will not have this constraint. Vegetables requiring little or no preparation, i.e. ready to eat, would be preferred. Crops with a high harvest index

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(the edible portion of the plant) would provide more food with less solid waste production (inedible biomass), and lessening the requirement of O_2[1]. In their review of requirements for food systems for long space missions, Cooper et al.[2] focus on an appealing dietary fare, while Massa et al.[3] stressed the importance of some horticultural, dietary and organoleptic factors.

In the ongoing EDEN ISS project[4] attention is being paid to the selection of crops suitable for the crew on space missions. The project anticipates the development of higher plant cultivation technologies for use on the International Space Station (ISS) and is currently designing an International Standard Payload Rack (ISPR) for testing on the ISS. In addition, a Future Exploration Greenhouse (FEG) is being designed as demonstration of a future planetary bio-regenerative life support system, to be deployed at the Antarctic Neumayer III research station.

So how to select the proper crop candidates for fresh food on space missions? With respect to EDEN ISS with its limited plant cultivation volume, it is more tailored to missions in which the plant production system does not necessarily provide a significant portion of the crew's diet, thus representing shorter duration or transit missions. Crew members aboard the ISS and acquiring fresh food from the ISPR can only realize relatively small amounts of fresh food, and require a regular daily flow of fresh food, that is especially tasty and spicy with a 'bite'. This entails a periodic production of smaller amounts of fresh food, so that the crew feels in touch with Earth. Thus, without detracting from dietary[5], nutritional and organoleptic requirements[3], the research within EDEN ISS project[4] has chosen to focus more on the maintenance of the crew's psychological well-being. In doing so, the selection of crop species for fresh food on space missions in this research has concentrated more on human well-being and horticultural aspects of plant production, the continuous flow of fresh food to supplement the crew's packaged diet. Although the selection methodology shows similarities to the selection methods described earlier[3,5,6], the selection criteria used here preclude the selection of crops that are not ready to eat and require preparation, e.g. cabbage, wheat or rice.

Eating food is a fundamental human requirement and plays a major role in the maintenance of good physical and mental health[7]. Prepackaged food systems are often used in a microgravity environment, which sometimes taste differently and are less variable than what astronauts are used to eat on Earth. Furthermore, the microgravity environment causes chemosensory alterations in the human body, leading to a reduced flavor perception. Consequently, the psychological well-being of astronauts operating on long duration space missions could potentially be affected[8]. While the relationship between eating fresh food and the mental well-being of astronauts has not been properly addressed, it is well known that astronauts frequently have a craving for fresh food 'with a bite'. Thus this psychological aspect is also important, in addition to essential factors like light, temperature and nutrients, and growth rate, i.e. how quickly can the crew expect to eat a newly sown vegetable, and how much and how often is edible fresh food available?

This work involves the process of selecting plants to be grown in the FEG and later, on-board the ISS and is aimed not only to produce a continuous supply of fresh and tasty food for the crew, but also to contribute to their psychological well-being. For the selection process, a methodology was developed and applied to select plants for cultivation in space. The methodology includes a framework for the selection process, a list of relevant criteria based on plant characteristics, engineering constraints and human nutrition and psychology. It entails scoring systems to assess these criteria for each plant including weighting factors to rank the choices. As has been the case in other plant selection studies[2,3], the results are based in part on assumptions that will have to be improved by ongoing research. Cultivation experiments with these crops are currently being performed, in order to provide additional data for the development of cultivation recipes. Thus, further modifications in this plant selection process are inevitable.

II. Methodological framework for plant selection

A. Selection criteria

The choice of plants for extended space missions is initially determined by the physical constraints of the facility in which they are to be grown, in this case either the full rack form factor ISPR on ISS or the FEG in the Antarctica. The ISPR is a small cultivation rack, housing all necessary support systems for cultivation of higher plants[9]. It has a relatively small volume for that use, 0.5-1 m^2, depending on if 1 or 2 cultivation layers can be installed in the rack. The FEG is a larger test environment designed to conduct innovative plant cultivation experiments *in situ* at the Neumayer III Antarctica station. The FEG is one section of the overall EDEN ISS Mobile Test Facility and has a volume of ca. 31 m^3 with an area of ca. 12 m^2 available for plant cultivation[9]. Special cultivation techniques will be used to enable the production of larger quantities of fresh food for the crew, in order to investigate the different psychological aspects that higher plants have on isolated crews.

A methodological framework for plant selection was developed based on the physical constraints specific for the FEG and ISPR given above, on plant growth and development aspects, as well as quality and human perception aspects pertaining to fresh food crops. Within these main aspects, a number of underlying criteria (Table 1) was implemented in the selection methodology and were defined as 'hard' or 'soft'. Hard criteria were scored with a 'yes' or 'no' which determined whether or not the crop could be included in total list of potential crops. Soft criteria were scored on a gradual scale of 0 to 1 indicating if they were unsuitable (0) or very suitable (1).

Table 1. Hard and soft criteria within each of the three main aspects: human quality, cultivation and yield aspects, with their units or scores in brackets.

Hard criteria	Soft criteria
Human quality aspects	
• Edible [yes/no]	• Appearance [0-1]
• Ready-to-eat [yes/no]	• Taste [0-1]
• No alternative form possible [yes/no]	• Texture [0-1]
	• Pungency [0-1]
Cultivation aspects	
• Crop is commercially available [yes/no]	• Spread harvesting [0-1]
• Maximum plant height [cm]	• Handling time [0-1]
• Suitable for artificial production system [yes/no]	• Shelf life [0-1]
• Harvest possible within mission time [yes/no]	• Disease resistance [0-1]
• Growth possible under 600 µmol m^{-2} s^{-1} [yes/no]	
Yield aspects	
	• Production efficiency in time and space [kg m^{-3} d^{-1}]
	• Light and energy use efficiency [g μmol^{-1}]
	• Harvest index [0-1]

A large preliminary list of edible crops was first subjected to the hard criteria indicated in Table 1. Those crops that could meet with all these criteria were included in a list of potential fresh food crops for cultivation on either the ISPR or FEG. That meant that crops like wheat and potato considered for cultivation on space missions in former studies[10] were not included, either because they were not ready to eat, an alternative form was available, or were not suitable for an artificial production system. Only fresh, ready to eat crops were included and subjected to the selection process. For the EDEN ISS project, the initial aim was to narrow the field of crops to be cultivated in the ISPR to a maximum of 3 crops, and to 5-8 crops in the FEG.

The soft selection criteria were defined with the focus on the greatest benefits for crew members. Thus, human quality aspects were considered to be the most important aspect of the three with respect to the ISPR, as its spatial constraints severely limit larger amounts of fresh food production and food quality was deemed to be most important. The criteria taken into account were taste, texture, appearance and pungency, the first three criteria of more obvious importance, and pungency due to the reported inhibited perception of spiciness on space missions. Other criteria like nutritional value, allergic potential and digestive quality were not taken into account due to plant cultivation spatial limitations in the FEG and ISPR. Production aspects concentrated on the physical dimensions and constraints of the growth modules in Neumayer III and ISS and the necessary technical aspects of cultivation. The criteria chosen were related to labor requirements (transplantation, pollination, pruning and harvesting), disease control and shelf life. Yield aspects were limited to harvest index, light use efficiency and efficiency of cultivation space and time. The last criterion focusses on the volume required to grow a plant/crop, the time from sowing to first harvest and the amount of harvest realized.

With these criteria, aspects of methodologies used earlier in selection processes were combined to produce a methodological framework:

- with which the most suitable crops could be selected for cultivation in the ISS and FEG facilities,

- that could be re-used, re-evaluating the plant selection with the same criteria but with new plant species, new insights or newly acquired data relevant for the evaluation.

B. Description of the selection process

Three previously used selection methods were combined to produce a suitable plant selection methodology for the EDEN-ISS project. First, an objective decision tree was used to exclude plants that are not compatible with the hard criteria, e.g. edible and ready-to-eat or plant size. It was used to exclude plants that could definitely not be grown on-board the ISS or in the FEG, respectively. These important constraints are so called hard criteria and the decision tree requires a "yes" and "no" answer to categorize the crop.

Secondly, a pairwise comparison based on David[11] was used to weigh the main selection aspects as well as the soft criteria for application in either of plant growth facility. The most important criterion in each aspect was selected and the remaining criteria were compared to it. In this way the total weight for a certain criterion can be calculated by multiplying the individual criterion score by relative importance of the whole aspect. The scales of each table of comparison were normalized to allow comparisons between different tables.

Lastly, the 0, 1, 2-method used by Hoff et al.[12] was adapted to weigh the crop's fulfilment of the criteria. Instead of a 0, 1, 2-scale, a scale of 0 to 1 was applied. The gradual 0 to 1 scale gives the possibility to not only assign scores based on the plant's compatibility with the criterion, as described earlier, but also to integrate criteria expressed in absolute values. This is necessary for example, for the Harvest Index, which is expressed in a number between 0 and 1. Furthermore, in this way the plant score for a specific criterion could be multiplied with the relative weighting factors of the criterion so that, in the end, plants could be ranked based on a final crop score between 0 and 1; with 0 being not suitable to grow in space at all and 1 being the perfect plant according to the different constraints.

The result is that the final score of the crop will be determined by the addition of all combinations of criteria weights and crop factor fulfilments. The final score of each crop is based on the multiplication of each criterion weight and its score, and then the values for each criterion are added up to determine the final score of the crop. The equation that dictates this procedure is:

$$P_x = A_1(C_{1.1} *S_{1.1} + C_{1.2} *S_{1.2} + C_{1.n} *S_{1.n}) + A_2(C_{2.1} *S_{2.1} + C_{2.2} *S_{2.2} + C_{2.n} * S_{2.n}) + A_3(C_{3.1} *S_{3.1} + C_{3.2} *S_{3.2} + C_{3.n} *S_{3.n}) \tag{1}$$

Where P_x is the final crop score, A is the relative importance of the main aspect, C is the weighting factor of the criterion and S is the score of the crop for that criterion. This is applied for n criteria.

C. Input data

For each of the soft criteria, a value was then given to each crop (Table 2). The 'quality criteria' were each given a (subjective) score from 0-1 by a number of breeders and growers who are well acquainted with these crops in

Table 2. Scores and calculated values for the soft criteria.

Crop	Yield aspects			Cultivation aspects				Quality aspects			
	Space/time efficiency [kg/m³/d]	Harvest Index [scale 0-1]	Light/energy use efficiency [g/mol]	Disease resistance [scale 0-1]	Shelf life [scale 0-1]	Handling time [scale 0-1]	Spread harvest [scale 0-1]	Pungency [scale 0-1]	Taste [scale 0-1]	Texture [scale 0-1]	Appearance [scale 0-1]
Lettuce	209	0.95	9.07	0.65	0.57	0.95	1	0.2	0.4	0.5	0.6
Tomato	110	0.58	5.66	0.25	0.86	0	1	0.2	0.6	0.5	0.6
Dwarf tomato	116	0.55	2.98	0.25	0.86	0	1	0.2	0.6	0.5	0.6
Cucumber	160	0.55	8.33	0.35	0.57	0.65	1	0.2	0.2	0.8	0.6
Bell pepper	41	0.50	3.56	0.5	0.86	0.55	1	0.4	0.4	0.6	0.5
Water cress	24	0.80	0.87	0.65	0.71	1	0	0.8	0.9	0.4	0.7
Red mustard	28	0.90	1.22	0.65	0.57	1	1	0.8	1	0.6	0.9
Swiss chard	48	0.80	2.78	0.65	0.57	1	1	0.1	0.2	0.4	0.4
Strawberry	70	0.40	3.04	0.5	0.29	0.75	1	0.2	0.8	0.6	0.8
Radish	68	0.60	2.95	0.6	0.86	1	0	0.7	0.7	1	0.7
Spinach	60	0.80	2.60	0.65	0.57	1	1	0.2	0.3	0.4	0.6
Chives	110	0.90	4.77	0.9	0.57	1	1	0.6	0.6	0.5	0.6
Basil	7	0.90	0.30	0.75	0.29	1	1	0.4	0.8	0.4	0.7
Coriander	30	0.70	1.30	0.85	0.57	1	1	0.6	0.4	0.6	0.4
Parsley	60	0.70	2.60	0.9	0.57	1	1	0.6	0.4	0.6	0.4

relation to these quality aspects. 'Yield criteria' were calculated using data from trials at Wageningen UR and from literature data, and in some instances (e.g. harvest index) were estimated. 'Cultivation criteria' were accorded a value between 0 and 1. For example, spread harvest is either possible or not possible (1 or 0), while shelf life was given a fraction of 0.14 per day, so that a crop with a shelf life of 1 week received a score of '1'. Handling time was treated pragmatically, subtracting a certain fraction from 1 for each time it is performed: transplanting (0.05), pollination (0.05), pruning (0.1) and seed treatment (0.2). Resistance to disease was also calculated by subtracting 0.1 from 1. Crops with no known susceptibilities scored 1.

D. Implementation of the methodological framework

A spreadsheet was developed in Microsoft Excel to support the selection of the plants and made use of equation 1. It was developed with Visual Basic Applications macros (VBAm) and is designed to process 19 different criteria, classified within in 4 main aspects, including the hard criteria. The other soft criteria are added with additional information fields, including a unique ID number for each crop, the main aspects, individual criteria and threshold values or target values. The candidate crop list input can contain up to 30 crops. The spreadsheet sets up a structure to classify the plants according to their fulfilment of the hard and soft criteria. Plants that do not meet the hard criteria are automatically eliminated from the final list. The rest of the plants are ranked according to the final score formula. The values for application of the methodology were taken from published and unpublished horticultural research data, values given by plant breeders, and in some cases assumptions were made. Tabs in the spreadsheet for the comparison of criteria were created and separated per aspect. The aspects were compared separately in an additional tab. The final weights and scores were then displayed in a results tab.

III. Results & Discussion

Once the basic scores were established (Table 2), the main aspects and underlying soft criteria were each ranked in order of importance, separately for the ISPR and for the FEG. Some of the hard criteria differ significantly between the two systems, e.g. the maximum allowable height in which the crops can grow is much higher in the FEG (ca. 180 cm) than in the ISPR (ca. 60 cm). The physical constraints for food production in each facility dictates different priorities. The ISPR for example has an available area for plant cultivation of 0.5-1 m^2 while that of the FEG is much larger (12 m^2)[9], which means that the lesser amount of fresh food that can be produced in the ISPR implies that other criteria, like quality aspects, may be more important than yield.

E. Ranking of the selected crops for the ISPR

The ranking, i.e. relative importance of the main aspects quality, yield and cultivation, as well as their underlying criteria for use in the ISPR are given in Table 3. Of the main aspects, quality was considered to be most important and was given a ranking of 100% (100:100); the small amount of fresh produced must be tasty, look good, and be spicy. Cultivation aspects followed in importance (65:35, indicating 65% for quality:35% for cultivation). A gradual or spread harvest is important to have even a small amount of fresh food on a daily basis, the plants are cultivated on a small area and the potential spreading of disease is an important issue as well. Naturally, the amount of fresh food to be produced is also important, but was ranked lower than the former two aspects (80:20, or 80% for quality:20% for yield). Naturally, the ranking is subjective, but these choices were made in view of the physical constraints of the ISPR and needs of the crew. Within each main aspect, the underlying criteria were ranked in a similar manner. The ranking, or weighting of criteria is a relative score and has different implications for the various crops which eventually will result in a relative suitability for each crop grown in the ISPR.

Table 3. Relative importance of the main aspects and underlying criteria for crop selection for the ISPR.

Main aspect*		Criteria within each Main aspect					
		Quality		Cultivation		Yield	
Quality	100:100	Taste	100:100	Spread harvest	100:100	Light use efficiency	100:100
Cultivation	65:35	Texture	65:35	Disease resistance	65:35	Harvest index	65:35
Yield	80:20	Appearance	80:20	Handling time	80:20	Space/time efficiency	80:20
		Pungency	90:10	Shelf life	95:5		

*ranking: quality (100:100) > cultivation (65:35) > yield (80:20)

Thus, the crops that met with the hard criteria together with their individual scores or calculated values for each soft criterion were subjected to the selection methodology. The results are given in Table 4 and indicate not only a priority ranking, but an overall score as well. The score provides an indication of how much a crop distinguishes itself from the others in terms of its suitability as a source of fresh food, in this case for cultivation in the ISPR.

Table 4. Final score (*Px*) and ranking of selected crops for use in the ISPR.

Crop	Score	Crop	Score
Lettuce	7.6	Water cress	4.7
Radish	6.1	Parsley	4.3
Chives	6.0	Basil	4.1
Strawberry	5.8	Spinach	3.7
Dwarf tomato	5.8	Coriander	3.6
Red mustard	5.8	Swiss chard	3.0

The differences in suitability shown in Table 4 are not extreme, with relatively small differences between crops ranked next to each other. Lettuce scored the highest, closely followed by radish, strawberry, tomato and red mustard, with chives as the best herbal species in between.

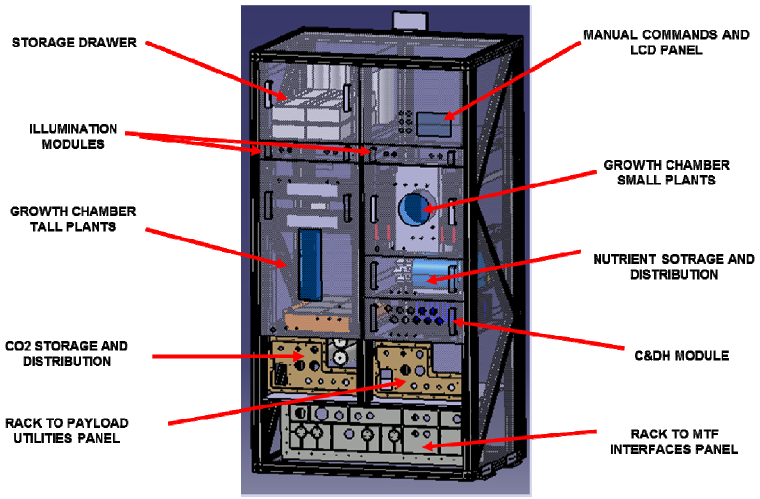

Figure 1. EDEN ISS ISPR cultivation system concept.

There are some comments to be made on the practical use of some of these crops however. Tomato has a relatively low HI (0.55), compared to lettuce, red mustard, spinach and the herbal crops. If strawberry is to be cultivated on the ISS, it must be brought there as seed, and the projected crop cycle is long, approximately 26 weeks, which is perhaps longer than the crew can 'afford' given the space limitations of the ISPR. It also requires a brief period of vernalisation in order to induce the production of new flowers and fruits. Red mustard grows rapidly and is quite spicy, which might make it a popular crop to grow, as well as water cress and the herbs. And then when assessing a crop like lettuce for example, in which the crispy green cultivar 'Expertise' was used for this study, different cultivars will provide different results. However, in most cases differences between crops will be larger than differences between cultivars. Thus, these are also considerations that must be taken into account when choosing crops for fresh food aboard the ISS.

The herbal crops included in the list of potential crops produce relatively small amounts of biomass, but have other qualities, taste and pungency, for which they are mostly consumed. Given their scores for quality, yield and cultivation criteria however, the selection methodology does indicate that chives are the most, and coriander the least suitable herb for cultivation in the ISPR. A number of criteria which might be used in this methodology, e.g. antioxidant content or nutritional value, have not been addressed here,primarily because the main aim was to develop the methodology.

F. Ranking of the selected crops for the FEG

The FEG is a very different plant growth facility or chamber for crop growth and cultivation than the ISPR. The FEG has a larger cultivation area, 12-24 times larger than the ISPR[9], with consequences for the weighting of selection criteria. Within the EDEN ISS project[4] the goals for fresh food production in the FEG in Antarctica are the maximum amount of fresh food production, with a continuous daily flow of fresh food for the crew members. Thus the relative importance of the main aspects and their underlying criteria were determined once again, but now for altered cultivation conditions and aims with respect to fresh food production (Table 5). Thus, the yield was considered to be most important main aspect (100:100), followed by cultivation aspects (70% yield:30% cultivation), followed the human quality aspect (80% yield:20% quality). Within each main aspect, the underlying criteria were ranked in a similar manner.

Table 5. Relative importance of the main aspects and underlying criteria for crop selection for the FEG.

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

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

Light is the most important main factor in determining plant growth and production, and thus the light use efficiency is deemed the most important criterion within the yield aspect. A small area in the FEG is dedicated to germination and seedling growth at light levels of 150-250 µmol/m^2/s, while the rest of the leafy green vegetables (e.g. lettuce, spinach) and fruiting vegetables (tomato, pepper, cucumber) require higher light intensities varying from 300-600 µmol/m^2/s. The energy requirement of the FEG during the day is expected to be ca. 12 kW and ca. 7 kW at night[9], which means that the use of artificial light for plant growth accounts for the greater part of the day/night difference. The energy use by artificial lighting at an intensity of 600 µmol/m^2/s will exceed the 6 kWh capacity, which emphasizes the importance of light use efficiency and accounts for its high priority. With respect to artificial lighting for crop production, attention should and will also be paid to utilizing the light spectrum, in addition to light intensity. A light recipe with the proper spectrum will influence the production of secondary metabolites like phenolic compounds, ascorbic acid and anthocyanins[13,14], increasing the quality of fresh food. The space is possibly of lesser importance, but the time factor for a whole plant cycle is also very important for continuous food production. Then, due to a larger area for production, criteria for cultivation and production aspects, like handling time (i.e. pollination, pruning, harvesting) rank higher in importance than the human quality aspects. Thus, the priority of the criteria for the FEG (Table 5) differ form that for the ISPR growth facility.

Figure 2. Impression of the Future Exploration Greenhouse at Neumayer Station III.

Crops that met with the hard criteria set for the FEG, together with their individual scores or calculated values for each soft criterion were then subjected to the selection methodology. The results are given in Table 6 and indicate not only their suitability for cultivation in the FEG, but also how better, relatively speaking, they are suited for fresh food production in the FEG.

Some larger crops like cucumber, bell pepper and tomato, can be grown in the FEG that could not meet the hard constraints of the ISPR. These rank relatively high due to the amount and rate of fresh food they can produce. However, the shorter cropping cycle of lettuce makes it the number 1 crop in the list again, followed by cucumber and dwarf tomato. Lettuce and cucumber stand out with the highest scores (38-49), followed by the group with the tomatoes and chives (score 26-27).

Figure 3. Overview of selected crops.

In the FEG system too, some additional factors will have to be taken into account in finally choosing the crops to grow. Especially the larger fruit-bearing vegetables have extra requirements for their cultivation. Cucumber and tomato as vine vegetables bearing small fruits for example, require extra cultivation measures (e.g. pollination, pruning) and some growth guidance like a spiral wire to grow along, allowing proper plant growth and less handling while pruning or harvesting. They also require more volume in which to grow, thus small cultivars are better options. Then strawberry as mentioned earlier, has a relatively long growing cycle and requires a certain degree of vernalisation, which imposes extra requirements of the climate conditions in certain areas of the FEG. Bell pepper requires accurate shoot and fruit pruning to realise continuous production, but often distinguishes itself with fruit setting issues, irregular flowering and has a relatively low harvest index.

Table 6. Final score (*Px*) and ranking of selected crops to be cultivated in the FEG.

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

IV. Conclusions

A consequent methodology, even it makes use of estimated scores in some cases, is preferred over a simple listing of plants. This is because it has, in our opinion, an argumented basis which can be repeated with new crops or be adapted later on if good reasons for alteration occur. This does not only mean that new species can be evaluated but also that new cultivars, for example shorter tomato plants, can be included in the selection procedure. Furthermore, the criteria in this methodology were grouped into a few themes (main aspects) so that criteria with similar characteristics relevant for a specific facility could be given a higher or lower priority as a group. It is of great importance that the methodology is flexible so that it can be adjusted when new research warrant its change. It must also be flexible because there will likely be changes in conditions before and during the implementation of the ISPRs on-board the ISS and future space missions. If so intended, this methodology can also be adapted to include other criteria aiming to provide a significant amount of the crews' diet in future plant cultivation.

The designed methodology aims to be objective, preventing suboptimal selection of plants due to personal bias, e.g. ‘attractive vegetarian diets’[5]. Having a methodology saves time in the selection of crops as it takes into account the most important constraints involving (human perception of) quality, plant and physical factors and can also be used for different purposes in other types of missions, i.e. Neumayer III or ISS. Careful analysis of the results can lead to the future development of breeding guidelines for new cultivars that would be better suited for growing in space.

The aims and benefits of fresh food production for crew members and the crop choices for the ISPR and FEG differ due to the specific characteristics and constraints of each facility. Having made use of this methodology resulted in a prioritized list of vegetables and herbs for both the ISPR on the ISS as well as the FEG at the Antarctic Neumayer Station III. It is our opinion that this has resulted in optimizing the amount and quality of fresh food production for each facility.

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