Possible nutritional output of rapid-deployable CEA greenhouses for emergency scenarios

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Abstract

Space research is a catalyst for innovation and has for decades provided many tools for the improvement of life on earth. The development of space food and the demand of new methods for on-site food production for long-term space missions may, in fact, help solve the issues regarding food insecurity on earth. The German Aerospace Centre (DLR) has since 2011 undertaken the task to develop the method for on-site food production, with the development of EDEN ISS, a Controlled Environmental Agriculture (CEA) greenhouse module for space applications.

Space greenhouse systems have stringent requirements since optimal growing conditions need to be achieved with very limited resources and with no room for failure. Whereas many areas on earth face similar problems, plant cultivation methods for space may also translate into terrestrial applications where food production is otherwise difficult. For instance, space greenhouse systems may provide ideal solutions for humanitarian assistance scenarios that are in urgent need of new and innovative solutions to combat food insecurity. As a result, DLR and WFP have started a spin-off collaboration of EDEN ISS called MEPA. MEPA is a mobile CEA greenhouse that combines the hydroponic methods of nutrient film technique and aeroponics in a flexible seed cultivation mat, to make an easily transported food production system for humanitarian food aid scenarios.

This study primarily examines the CEA cultivation methods and their applicability in space and on earth, followed by a description of the MEPA system and its potential as a tool in humanitarian aid scenarios. In addition, the study investigates the potential of MEPA as an easy-to-use CEA micronutrient production system.

The study of the MEPA system was conducted in several steps. First a growth test and an experimental set up of MEPA was performed by constructing and testing the seed cultivation mat. The study indicated that the seed cultivation mat has no issues growing beans, lettuce, and purslane. The growth system was almost autonomous and needed almost no supervision. Second, the nutritional yield and the potential nutrition adequacy of MEPA was estimated by comparing different indicators of nutritional quality. The calculations estimated that depending on crop choice, a 20ft container of MEPA units have the potential to feed up to 100 people with a micronutrient content adequate for up to 350 people. Subsequently, the calculations led to a proposal of new metrics that measures the nutritional quality of the potential output, which may fill a gap in current crop choice methods.

Keywords: Hydroponics, Aeroponics, NFT, Food aid, Humanitarian assistance, Space food, Nutritional yield, Nutritional adequacy, MEPA, EDEN ISS, Controlled environmental agriculture, Sustainable development.

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Abbreviations

WFP	World Food Program
DLR	German Space Center
CEA	Controlled Environmental Agriculture
SCM	Seed Cultivation Mat
BLSS	Bio-regenerative life support system
NDS	Nutrient Delivery System
ASU	Automated Support Unit
EDEN ISS	Evolution & Design of Environmentally closed Nutrition-Sources International Space Station
RTE	Ready to eat vegetables
NFT	Nutrient film technique
EC	Electrical conductivity
DO	Dissolved oxygen
RZT	Root zone temperature
rH	Relative humidity
aW	Water activity
VPD	Vapor pressure deficit
BLSS	Bio-regenerative life support system
MTF	Mobile test facility
FEG	Future exploration greenhouse
MEPA	Mobile Entfaltbare PflanzenAnbaueinheit
LLDPE	Linear low-density polyethylene
PET	Polyethylenterephthalat

1. Introduction

Space research is a catalyst for innovation and has for decades provided many tools for the improvement of life on earth (NASA 2022). The situation is no different when in situ food production will become a future requirement for long-term space missions. The German Aerospace Centre (DLR) has undertaken the task of developing EDEN ISS (Evolution & Design of Environmentally closed Nutrition-Sources International Space Station), a Controlled Environmental Agriculture (CEA) greenhouse module for space applications. Space greenhouse systems have stringent requirements, so that optimal growing conditions can be achieved with very limited resources and with no room for failure. The CEA plant cultivation methods for space can also be beneficial for earth, especially in areas where food production is otherwise difficult. In short, the CEA method may help combat food insecurity which is already an urgent global threat, in part due to political instabilities and the climate changes that we already face.

According to estimates from the United Nations' World Food Program (WFP), 811 million people do not have sufficient access to food, and no less than 45 million people in 43 countries are at risk of famine (WFP 2018; 2022). More than 80% of these people live in countries with arid lands prone to environmental shock and ecosystem degradation. Crop failures due to environmental conditions, pests, lack of knowledge, or lack of fertilizers are not unusual. The situation can also worsen quickly in the event of natural disasters such as hurricanes, cyclones, droughts, floods, and earthquakes.

In addition to natural factors, it is not uncommon that the already fragile situation in food insecure countries gets aggravated by political instability, conflict, rapid population growth or unplanned urbanization. Consequently, conditions may further deteriorate and reverse many of the developmental gains that the areas have had in the past (Sahinyazan et al., 2021). To add further complications, the delivery of food assistance to affected communities is critical. As of today, the WFP delivers up to 4 million metric tons of food annually to affected people around the world, however, with poor infrastructure and sometimes high levels of insecurity, this type of distribution provides logistical challenges (WFP 2015; 2018 Sahinyazan et al., 2021).

Another challenge is to provide an adequate amount of macro and micronutrients. The in-kind food aid is normally fortified and under constant development to increase the bioavailability of the nutrients they contain (Webb et al., 2011; Bounie et al.,2020). Nevertheless, in-kind food cannot satisfy every nutritional need and should therefore be complemented with other products (WFP 2014; Sahinyazan et al., 2021). Dietary diversity is paramount to provide an adequate amount of nutrients and to avoid malnutrition. Moreover, food variety usually decreases with house income and may be scarce in underdeveloped areas or areas that are in the need of food assistance (Skoufias & Zaman 2011). As soon as the state of emergency has settled in an area, vouchers and cash programs can be delivered as food assistance, to help communities rebuild and return to normality (WFP 2020). However, even though proven effective, these cash and voucher programs are largely dependent on an already well functioning market structure and are therefore not always applicable (Peters et al, 2021; Sahinyazan et al., 2021; Sahinyazan et al., 2021; Hidrobo et al., 2014; Doocy & Tappis 2017; FAO 2017). Also, researchers have criticized cash and voucher programs for not resolving food insecurity long-term since communities may develop a dependency on food aid programs (Sahinyazan et al., 2021). Subsequently food aid programs tend to disincentive rural development and impede the resilience of the local food system.

To overcome the challenges described above, many organizations have worked to implement soilless cultivation systems, such as hydroponics in affected areas, which has proven to be an effective method to incentive rural development and fresh food production (Nanama & frongillo 2012; Hatcher et al.,2019; Verner et al., 2017; Ouchene & Massebiau 2018). Nevertheless, most hydroponic programs are not adapted for rapid disaster relief aid, as they take time to set up, require previous knowledge of plant cultivation, and the materials can be bulky and difficult to transport. In addition, for uniform results, optimization and to minimize the risk of crop failure, the environment around the cultivation system has to be enclosed so that abiotic and biotic stressors can be avoided.

In conclusion, food aid programs are in need of new and innovative solutions that may aid in the provision of fresh food during humanitarian crisis scenarios. As a result, the development of EDEN ISS has in turn led to a spinoff collaboration between WFP and DLR, called M.E.P.A (Mobile Entfaltbare PflanzenAnbaueinheit), a CEA food production system designed for humanitarian food aid scenarios. The intention of MEPA is a small and mobile semi-closed CEA greenhouse that combines the hydroponic methods of Aeroponics and Nutrient Film Technique (NFT) in a Seed Cultivation Mat (SCM). The SCM is the growth channels of the hydroponic system, which can be folded or rolled up into a compact and lightweight roll subsequently requiring minimal space during transport. Additionally, the MEPA system should not require any previous experience in crop production, be fast to set up, simple to use, almost autonomous and require little supervision.

MEPA is still in the Assembly, Integration and Test Phase (AIT), and at the current stage, the SCM needs to be constructed and tested. Moreover, to determine the potential of MEPA as a micronutrient production system, alternative metrics to biomass output need to be calculated. There is a large amount of literature on methods of the calculation of different nutritional indicators. However, there is a significantly lesser amount of literature measuring the nutritional quality on agricultural outputs. Combining the edible biomass output with the correct nutritional quality indicators suitable for the type of crops, grants an overview of the nutritional quality of the production system. Furthermore, using different nutritional quality indicators fills a gap in current crop choice methods. A common error in crop choice methods is that they either rely on solely biomass output or that the nutritional quality indicators are not compatible with the selected crops.

The aim of this study is to first construct and test the limitations of the SCM. Second, to provide an estimate of the micronutrient yield of MEPA, hence, to provide an assessment of MEPA as a potential tool for humanitarian food aid.

1.1 Paper outline

This study first provides a background of the CEA cultivation method and its applicability in space and on earth. The background is conducted as a literary review, divided into thematic chapters, providing information about soilless cultivation. The chapter further highlights the benefits of CEA systems, as well as the most relevant factors regarding plant growth.

A description of MEPA and the potential of CEA systems as an agronomical and socio-economic tool in humanitarian scenarios are investigated and briefly discussed, followed by a description of the MEPA design and a brief framework for crop selection.

Additionally, the potential of MEPA as an easy-to-use CEA micronutrient production system was investigated. First, a growth test and an experimental setup of the MEPA were performed by constructing and testing the SCM. Second, based on the biomass output data from EDEN ISS, the nutritional yield and the potential nutritional adequacy of MEPA were estimated in relation to different indicators of nutritional quality.

2. Background

2.1 Controlled Environment Agriculture

Controlled Environment Agriculture (CEA) are enclosed systems that are designed to have complete environmental control, meaning that plant nutrition, water air and root temperature, atmospheric gas composition, light wavelength, light intensity, and light duration need be controlled and monitored. CEA opens the possibility to grow food everywhere, at any time regardless of season and external environmental conditions which makes CEA a popular topic regarding food security. In addition, this high precision crop growing leads to major reductions in yield gaps, resulting in predictable maximizations of crop yield without sacrificing quality or uniformity (Jones 2005, Ragaveena et al., 2021). There are a varieties of different CEA systems, some of which that are highly technological and require multidisciplinary expertise in order to develop the sensors and control systems that runs them. These systems can be operated manually but may also be controlled completely via automation (Ting et al., 2016).

2.1.1 Soilless Cultivation

In CEA greenhouses, plants are commonly grown in soilless systems since soil is a less controllable variable. CEA may be extra useful in areas where soil-based agriculture would otherwise be difficult, for instance in areas prone to extreme environmental stress. Additionally, soilless cultivation does not require the labor-intensive methods of soil-based agriculture such as tilling, weeding and watering, making it suitable for situations where food production is handled by inexperienced work labor. Further, without soil, the roots can be supplied with readily available nutrients, and additionally there is no mechanical hindrance of the roots to develop, resulting in faster growth rate of the plants. (Sharma et al., 2018, Manzocco et al., 2011). Moreover, soilless cultivation is particularly beneficial when growing ready to eat vegetables (RTE). The higher pH value and water activity (aW) in RTE makes them more susceptible to bacterial invasions, especially from certain pectinolytic species of the genera *Pectobacterium, Xanthomonas* and *Pseudomonas* all of which originate from soil. However, microorganisms are opportunistic, and the onset of spoilage depends on various factors, but is normally a result from water loss, wilting or physiological stress from cuts, pests and harvesting itself. Furthermore, even if food borne illness rarely originates from vegetables, enteric pathogens such as *salmonella, shigella, listeria monocytogenes* and *e. coli* as well as *Yersinia enterocolitica* and *Aeromonas hydrophilia* may be a valid concern. Particularly when equipment for further food processing, hygienic practices and storage facilities are limited. However, these enteric pathogens originate from soil, bird droppings or organic fertilizer and may therefore be avoided in soilless cultivation. Nevertheless, pathogens may still be transmitted to plants from workers and hygiene is therefore paramount (Sant'ana et al 2012,. Taban & Halkman 2011). However, despite the many benefits of soilless agriculture, there are still certain challenges to overcome. For instance, soil works as a buffer, which is useful in case of fluctuating conditions or during system failure. Soilless cultivation systems also often rely on specialized parts that may be hard to come in more remote locations if spare parts are needed.

There are many different types of soilless agriculture, this paper will focus on mainly two hydroponic methods, nutrient film technique (NFT) and aeroponics.

Aeroponics

In Aeroponics, roots are suspended in the air and the nutrient solution is sprayed through pressure nozzles into a fine mist on the roots either constantly or intermittently. This allows for water conservation and can be optimized and increase the total factor productivity of the system. The limited contact between plants and the irrigation system allows for unconstrained root growth as well as providing excellent aeration (Lakhiar et al., 2018, Morgan 2021). Due to the unconstrained roots, aeroponics have shown promising results in growing potatoes and other tubers which may otherwise be difficult in soilless cultivation systems (Ritter et al., 2000, Nichols 2005). Disease transmission may also be limited since the contact between the plans is reduced and the nutrient solution can be sterilized (Clawson et al., 2000). However, aeroponics is technology driven and requires multiple sensors and high-pressure pumping systems which need to be calibrated for certain droplet size. Subsequently, the required maintenance, initial investment, and energy cost for running the system is relatively high in comparison to other systems (Morgan 2021).

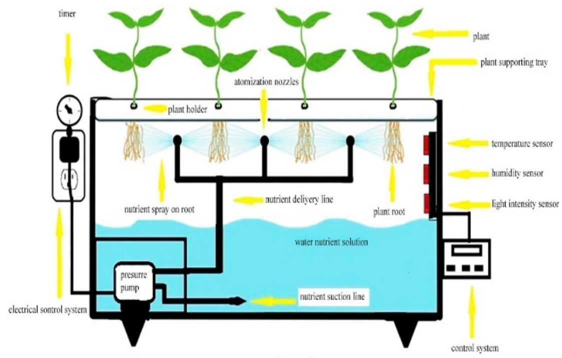

Figure 1 Diagram of an Aeroponic system (Lakhiar et al., 2018)

Nutrient Film Technique (NFT)

The Nutrient film technique works similarly to the deep-water culture but eliminates the problems of continuously submerged roots. The nutrient solution which sits in a separate reservoir is pumped up into slightly tilted channels, normally constructed from PVC piping which then drains back into the reservoir creating a circular system. The plants are placed along the channels with or without a solid rooting medium. The roots hang freely and are not completely submerged, which additionally allows for sufficient oxygen supply. The water flow is adjusted so that only a film of two to three cm of water runs past the roots supplying them with nutrients which should correspond to one to three liters per minute. If the flow rate is too low, there is a risk that the plants in the lower end of the channel will be malnourished. Similarly, if the channel is too long, the downstream plants may only receive nutrient depleted water (Jan et al., 2020, Morgan 2021). However, like other systems, NFT is not without constraints. Nutrient management is critical and fast-growing crops may deplete the system of certain nutrients faster than it may be replenished. NFT is also more oriented towards fast growing crops. Crops that need to grow over a longer time can easily clog the pipes due to the size of the root systems. This will restrict oxygenation levels in the system as well as nutrient supply and water flow. An uneven growth of the crops may also cause stagnant areas along the channel system and affect water flow (Morgan 2021, Jones 2005). Nevertheless, the system allows for a variety of crops and the benefits outweighs the constraints which in turn are manageable. NFT is also simple, relative to other soilless cultivation methods.

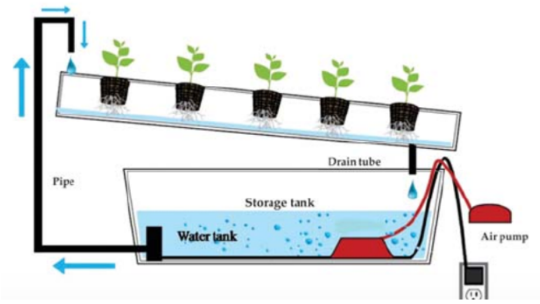

Figure 2 Diagram of a Nutrient Film Technique (Sharma et al., 2019)

2.1.2 Nutrient Solutions

In a hydroponic system, the nutrients are provided in their inorganic form, mainly from soluble salts, and are prepared in an aqueous solution. Since there is no soil to provide essential minerals, these need to be included in the nutrient solution (table 1). Other non-essential elements such as sodium, silicon, vanadium, cobalt, iodine, and aluminum are not included in table 1. These nutrients still provide beneficial nutritional roles in plants by acting as less specific coenzymes, stimulating growth or compensating for certain toxic effects (Kiferle et al., 2021, Kaya & Ashraf 2022, Trejo-Téllez et al., 2012).

Table 1 Essential plant nutrients, their primary function and chemical form taken up by the plants (Jones 2005: Trejo- Tellez et al., 2012)

Nutrient family	Nutrient	Form taken up by plants	Primary Function
Primary macronutrients	Carbon (C)	CO_2	Carbohydrate synthesis
	Oxygen (O)	H_2O	Cellular respiration
	Hydrogen (H)	H_2O	Electron transport chain pH regulation Carbohydrate synthesis
	Nitrogen (N)	NO_3^- NH_4^+	Protein & amino acid constituent
	Phosphorous (P)	$H_2PO_4^-$ HPO_4^{2-} PO_4^{3-}	Nucleic acid & membrane phospholipid constituent High Energy transfer (ATP and ADP)
	Potassium (K)	K^+	Maintain proper ion balance via ion pumps Enzyme cofactor Carbohydrate metabolism
Secondary macronutrients	Calcium (Ca)	Ca^{2+}	Cell wall structure, intracellular signalling, enzyme cofactor
	Magnesium (Mg)	Mg^{2+}	Major constituent in chlorophyll Enzyme activator relating to energy transfer processes CO_2 fixation in C3-type plants
	Sulphur (S)	SO_4^{2-}	Compound in certain amino acids, thiamine, coenzyme A and lipoic acid
Micronutrients	Iron (Fe)	Fe^{2+} Fe^{3+}	Energy transfer Chlorophyll formation Involved in chelate complexes Enzyme activity
	Zink (Zn)	Zn^{2+}	Enzyme activator for protein synthesis
	Copper (Cu)	Cu^{2+}	Electron transport Enzyme activator Chloroplast constituent
	Chlorine (Cl)	Cl^-	Cellular development Stomatal regulation
	Manganese (Mg)	Mn^{2+}	Photosynthetic electron transport system Enzyme cofactor
	Boron (B)	H_3BO_3 BO_3^{3-} B_4O_7	Carbohydrate synthesis Cellular function and development Pollen development
	Molybdenum (Mo)	MoO_4^{2-}	Enzyme component

Due to the inclusion of all essential nutrients in the solution, the availability and composition of the nutrients can easier be controlled and therefore optimized accordingly. However, there are certain parameters that affects nutrient uptake in plants such as plant growth stage, relative proportion of nutrients, O_2 level, pH, electrical conductivity, temperature, and ionic mutual ratio. First, in order to achieve and ionic balance in the nutrient solution, the ions and anions need to have a mutual ratio. For this reason, the addition of an anion must be accompanied by a corresponding cation in order to achieve the principle of electroneutrality and maintain a proper quantitative relationship between the ions and therefore not negatively affect plant performance (Steiner 1961, Jones 2005). Second, not to be confused with the mutual ionic ratio is the total ionic concentration. A fundamental part in optimizing plant growth is a sufficient management of the nutrient solution. An incorrect concentration of nutrients in the solution may result in either a nutrient deficiency, toxicity or hindered nutrient uptake due to osmotic pressure. To define the total salt concentration, electrical conductivity (EC) is measured, which in turn also is an indirect measurement of osmotic pressure (Ding et al., 2017). The ideal EC varies dependent on plant and environmental conditions but can also be adjusted dependent of preferred result. Studies have sown for example that tomatoes grown in higher EC will have smaller fruits but have an increased concentration of volatile aroma compounds, sugars and, acidity and improved visual and textural attributes, thereby higher tomato quality. (Cliff et al., 2011, Thybo et al., 2005, Dorais et al., 2000., Auerswald 1999). Third, in order for the plants to take up nutrients, they need to be in a certain chemical speciation which is largely affected by pH. This means that the bioavailability of certain nutrients changes with pH (figure 3), and nutrient uptake in hydroponic systems is therefore closely related to pH regulation (Jones 2005, Trejo-Téllez et al., 2012).

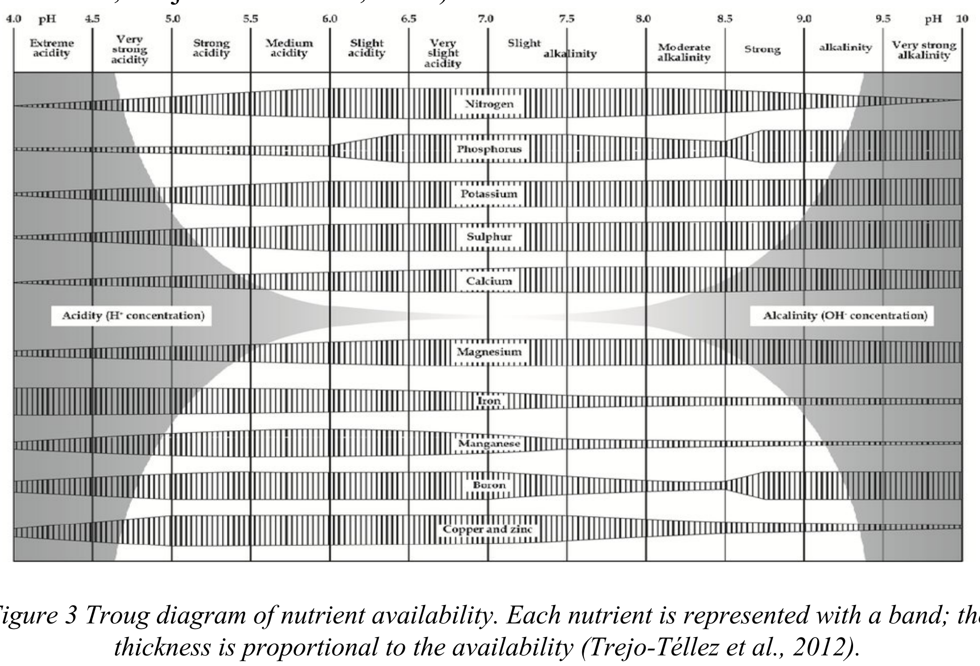

Figure 3 Troug diagram of nutrient availability. Each nutrient is represented with a band; the thickness is proportional to the availability (Trejo-Téllez et al., 2012).

Moreover, in order for nutrients to be absorbed, the plant need to have a well-functioning respiration and it is therefore important to supply the solution with adequate dissolved oxygen (DO). Sufficient levels of DO in the solution will also promote plant root growth as well as providing an aerobic environment, preventing the growth of anaerobic microorganisms. However, the O_2 solubility decreases with increasing temperature whereas plant respiration increases significantly with increasing temperature, it is therefore important to keep hydroponic systems well aerated (Jones 2005; Morgan 2021) Likewise, nutrient uptake and translocation are also affected by temperature. The root zone temperature (RZT) is another important parameter affecting various factors. For instance, temperature has a direct effect on root pressure and hydraulic conductivity, effecting water, oxygen and nutrient uptake which decreases with lower RZT (Yan et al., 2012). Furthermore, similar to air temperature, the RZT can affect certain metabolic pathways causing alterations in secondary metabolite production. Extreme RZT may inhibit plant growth by affecting plant transpiration and inhibiting photosynthesis by altering the efficiency of Photosystem II and the electron transport rate, subsequently causing oxidative stress in the leaves (Sakamoto & Suzuki 2015, Sakamoto et al., 2016, Al-Rawahy et al., 2018, Adebooye et al,. 2010, Sakamoto et al., 2015, Odhiambo et al., 2018, He et al., 2020). Adjusting RZT may therefore affect nutrient uptake, yield and nutritional quality.

2.1.3 Atmospheric Environment

The atmospheric environment affects plants both directly and indirectly. Parameters such as relative humidity (rH), Vapor Pressure Deficit (VPD) gaseous nutrients and temperature affects plants differently. Even airflow affects the moisture movement within the leaves and water evaporation from the leaves and therefore the plant transpiration. There is however a variety of parameters that affects plant transpiration, one of them being rH. If the rH is too high, the water from the plant will not evaporate which subsequently affects nutrient uptake and result in abnormal growth and disease susceptibility. Conversely if the rH is to low, the plant may suffer from dry tips, wilting and stunted growth. However, in response to a lower rH, the stomata openings will close in order to avoid excess water loss. This will in turn affect the carbon balance and sugar production since CO_2 uptake decreases. Optimizing the gas interface in a greenhouse may however come with certain limitations since plants and humans have different comfort zones (figure 4). On average, the plants require both higher rH and CO_2 levels than humans, but there are overlapping tolerable zones (Schubert 2018; Diesen et al., 2020).

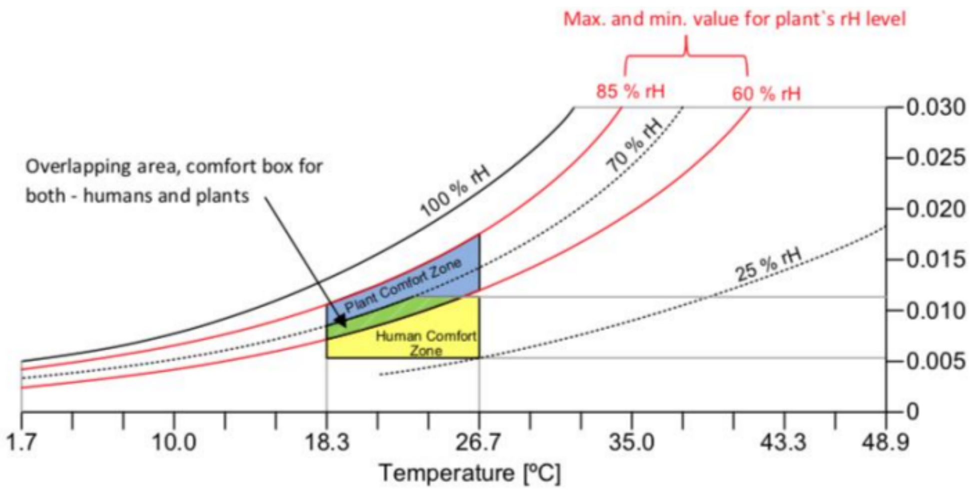

Figure 4 absolute humidity comfort area for humans (yellow) and plants (blue) and their common sector (green) (Schubert 2018)

Temperature, which is directly related to relative humidity will affect plant growth in a variety of ways. Temperature stress can be similar to drought stress and will mostly affect growth rate, cell division and elongation rates and leaf size. Plants have many mechanisms in response to fluctuating temperatures. Higher temperatures will affect the enzymatic activity of Ribulose bisphosphate carboxylase/oxygenase (RuBisCO), a rate limiting enzyme which catalyzes the carboxylation of Ribulose-1,5-bisphosphat (RuBP). During higher temperatures, the RuBisCO RuBP complex favors oxygenation over carboxylation, essentially mistaking O_2 for CO_2, which lowers the photosynthetic rate by half (Jensen 2000). Moreover, in order to maintain cell membrane fluidity, the saturation of lipids change with increasing or decreasing temperatures. Warmer temperatures lead to a larger ratio of saturated and monounsaturated fatty acids, whereas lower temperatures favor unsaturated fatty acids to retain membrane mobility. The changes in fatty acid composition may interfere with the fluid mosaic and disrupt cell signaling pathways, disrupting many cell functions (Guy et al., 2008; Niu & Xiang 2018; Zhang et al., 2022). However, high, or low temperature does not always induce stress responses. Fluctuations in photoperiod, temperature and humidity interacts with the plants circadian clock, influencing the growth and developmental phases in the plant. For this reason, alterations in the atmospheric environment can be used to control the developmental phases of the plant. However, minor fluctuations or malfunctions in the atmosphere management systems may lead to the inducement of unwanted growth phases, such as dormancy or premature flowerings (Bahuguna et al., 2015).

2.2 Controlled Environment Agriculture (CEA) for space and how the method can be applied on Earth

DLR have, with the start of EDEN ISS, undertaken the project to develop greenhouse modules for space applications. The development of ideas for such extreme environments such as space requires out of the “thinking outside the box” so that the current limits of what is possible can be pushed. The tools required for human survival in space are far more stringent than those on Earth, and the survival in space requires detailed insight of every variable and parameter that affect both human and plant physiology as well as the resources required to sustain all living organisms. The difficulty to create sustainable circumstances for living organisms in space becomes particularly apparent in the design of closed loop facilities for artificial habitats in space. The idea of these closed-loop life support systems is that every resource and material can be recycled and reused so that oxygen and water are created as a part of the recycle loop. The goal of livable atmospheres with sustainable life support systems in space has become a more urgent task for researchers to achieve since human space travel becomes longer and farther, which prohibits resupply missions from earth and makes in situ food production necessary (Duatis et al., 2008).

The addition of crops for in situ food production have led to the development of Bio-regenerative Life Support Systems (BLSS). BLSS includes a controlled environment greenhouse module, not only to produce food, but to utilize biological based processes of plants, similar to the carbon cycle on earth in order to create a livable environment (Ziedler et al., 2017). BLSS has limited room for malfunction, and the occurrence of system shutdowns in space can lead to devastating effects. Moreover, except for the extraction of frozen water from moon regolith, or minerals from Martian regolith, research of what and how resources can be exploited in space is limited (Wasilewski 2018; Sowers & Dreyer 2019). Therefore, BLSS are designed to function in places where optimal growing conditions can be achieved without any external inputs, running on very limited resources and with no room for failure. The systems’ benefits on earth should not be overlooked, the efficiency of BLSS is made to reduce the ecological footprint zero (Liu et al., 2021, Maiwald et al., 2021). For this reason, derivates from BLSS may have many terrestrial applications. For instance, in the aforementioned scenarios of humanitarian aid where BLSS derivates may be used to improve living conditions in remote areas or where food production would otherwise be difficult. Greenhouse modules derived from space applications, could be deployed to provide fresh food, and help contribute towards food security. In addition to rapidly provide fresh food, the greenhouses could reduce the stress on existing agricultural systems by lessen the demand for external inputs and intense food production allowing the rehabilitation of agricultural land. Subsequently, this would allow people who live in these areas to spend less energy on finding food and more on rebuilding their livelihoods (Maiwald et al., 2021). For this reason, DLR has started a collaboration with WFP to develop a spinoff of EDEN ISS called M.E.P.A, which is a food production system that is designed for humanitarian food aid scenarios.

2.2.1 EDEN ISS

The EDEN ISS is an international multidisciplinary collaboration led by the DLR and is derived from a project called the EDEN research initiative. The project started in 2011 at the DLR institute of space systems in Bremen, Germany. The focus was to investigate how CEA could be implemented into space hardware systems to create biological life support systems and greenhouse modules with possible habitat integration for extended interplanetary space missions. The ambitions and outcome from the EDEN research initiative led to the start of EDEN ISS (Schubert, 2018). The aim was to make a closed loop food production system in a space analogue environment using the CEA methods from the previous EDEN program and make them applicable to space. In addition to food production, the cultivation of higher plants revitalizes air, recycles water, provides raw material as well as impacting the psychological well-being of the crew, thus being a central part of BLSS. A main objective of the EDEN ISS was the development of a space analogue greenhouse system in a so-called Mobile Test Facility (MTF) (figure 5) placed next to German Neumayer Station III (NM-III) in Antarctica. The remoteness of the location in Antarctica and the extreme conditions as well as biologically sparse environment are comparable to those of Mars, Moon, and other remote locations on earth where EDEN ISS would be applicable. This allowed further investigations of crew -plant interaction, food safety and handling as well as simultaneously providing the over-wintering crew at NM-III with food, allowing for further insight of the psychological benefit of fresh food during isolation (Schubert & Zabel 2020; Zabel et al., 2015; 2017; Schroth 2021; Schubert 2018; Ziedler et al., 2019).

With the lessons learned from the EDEN ISS, reliable CEA technologies can be implemented in BLSS deployments for future long duration space missions. The design of a new greenhouse module that will implement all of EDEN ISS subsystems and be a part of a future lunar and Martian base is underway. An additional technology under development is the implementation of augmented reality (AR), connected to the subsystems in the MTF, that will provide plant information to the crew to further optimize crop production.

However, as previously mentioned, the outcome of EDEN ISS is not solely applicable for extra-terrestrial missions. Similar to the Moon and Mars, arid and barren lands on Earth are ubiquitous. Food security is an increasing issue, and many people live in remote or harsh environments that may be inaccessible, consequently making food distribution difficult. Furthermore, climate change has continuously negative effects around the globe and natural disasters are an increasing issue. Access to freshly grown food is highly variable and may not always be accessible. Plant cultivation methods designed for space such as the EDEN ISS may therefore provide ideal solutions for various humanitarian assistance scenarios. For this reason, the EDEN ISS project will bifurcate into BLSS for space and M.E.P.A for terrestrial food production.

Figure 5 EDEN ISS MTF in Antartica (DLR)

3. M.E.P.A

MEPA is an acronym for *Mobile Entfaltbare PflanzenAnbaueinheit*, i.e a mobile deployable plant cultivation unit. MEPA is derived from the EDEN project with the intention to fit the subsystems of EDEN ISS into one mobile deployable unit. Aside from producing fresh food and providing micronutrients to counteract malnutrition, MEPA can provide a great tool for agricultural and rural development. For instance, since MEPA is independent of fertile soils, it may be applied anywhere from arid lands to courtyards and rooftops in urban environments. Furthermore, due to the absence of weed growth or contaminations from soil, along with reduced pest management and lack of certain seasonal limitations, MEPA does not require pest and weed management or any labor-intense cultivation methods. Neither does it require any additional inputs other than water, seeds, and nutrients, meaning that the system has a relatively high total factor productivity. As a result, similar solutions have been applied around the world to combat malnutrition and poverty in a variety of different scenarios, from urban applications, refugee camps to fodder production on arid lands (Orsini et al., 2010; Shukla et al., 2018; Malhi et al., 2020; Ouchene & Massebiau, 2018; Verner et al., 2021; Hadad 2021).

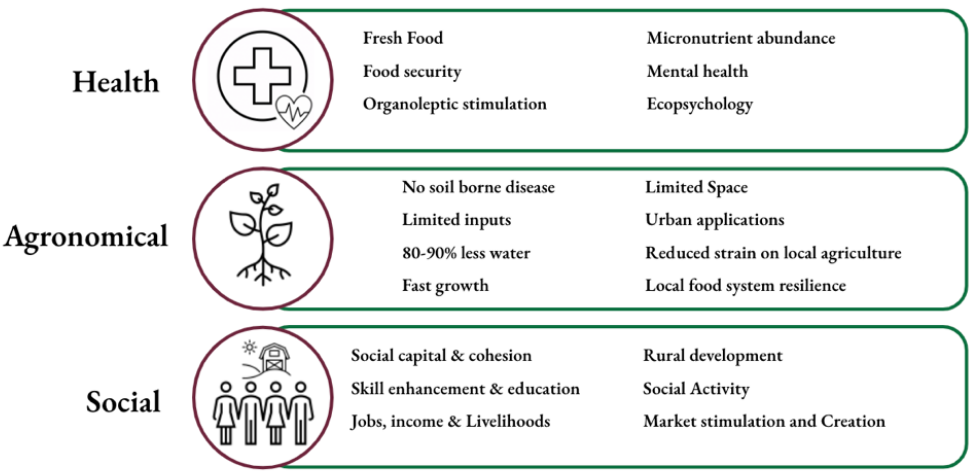

Figure 6 Possible beneficial outcomes of MEPA in terms of Health, Agronomy, and social qualities

As for agricultural development, MEPA may reduce the strain on the local agriculture. In the event of natural disasters or conflicts, it is likely that much of the arable land in the area may have been contaminated or destroyed from either mechanical damage or sabotage. In many events, due to the rush of production of food or other agricultural commodities, soils easily become stressed without being allowed to regenerate. Stressing the soils will consequently lead to more erosion, soil depletion and eventually desertification. Allowing agricultural lands to regenerate is key if the communities or countries dependent on them are ever going to recover. Therefore, applying MEPA units to divert food production from the available land to mobile hydroponic units, may alleviate the pressure put on the land and reduce the strain on the local agriculture, allowing for agricultural regeneration. Moreover, if this diversion of food production can be sustained for a longer period, it may be possible to lead a transition towards a more sustainable type of agriculture suited for the area and situation. This agricultural transition may help to improve biodiversity, soil fertility, and grant an overall thriving ecosystem. As a result, it may be possible to create a more resilient agriculture that may even be less prone to damage during future catastrophic events.

Since a functioning agriculture may in many ways be considered the backbone of a functional society, these agricultural benefits are synergic with rural development. One of the advantages of MEPA is that the food production may also be handled by inexperienced workers. Once people are taught how to maintain a basic hydroponic system, people in the area obtain a certain skill development and education about crop production., which may lead to a more long-term improvement of a province's agricultural development. Hopefully the skill enhancement may thusly contribute to entrepreneurship and innovations within the communities where MEPA has been applied.

As of recently, investigations from refugee camps in Mena and western Sahara have concluded that food, which is produced in excess, can be sold, which in turn leads to the creation and support of local markets. The generated revenue allowed people to meet other basic needs, and other entrepreneurial opportunities arose that, created additional jobs that were not directly related to hydroponics within the communities (Verner et al., 2017; Ouchene & Massebiau 2018). Another outcome that may arise from MEPA is the psychological benefits and impact is has on social structures. For example Nanama and Frongillo, (2012), highlight the psychological conditions closely related to food insecurity and the consequences it may have on physical wellbeing. People that do not have access to fresh food, or that receive food aid may develop feelings of alienation and deprivation, which can lead to stress and anxiety which in turn may harm the social constructs within the households and communities (Nanama and Frongillo, 2012). The access to a local production of fresh food may counteract these problems, not only by the production of the fresh food itself, but also the benefits of sustaining such a production system.

In conclusion, the investigation of the impact of hydroponics in refugee camps in Mena has demonstrated that working with plants can be therapeutic, relaxing and have a positive effect on mental health since it provides a social activity and a distraction from the current situation, as well as a sense of responsibility and nurturing (Verner et al., 2017). Therefore, MEPA may not only have a great impact on people's livelihoods, but also, MEPA may additionally affect the social capital and cohesion within households and communities.

3.1 MEPA design

The intention of the MEPA is a semi-automatic NFT and aeroponic hybrid system that can be fitted into a small and compact transport box for easy transportation. MEPA is still in its developmental phase and the design is yet to be finalized. However, the future MEPA will be a conjoint result of four different designs (Figure 7). Currently, MEPA consists of the Automated Support Unit (ASU) (figure 8), an inflatable freshwater tank, and two Seed Cultivation Mats (SCM) sitting on top of a portable table construction. The table construction allows the adjustment of the angle required for the NFT system to work properly on uneven terrain. The table construction is intended to be lowered and fitted with an inflatable tent to provide a CEA system protecting the crops from the external environment and abiotic stress.

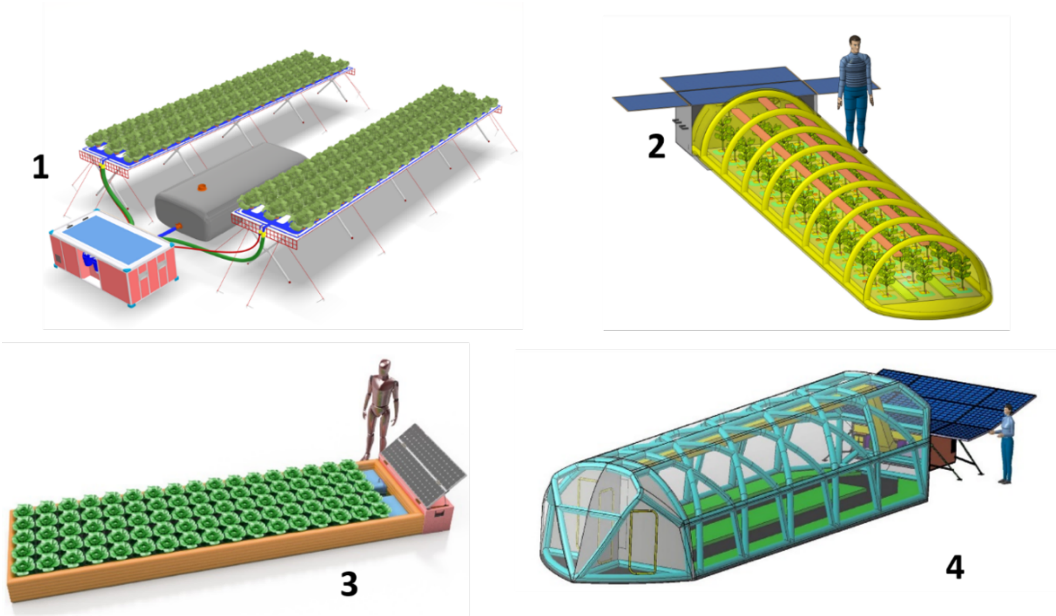

Figure 7 Various designs of MEPA. 1. the most current work in progress with an inflatable external water tank and the SCM sitting on top of a portable table construction .2. Enclosed MEPA structure with led lights (DLR). 3 Inflatable Deep-water culture version (Lipps 2020) 4. Larger walk-in enclosed MEPA structure (Cekosuv 2018)

The ASU will contain the CEA subsystems, some of which are derived and adapted from the subsystems on EDEN ISS. While the Nutrient Delivery subsystem is currently under development, there is a plan to include an Atmosphere Management System, Command and Data Handling, Power and Distribution Unit, and Plant Health Monitoring in the ASU. All of which will be a part of future research projects.

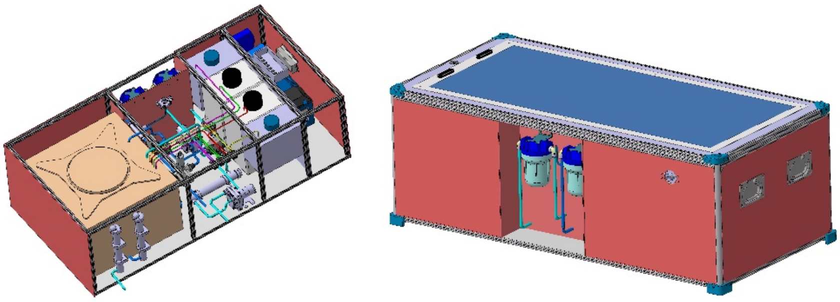

Figure 8 internal and external view of the ASU (DLR)

Nutrient Delivery System (NDS)

The NDS consists of a nutrient mixing unit and an irrigation element that is combined by the NDS. The nutrient mixing process changes continuously throughout the plant's life cycle to meet the needs of the different growth stages. A highly concentrated stock solution and pH adjustment fluids are added to a bulk solution tank via micro pumps. The nutrient solutions can be modified with respect to nutritional compositions, EC, DO, temperature, and pH if needed, and are continuously monitored via sensors. The nutrient solutions are then supplied to the SCM according to a preferred interval, and then runs back into the bulk tank. Similar to EDEN ISS, the NDS need to be controlled for pathogens. The NDS in EDEN ISS have an integrated ozone generator in the bulk solution tank. This integration may also be implemented in the NDS in MEPA.

Seed Cultivation Mat (SCM)

The SCM is the rollable mat containing the growth channels of the NFT system. The SCM is made from a flexible and foldable material with rockwool fitted plant holders. The future aim is to remove the growth substrate and the plant holders all together, to create a hybrid between NFT and aeroponics. Aside from requiring a flexible and resistant material to easily be folded or rolled, the SCM also needs to be safe, have low oxygen permeability, as well as certain barriers that inhibits the growth of microorganisms and algae. These requirements are similar to those of food packaging and the construction of the SCM is thereby similar to bag-in-box bladders. The mat is a multilayer triplex laminate consisting of

Polyethylenterephthalat (PET), Aluminium and linear low-density polyethylene (LLDPE) (figure 9).

- Aluminium provides with barrier against oxygen, moisture, and light. It also provides tensile strength and due to its opaque and glossy surface, aluminium allows for heat reflection, making temperature control inside the mat more manageable (Lamberti & Escher 2007).

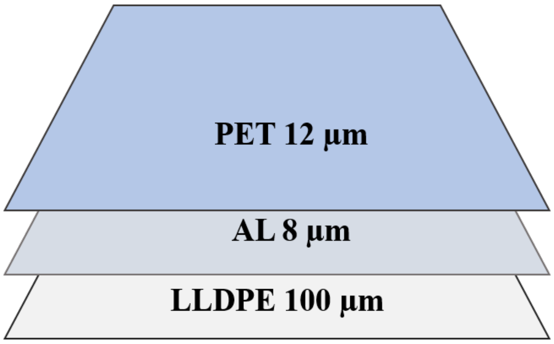

Figure 9 SCM triplex composition

- LLDPE is somewhat UV resistant and has a good water vapor barrier, but is mostly used for its flexibility, puncture resistance and tensile strength (La Mantia 2006).
- PET provides a moisture barrier as well as a good barrier to oxygen (6–8 nmol/ms GPa), dielectric strength, some UV resistance and some resistance to weak acids and bases (Vasile et al., 2017 Ebnesajjad 2013, Dixon 2011).

These properties help to keep the SCM resistant against wear and tear as well as preventing algae and other microorganisms to grow inside the cultivation mat. The different irrigation channels are laminated into the SCM and the mechanism for water distribution is relatively simple. First a pump in the ASU pulses the nutrient solution into the inlet which then flows into the water bladder. Filling the water bladder slightly lifts the mat for an increased angle. The water flow to the individual plant growth channels are then controlled by the width of the inlet to the channel, similar to a bottle neck between the water bladder and the growth channel. This will not only help control the water flow, but also create a pulse irrigation, allowing the roots to breathe.

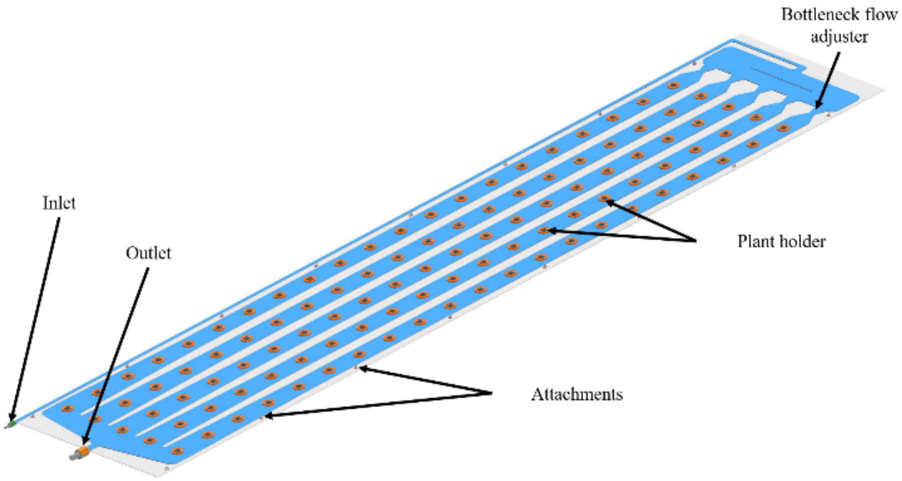

Figure 10 CAD illustration of SCM (Volling 2019)

The plant holders (figure 11) work as structural support for the plants and are placed in regular intervals dependent on plant preference. The rockwool cube that is fitted for the holder is coated in hydrophobic wax on the top, to provide a sufficient seal and minimize the growth of microorganisms. The root zone is only 2 cm. It is therefore important to optimize nutrient uptake and root efficiency so that the roots will not overgrow searching for more nutrients. Currently the plant holders are a similar construction to those of the aeroponic system in EDEN ISS. However, to improve the SCM rollability and compactness, the holders will need to undergo further development. The aim is to reduce the size of the holders to the point where they are small enough, but can support at plant structure, preferably made from a viscoelastic material that could withstand polymer degradation and provide a barrier between the internal and external environment. An additional requirement is that the plugs should be easily replaceable in case of wear. Another potential design of the plant holders is to include them in the SCM foil, thereby limiting the required material, improving rollability and potentially the durability.

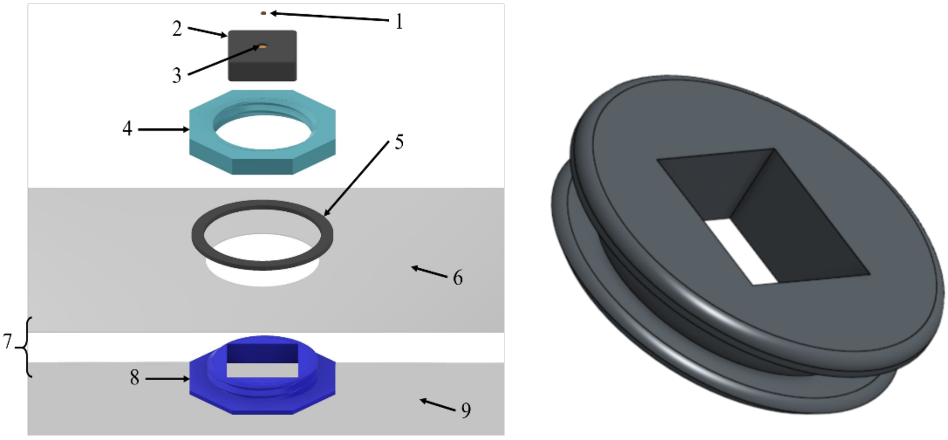

Figure 11 Left: Plant holder deign in CAD (Volling 2019) 1. Plant seed, no need for plant nursery, the seeds can be planted directly into the rockwool cube. 2 Wax coated rockwool cube. 3 seed hole. 4 Top screw of plant holder. 5 Sealing ring to ensure sufficient seal. 6 Top sheet of the SCM. 7 Root zone or Plant growth channel in the void between the SCM sheets. 8 Plant holder base, fitted for rockwool cube. 9 Bottom sheet of the SCM. Right: CAD design of possible new plant holder.

MEPA will be fitted into two transport boxes adapted for 20ft or 40ft shipping containers. The size of the box is yet to be determined; however, the ASU is 165 cm x 85 cm x 56 cm, and the second box containing the SCM, the tent and the table construction will roughly be the same size. Therefore, based on these measurements, a 20ft container may hold up to 40 transport boxes, or 20 full MEPA units and a 40ft container may hold up to 80 transport boxes, or 40 full MEPA units. This means that a growing area of 480 to 960 m^2 may be delivered per shipping container.

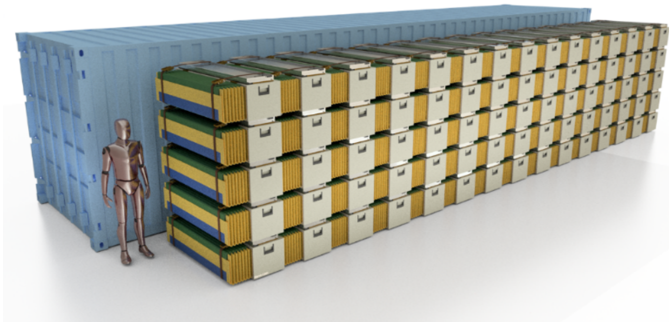

Figure 12 Illustration of MEPA units beside a container. According to calculations 40 units will fit in a 40-foot container (Lipps 2020)

Upon deployment, a solar panel attached on top the ASU will provide MEPA with electricity. The SCM (figure 10) will be unfolded and attached to the ASU. Similar to the EDEN ISS, the aim is to make MEPA almost fully automatic, with minimal need for human interference. These properties allow for the cultivation fresh food regardless of location, available resources, or prior knowledge about food production. Subsequently making the MEPA ideal to use in climactic inhospitable regions, relief for areas of natural disaster or other humanitarian crisis scenarios.

3.2 Crop selection

The criteria for crop selection on MEPA share some similarities to the crop selection of early space mission scenarios described by Schubert 2018. Aside from providing positive olfactory stimulation, the crops need to go through some selection criteria. The events where MEPA need to be applied most presumably demand a more rapid food production with ready to eat crops. During these situations, post processing equipment and the required skillset to run them should not be expected. Therefore, crops should require little to no post-harvest processing such as drying, milling, freezing, or baking. Furthermore, during the primary deployment of MEPA, functioning cooking equipment should not be taken for granted, limiting crop choice to food that may be consumed raw. An additional requirement is the demand of input in relation to output. The crop should preferably not require a higher amount of inputs than the output that it yields. This is also synonymous with the harvest index of the crop and the edible biomass that it produces. It is for instance preferable if the energy and nutrients going into the system is not wasted on roots, inedible leaves, or lignified stems. All though in a closed loop system, the crops should still have a tolerance to environmental fluctuations in the atmosphere or light compositions. If the crops are more resilient, they are also more likely to grow well together with other crops in the same system or prone to less damage during an eventual system failure. Moreover, certain crops produce root extrudates into the rhizosphere as a way communication or a response to competition. Having toxic root extrudates in the circulating nutrient solution could be detrimental. Crops with this property should therefore be avoided. The complexity of the plant treatment is another important factor. The intention is that MEPA should be operated by anyone regardless of previous skills about plant cultivation. Therefore, crops should require little work attendance, meaning that pruning, thinning, propagation and potential training should be relatively simple, or that the crop should not require artificial pollination. Additionally, certain perennial crops have different phases, such as dormant phases that requires different resources. Adapting to these requirements or spending inputs on dormant plants is not feasible in the situations where MEPA is applied, at least not for the primary deployment of the unit. Likewise, the crop selection may vary dependent on the deployment stage of MEPA. For instance, as illustrated in figure 13, some crops have a long lag phase or log phase, but provide a higher yield, whereas other crops may have a faster growth rate and allow for an early and in some cases, a continuous harvest.

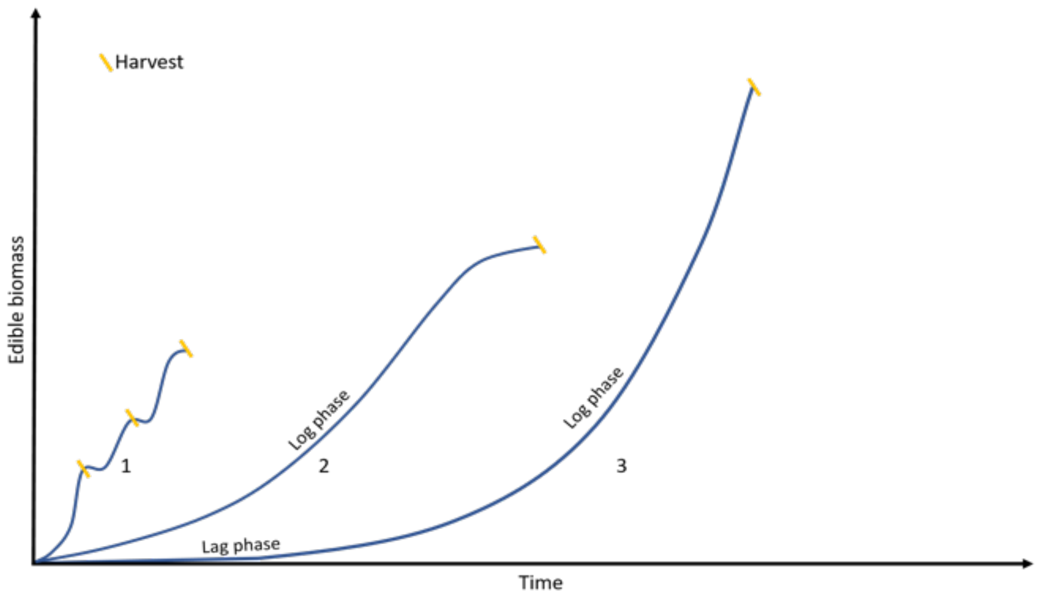

Figure 13 Illustration of plant growth over time for different type of plants. 1 is more fast growing and allows for continuous harvest but yields less over time. 2 has a longer growth time but yields higher more over time. 3 grow slowly over time but has a much higher yield

Upon the first deployment of MEPA, the crop selection of the initial phase should therefore consist of fast-growing crops which allows for a quicker build-up of an initial food supply. However, over time a combination of fast and slower growing crops would be ideal to diversify the crop selection, and to maximize biomass production. Additionally, with a succession planting method a continuous harvest can be achieved, which would allow for a constant food supply.

Most importantly, the crops should be nutritionally adequate. This means that the selection of crops grown on MEPA should be able to fulfil all the recommended daily intakes of primarily micronutrients. In certain situations, the crops should also produce enough of certain nutrients to undertake common micronutrient deficiencies. These deficiencies may vary dependent on where the MEPA is being deployed, and for optimization purposes, crops could be selected thereafter. However, in many of the areas where emergency food aid is needed, iron, vitamin A, iodine and zinc deficiencies are the most predominant followed by thiamine, niacin, and vitamin C deficiencies (UNHCR, & WFP, 2011). Choosing crops according to their nutrient content may not always be perspicuous. Bioavailability and antinutrients need to be accounted for, and crops can be selected based on several nutritional quality indicators emanating from different nutritional traits.

4. SCM growth test and potential nutrient output of MEPA

4.1 Method

4.1.1 SCM growth test and experimental set up

For the initial test phase of the SCM, three SCM mats were constructed, one 120 x 450 with plant density of 18 plants per m2, and two 60 x 200 with a plant density of 16 plants per m2. Five nutritionally different plants were chosen for the growth test. Two lettuces of different micronutrient character, three pole beans of different color and one bush bean as protein producing crops, and one succulent were selected for its fatty acid content (table 2).

Table 2 Plant selection SCM growth test

Crop name	Cultivar
Lettuce	Lactuca Sativa Expertise RZ
Bush Bean	Phaseolus vulgaris
Pole Bean	Phaseolus vulgaris
Purslane	Portulaca Oleracea var. sativa
Radicchio	Cichorium intybus var. foliosum

The seeds were sown in cheese waxed coated rockwool cubes of 3.5 x 3.5 x 2 cm. The Expertise lettuce was sown directly in the larger seed mat whereas the remaining seeds were first sown in a nursery tray for 12 days. During the initial germination phase, small amounts of diluted nutrient solution was added to the nursery tray to keep the rock wool cubes moist. Similarly, for the larger seed mat, the irrigation pump was activated for 4 minutes for every 3 hours. The pH, EC, rH, VDP, temperature, water level and plant development according to BBcH growth stages were monitored daily.

The nutrient solution was mixed according to table 3. To avoid the formation of poorly soluble salts, in particular calcium sulphates, calcium phosphates and iron (II) sulphates, the plant nutrients were divided into two solutions: Solution A and solution B. Acid and base are added accordingly to adjust the pH, in a range from 5.2 to 6.5.

Table 3 Composition for 100l of nutrient solution used in the MEPA system. Solution A and Solution B are mixed separately to later be incorporated in a bulk nutrient solution tank. Acid and base are added accordingly to reach required pH, from 5.2 to 6.5

Compound	**Stock solution** g/l	**Solution A** ml of stock solution	**Solution B** ml of stock solution	**Acid** %	**Base** %
$Ca(NO_3)_2 4H_2O$	236.14	200			
Ferric DTPA	16.44	50			
$MgSO_4$ 7H2O	246.47		100		
NH_4HPO_4	115.02		50		
KNO_3	101.1		300		
HNO_3	50			25	
KOH	50				25
Micronutrients			100		
H_3BO_3	1.43				
$MnCl_2$-4H2O	0.91				
$ZnSO_4$-7H2O	0.11				
$CuSO_4$-5H_2O	0.04				
H2MoO_4	0.01				

The initial photoperiod during germination started at 06.00 and ended at 18.00 with full light intensity from 07.00 to 17.00 and approximately half of the full light intensity during the first and last hour to simulate sunrise and sunset. The light intensity varied between 110 and 160 µmol/(m^2*s) on the SCM and consisted of red 450nm, blue 650nm and far red 730 with a temperature at 5700K. When the plants reached BBcH 13, after 12 days, the EC was increased to 1.8 and the full light intensity photoperiod was extended to from 17.00 to 22.00. The atmosphere management system in the closed loop test facility was under construction, and the atmosphere settings could thereby not be controlled. However, rH, VPD and temperature was continuously monitored.

4.1.2 Nutritional calculations

As MEPA is still in the AIT phase, the previous growth test does not provide reliable biomass output data. Considering that MEPA is derived from EDEN ISS, growth data from the EDEN ISS experimental phases was used to estimate the output of each MEPA unit (Table 4). Biomass yield data for Swiss chard, arugula, romaine lettuce and frisée lettuce was used from the EDEN ISS 2018 experimental phase (Zabel et al,.2020). Biomass yield data for green kale and Bok Choi was taken from the EDEN ISS 2019 experiment phase. Worth taking into consideration is that the plant handling and data collection from 2018 were collected by a research team from DLR, whereas during 2019 these tasks were handled by staff at the NM-III. Due to the inexperience with CEA and other primary tasks, the 2019 experimental phase had longer crop cycles and lower yields.

Table 4 Edible biomass output data from EDEN ISS 2018 experimental phase in kg/m²/d (Zabel et al., 2020) converted to kg per MEPA unit every 30 days.

Vegetable	$kg/m^2/d$	Kg/MEPA/30 days
Swiss Chard	0.102	73.4
Arugula	0.188	135.3
Bok Choi	0.0549	39.5
Romaine	0.058	41.8
Green Kale	0.043	31.0
Waldmann's Green	0.043	31.0
Frisée Lettuce	0.058	41.8

The biomass output in the 2018 experimental phase was reported to be significantly higher in comparison to the same varieties grown in similar systems (Zabel et al,.2020). The aim is that MEPA will achieve similar results, therefore being able to produce 1 000 to 3 000 kg of edible biomass per shipping container per month dependent on crop choice. However, considering that the primary function of MEPA is micronutrient production, the biomass output was converted to micronutrient output in regard to Daily Recommended Intake (DRI). Additionally, estimates were made of the number of people adequately nourished by each MEPA unit, according to the DRI. The reference values for the DRI were adapted from guidelines on food and nutritional needs in emergencies provided by four UN agencies (UNHCR, UNICEF, WFP and WHO, 2002) as well as the Nordic nutrient recommendations (NNR 2012) and European Food Safety Authority (EFSA) (table 5). Nutritional data about each vegetable was retrieved from the Swedish Food Agency (SVL 2022).

Table 5 Daily recommended intake of 12 nutrients as well as dietary fiber and energy. The first 9 nutrients (Thiamine to Vitamin D) and their DRI including daily energy needs, are vitamins and minerals for a population needing emergency food aid, adapted from a collective report by UNHCR, UNICEF, WFP and WHO. Vitamin K (European Food Safety Authority 2022), vitamin E, Zinc, B6, Magnesium and dietary fiber (NNR 2012)

Nutrient	Daily recommended intake (DRI)	Reference
Thiamine (B1)	0.9 mg	UNHCR, UNICEF, WFP & WHO Vitamins and minerals for a population needing emergency food aid
Riboflavin (B2)	1.4 mg	
Niacin equivalents	12 NE/mg	
Folic Acid (B9)	160 µg	
Iron	6.5 mg	
Iodine	150 µg	
Vitamin A (retinol equivalents)	500 RE/µg	
Vitamin C	28 µg	
Vitamin D	3.8 µg	
Vitamin K	70 µg	European Food Safety Authority 2022
Vitamin E	5.5 µg	NNR 2012
Zinc	5.5 µg	
Vitamin B6	1.15 mg	
Magnesium	315 µg	
Dietary fiber	25 g	
Energy	2100 (kcal)	UNHCR, UNICEF, WFP & WHO 2009

The nutritional quality of the seven individual vegetables was calculated in terms of Nutrient Adequacy Score (NAS) and Nutrient Density. The nutrient adequacy score is the Mean percentage of DRI for key nutrients, as provided for 100g of food (Darmon et al,. 2005). This was calculated by first summarizing the fractions of DRI of each nutrient (i) per 100g of edible biomass for a particular food (j). The sum of fractions was then divided by the number of nutrients.

$$NAS = \frac{\left(\sum_{n100g}^{1000g}\left(\frac{Nutrient_i \;/\; ng_j}{DRI_i}\right)\right)}{nr\ of\ nutrients} \times 100$$

Additionally, considering that some crops may have an abundance of a certain nutrient, a logical test was made, and the nutrient fractions were capped at 1, indicating 100% nutrient adequacy. Thereby additionally providing information about the nutrient diversity in the selected foods. There are several calculation methods for nutrient density (ND). The nutrient density score used in this paper indicates the mean percentage of DRI fulfilled per 100 kcal. The ND was calculated by dividing the NAS with the energy density.

$$ND = \frac{NAS}{energy\ density} \times 100$$

Thereafter, crop combinations with respect to nutrient adequacy, nutrient density, nutrient diversity and yield were then compared by calculating the total Nutritional Yield (NY) to theoretically maximize the micronutrient production. Nutritional yield is an indication of the number of adults who would be able to obtain 100% of the dietary reference intake (DRI) of selected nutrients from food produced annually per hectare. NY is used to compare the nutritional output between crops and may translate yield to a more usable functional unit. NY is calculated by multiplying the fraction of DRI for each nutrient with yield and a conversion factor dependent on yield format.

$$NY_{ij} = \frac{Nutrient_i \ / \ 100g_j}{DRI_i} \times \frac{tonnes}{ha/year} \times \frac{10^4}{365}$$

Additionally, to calculate the adequacy of the nutrients produced by the MEPA system, the Potential Nutrient Adequacy for each crop selection was calculated. PNA is an indication of how many people will reach their DRI of the 14 nutrients from the selected production system.

$$PNA = \frac{\sum_{i=1}^{N}[NY_i > 1]}{N} \times \overline{NY}$$

To calculate PNA, a logical test for the NY values were performed so that each value below 1 would equal 0. Additionally, nutrients in overabundance were removed from the equation no get a more accurate reading on the data. The sum of the NY for each nutrient above 1, was divided by the number of nutrients (N) and multiplied with the average of potentially nourished people for all nutrients ($\overline{NY}$).

5. Results

5.1 SCM growth test and experimental set up

The total consumption of water over 41 days was 87 liters (table 6). However, there were leakages during the experiment, and this may therefore show a higher number of what is true. Similarly, the acid container was leaking from the NDS and may therefore show an untrue figure. The gap in figure 14 and 15 was due to a system failure during a power outage lasting for 14 hours.

Table 6 Total consumption of inputs over 41 days

Water	Solution A	Solution B	Acid	Base
l	ml	ml	ml	ml
87	613	613	1429	12

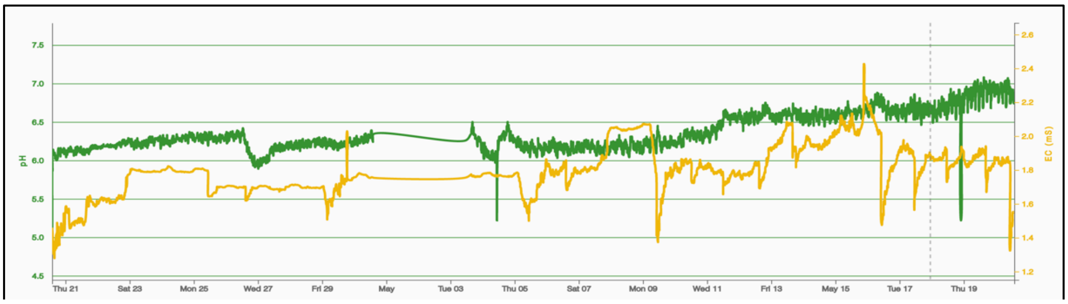

Figure 14 pH and EC over the full timeframe of the experiment measured every 15 minutes

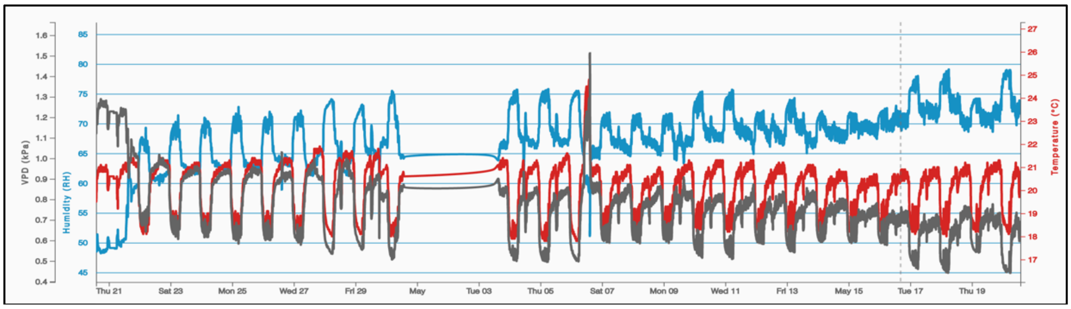

Figure 15 VPD, temperature and humidity over the full timeframe of the experiment, measured every 15 minutes

As expected, the water consumption increased exponentially with the development of plant phases (figure 16). The expertise reached harvest size after 40 days.

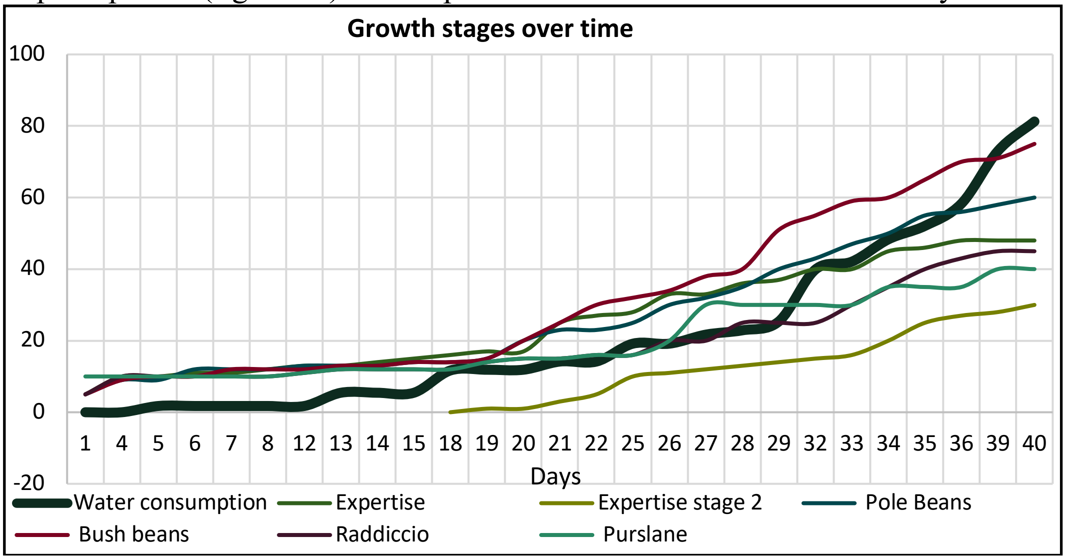

Figure 16 Growth stages over 40 days according to the BBcH scale. Water conssumption (thick line) meassured in liters over 40 days

Expertise lettuce varied in size most likely due to individuality. The pH meter was uncalibrated for the first 8 days, adjusting the pH in the nutrient solution to 4.1, resulting in slow growth and some chlorosis in the expertise. However, the plants quickly recovered after correcting the pH error (figure 17).

Figure 17 Expertise lettuce, 40 days (left) 12 days with clorosis 3rd true leaf (right)

Figure 18 Larger SCM with expertise lettuce

Moreover, the inlet to the individual channels on the SCM occasionally closed due to vacuum, consequently leading to uneven water distribution amongst the channels.

Purslane experienced no issues and reached 25cm in 41 days (figure 19). The Radicchio started bolting after 30 days, which could have been induced by vernalization at an earlier stage. This could explain the delayed head formation (figure 20)

Figure 19 Left: Purslane on the SCM. After transplantation, right: after 40 days of growth

Figure 20 Raddiccio on the SCM

The bush beans flowered and developed fruit earlier than the pole beans (figure 16). While the pole beans just started to indicate budding, the bush beans had already developed fruit.

Figure 21 Left: Bush bean on the left, pole bean on the right, intertwined on the SCM. Radicchio in the corner. Right: Bush beans 10 to 15 cm

The SCM was cut open (figure 22) No plant residues or signs of microbial growth was seen.

Figure 22 Exposed growth channels of SCM. No plant residues or indication of growth of microorganisms.

5.2 Nutritional calculations

Arugula and green kale score highest NAS overall (figure 24). Moreover, Bok choi has a higher nutrient content per 100g in comparison to swiss chard, but less micronutrient diversity which is indicated by the decreasing rate of the NAS of bok choi. Additionally, a clear negative correlation between nutrient density and nutrient adequacy can be seen (figure 23, 24).

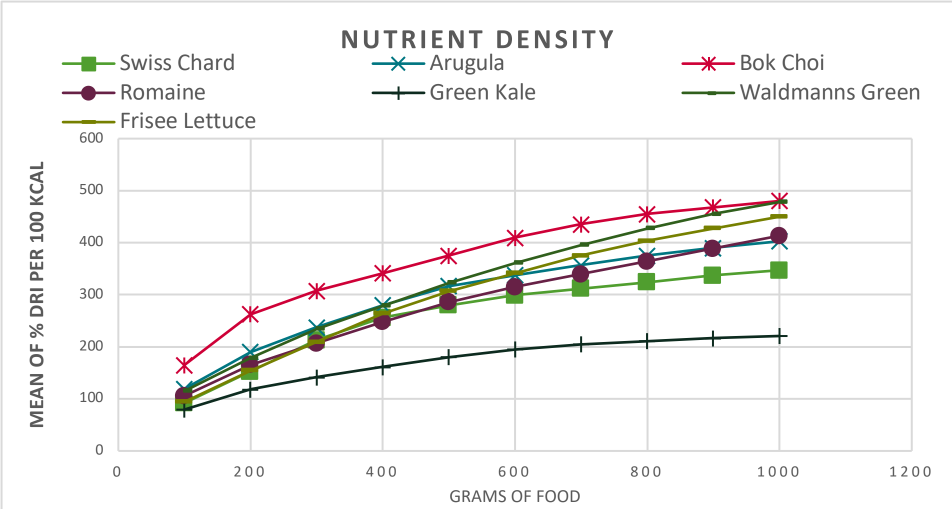

Figure 23 Nutrient density of selected vegetables per 100 grams

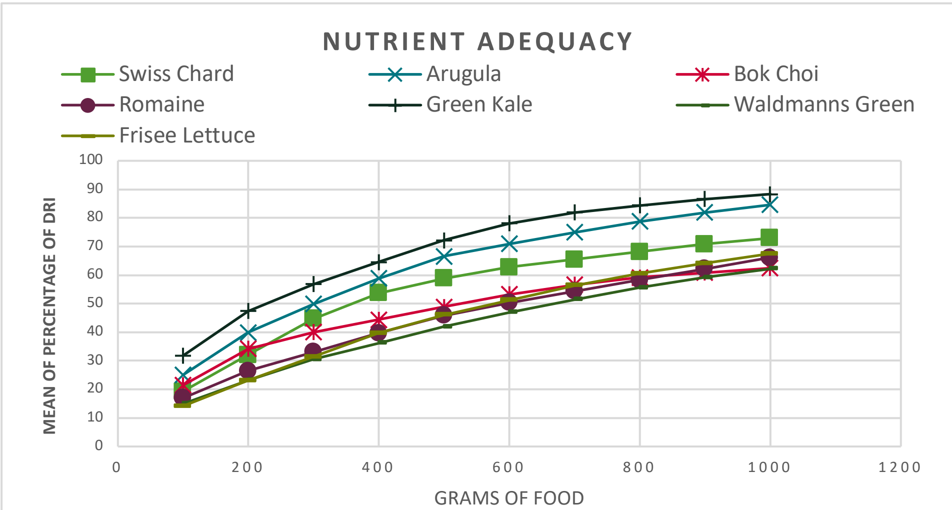

Figure 24 Nutrient adequacy of selected vegetables per 100 grams

Crop selections with regards to yield, nutrient density, nutrient adequacy, or nutrient diversity with respect to adequacy are displayed in (table 7). Each SCM has five plant growth channels, and the MEPA unit may therefore be divided into fifths per SCM or in tenths considering that one unit consist of two SCM.

Table 7 Crop selections with regards to four different nutritional quality indicators

Crop quality indicator	Composition	Potential edible biomass production per MEPA unit kg /30 days
Adequacy	20 % Arugula 40 % Green Kale 40 % bok choi	55
Density	40 % bok choi 30 % romaine 30 % frisee	41

Yield	20 % Arugula 40 % Swiss chard 40 % Romaine	73
Diversity	40 % Swiss chard 40 % Green kale 20 % Arugula	68

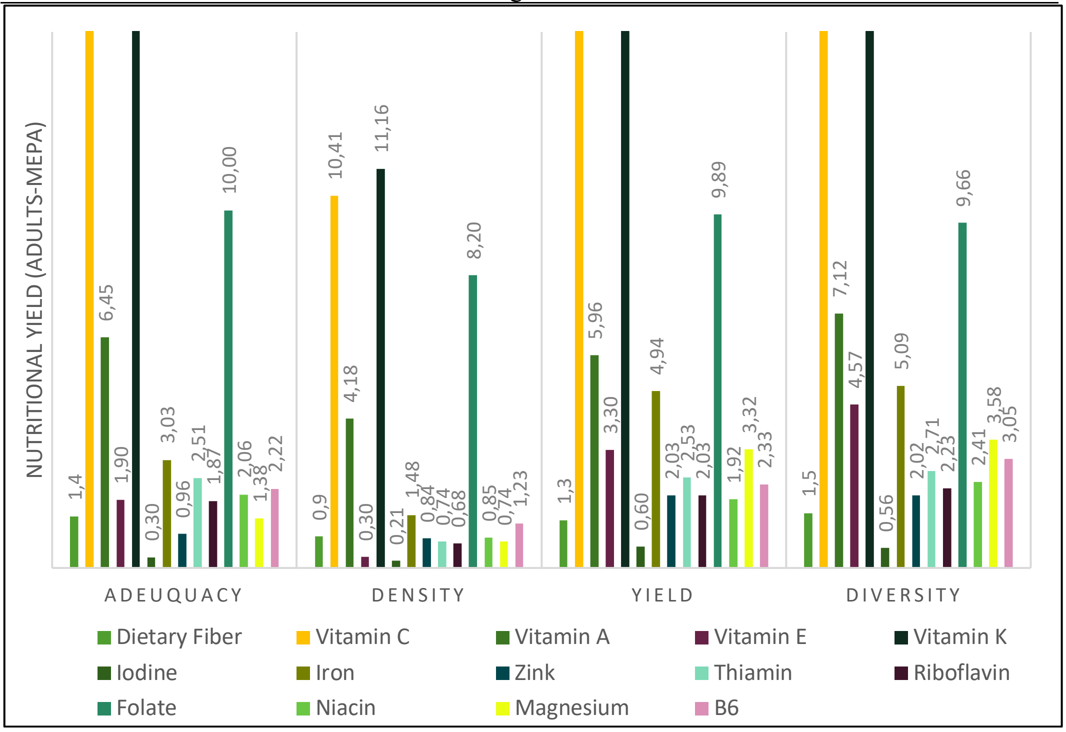

Figure 25 Nutritional Yield of different crop combinations in one MEPA system. Adequacy focus 20% Arugula, 40% Green Kale and 40% bok choi. Density focus 40% bok choi, 30% romaine and 30 % frisee. Yield focus 20% Arugula, 40% Swiss chard and 40% Romaine, Diversity 40% Swiss chard, 40% Green kale 20 % Arugula

As seen in figure 25 and 26, selecting lettuce according to nutrient density resulted in a lower nutritional yield and potential nutritional adequacy. Additionally, as predicted from the type of crops investigated, Vitamin C, Vitamin K and Folate are the most abundant nutrients for each crop combination whereas Vitamin D is absent. An additional observation is that a significant amount of vitamin A can be produced in each crop selection category whereas a substantial iodine supply is lacking in each category.

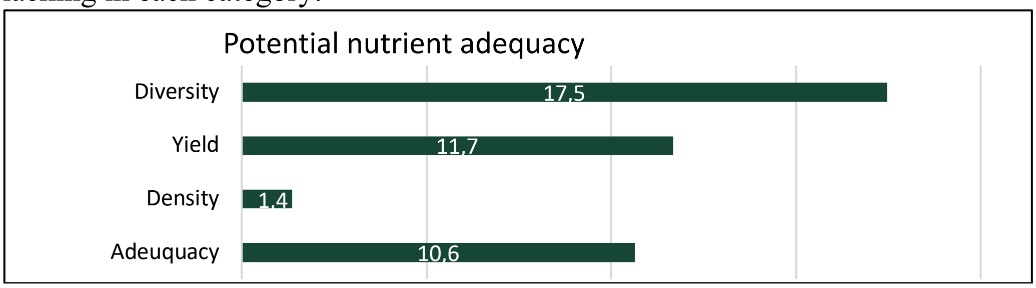

Figure 26 Number of people adequately nourished per MEPA system for each crop choice.

6. Discussion

6.1 SCM growth test

Due to issues such as instrument calibrations and low fertigation intensity, the plant growth in the study's investigation was slower than expected. An increasement of the fertigation rate may give a different result. The aim of the SCM growth test was to test the function of the SCM, the possibility to germinate the seeds directly in the SCM, and to test a variety of plants. Due to the limited time frame of this thesis, the final biomass output could not be included. Even though a nursery is more efficient, an exclusion of the nursery and germination of seeds directly in the SCM was no issue. Instead, to eliminate the nursery step saved time, material, and space as well as the possibility to avoid plant injuries when the plants transferred to the SCM. Additionally, to plant seeds directly into the SCM supports the simplicity that MEPA aims for.

Other than the vernalization of the radicchio, there were no issues regarding the selection of crops. On the contrary, a significant result was that of the possibility to grow beans on the SCM. The ability to grow larger, climbing vegetables, produced an opportunity to grow a wider variety of crops, which may allow for future production of macronutrients, such as proteins and fatty acids. Moreover, the possibility for a larger crop variety may introduce new opportunities for alternative SCM designs, for plants that e.g., demand more root space, or less crop density.

The plant holders were another critical part in the study that may need to undergo further development. First, the plant holders need to be durable since spare parts may not always be available. The plant holders will also need to be more space efficient to increase the compactness and rollability of the SCM. An additional requirement would be to test plant holder designs that can support the germination of a seed and plant growth without the utilization of growth media. Furthermore, the removement of the growth media may also simplify the system further and decrease the number of required materials. An additional consideration that occurred in the study, is if plant holder requirements could be met by redesigning the SCM, and thus, make the sheet material itself support the plant without any additional plant holders.

The SCM in the study looked clean, but it would be of interest to analyze the microbial activity inside of the SCM after repeated use. Also, the SCM microbiome may provide valuable information about the health and status of the system as well as the potential growth of pathogenic or beneficial microorganisms. In fact, beneficial microorganisms that promote plant growth have received limited attention in hydroponics. Further studies of the implementation of these beneficial microorganisms in considerations to nutrient solutions may provide valuable tools that could improve the efficiency of the growth system.

To further improve the efficiency of the system, side streams such as plant roots should be utilized as a resource rather than waste. Future projects of using plant roots and other inedible plant parts as substrates for insect farming or the cultivation of mushrooms could be implemented in MEPA. The addition of mushrooms and potentially insects could provide additional nutrients that are lacking in plants.

6.2 Nutritional Output

The potential number of people who are adequately nourished by the MEPA system largely depend on crop choice. As seen in figure 26 the potential micronutrient adequacy varies in between crop selection varieties. However, considering that each MEPA unit can sustain approximately 5 to 6 people in terms of biomass production, the MEPA has the potential to produce an abundance of micronutrients. As seen in figure 26, when the removement of Vitamin K, Vitamin C and folate which are all produced in overabundance, as well as each nutrient with an NY value of less than 1, sufficient micronutrients for up to 17 people can potentially be produced with the current selection of crops per MEPA unit. This means that one 20ft shipping container have the capability to produce fresh food for approximately 100 people, with a micronutrient content adequate for up to 350 people.

In addition to biomass production, the use different nutritional indicators in the selection of crops are important, as they will vary in both nutritional outcome and crop suitability. There are a wide variety of nutritional indicators, most of which focus on different types of food. However, to combine nutritional indicators with agricultural output has become increasingly popular as a novel metric to yield.

In terms of micronutrients, the terms *nutrient density* and *nutritional adequacy* are widely used when it comes to dietary recommendations, even though they are inversed. Another variable that needs to be taken into consideration, when crops are selected according to their NAS, is in fact, the daily portion size. For instance, if a more nutrient diverse mixture of crops is desired, bok choi can be exchanged for swiss chard. Similarly, even though arugula is both nutritiously adequate and dense, the portion size is significantly lower in comparison to the other crops. Another observation is that the nutrient adequacy and nutrient density are in this case negatively correlated. This is also shown in figure 25 and 26, where the nutritional yield is lower when selecting crops according to nutrient density alone. The figures indicate that it may be misleading, to compare lettuce by nutrient density since lettuce is energy dilute. Therefore, due to the low caloric content, lettuces are more likely to achieve higher density scores regardless of micronutrient content. Nevertheless, nutrient density may still provide a valid method when in the comparison of other types of food, especially when potential antinutrient contents of certain foods need to be considered. The calculation method of nutrient density with regard to antinutrients divides the sum of the nutrients per 100g with the DRI and subtracts the sum of antinutrients per 100g divided with the maximum daily intake for each antinutrient. However, since the lettuces that are used in this study have insignificant amounts of antinutrients, the density score would be similar to that of nutrient adequacy.

In conclusion, the potential micronutrient output will most likely vary dependent on what crops are compared. In addition, the nutritional values of the individual crops may also differ in between varieties and on how they are grown.

The values for nutritional composition used in this paper were standard values retrieved from the Swedish Food Agency's nutritional database (Livsmedelsverket, 2022) and may not necessarily be equated with the same crop grown in a CEA greenhouse. Moreover, the calculations in the study have not taken bioavailability and the function of potential chelating agents into consideration. Neither has the impact of the different food matrix on micronutrient properties been acknowledged. For this reason, the NY for iron should be significantly lower than what is displayed in figure 25. However, the bioavailability could be included in future calculations.

This method of calculating the nutritional yield and potential nutritional adequacy regarding certain nutritional qualities, provides an overview of the growth system to see if sufficient micronutrients are being produced by the system. The method also indicates precisely what nutrients will be produced and in what quantity which can be used to tailor crop varieties to certain situations. For instance, individual case studies of the regions where the MEPA are currently used may provide more information about the nutritional needs, physiology and eating habits of the targeted populations. As such, with the method described above, tailored crop selections can be made in accordance with the needs of the population that the MEPA provides for. Furthermore, future inclusions of macronutrient-producing crops that grow well within the boundaries of the MEPA system may also provide insightful comparisons. For instance, it is imperative to find a selection of crops that can produce adequate amounts of protein and essential fatty acids so that the need for dietary supplements can be significantly reduced or disappear completely.

Moreover, the calculations in this study, the yield format is expressed as the rate of growth ($g \times m^{-2} \times day^{-1}$), assuming constant plant growth. While this format is necessary to calculate nutritional yield, it does not take the growth stages of the plant and time to harvest into consideration. These factors are essential to determine suitable crop choices, particularly for the initial deployment of MEPA.

However, even though the calculations above may fill a gap in crop choice methods for both space and terrestrial greenhouse systems, human psychology is the determining factor. In fact, the primary reason for why in situ production of fresh food is important, is the effect food has on the human psychology. Food needs to be eatable and preferably appetizing in order to fill its primary function, i.e to be consumed into the human body. Therefore, dietary, and olfactory diversity is paramount to the development of greenhouse systems on both earth and in space if they will ever succeed.

7. Conclusion and outlook

The calculations in this paper, have predicted that a 20ft container of MEPA units has the potential to feed up to 100 people and thus produce adequate micronutrients for up to 350 people every month. Moreover, the use of additional metrics to biomass production such as nutritional yield may provide further insight to the nutrients that are being produced, which in turn allows for tailored crop choices in individual scenarios. Therefore, the use of correct nutritional indicators for respective crop, and calculating the potential nutritional yield, fills a gap in current crop choice methods.

The forthcoming phase of MEPA will be the integration of the SCM and ASU, creating a pilot assembled construction of MEPA. With this pilot assembly, the final growth system will be tested outdoors, whilst developing and integrating the remaining subsystems.

While there are still improvements that can be made on the SCM, there are no issues regarding plant growth. On the contrary, the growth system requires little supervision and is almost completely autonomous, and therefore, this study supports the idea that MEPA does not require any previous experience in hydroponics. Moreover, the study indicates that a variety of nutritionally diverse crops should be grown on the SCM, to further determine the potential nutritional output of MEPA, as well as implementation of potential macronutrient producing crops.

The improvement of life on earth calls for innovative ideas and the interdisciplinary platform of space research has proven to provide such creative solutions. It is imperative that researchers continue to develop food production systems for space that can solve the issue and maintenance of continuous food supply while minimizing external resources. In turn, the space research field can be a fruitful knowledge base of sustainable terrestrial development that can help regions in need to avoid food insecurity.

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Popular science summary

Space research is a catalyst for innovation and has for decades provided many tools for the improvement of life on earth. The situation is no different when food production will become a future requirement for long-term space missions. The German Aerospace Centre (DLR) has undertaken the task of developing EDEN ISS, a Controlled Environment Agriculture (CEA) greenhouse module for space applications. CEA greenhouses allows for complete control over the environment in the greenhouse and are for that reason not dependent on the external environment. CEA becomes a requirement for space since technologies and modules developed for space, like EDEN ISS, do not only need to function in the most extreme environments, but they must also be reliable, durable, easy to use and have very light weight. For this reason, the outcome of the EDEN ISS project is not solely applicable to space. The technology from EDEN ISS provides a great tool to combat food insecurity which is already an urgent global threat, in part due to political instabilities and the climate changes that we already face.

According to estimates from the United Nations' World Food Program (WFP), 811 million people do not have sufficient access to food. Many of these people live in areas where crop failures are not unusual. Some of the reasons may be due to environmental conditions, pests, lack of knowledge, or lack of fertilizers. The situation can also worsen quickly in the event of natural disasters such as hurricanes, cyclones, droughts, floods, and earthquakes. The delivery of food assistance to affected communities is critical. But to add further complications, due to the poor infrastructure and sometimes even political instability, the logistics of food aid delivery can be challenging. Another challenge is to provide a variety of palatable food with enough nutrients to end malnutrition. For all these reasons, food aid programs are in the need of new and innovative solutions that may aid in the provision of fresh food for humanitarian assistance.

As a result, the development of EDEN ISS has in turn led to a spinoff collaboration between WFP and DLR, called M.E.P.A, which is an acronym for Mobile Entfaltbare PflanzenAnbaueinheit, translating to mobile deployable plant cultivation unit in German.

Like the name entails, MEPA is a mobile semi-automatic partly inflatable CEA greenhouse system. MEPA is equipped with a solar powered automated support unit that controls and adjust the nutrient solution and water distribution. The automation allows for easy use and no previous plant growth experience should be required. MEPA is based on hydroponics, meaning that the plants do not depend on soil, but only a nutrient solution which will supply the plants with what they need. The plants grow in a so-called Seed Cultivation Mat (SCM). The SCM is made from a flexible foil material, like a bag-in-box or a juice pouch. The flexible material allows the SCM to be rollable, space efficient, light weight and therefore easily transported. To put it into perspective, a smaller 20ft container will be able to carry 20 MEPA units with a total of almost 500m^2 of growing area. This means that a 20ft container of MEPA units have the potential to feed up to 100 people and depending on crop choice, produce an adequate amount of nutrients that would fill the daily requirements for up to 350 people.

Improving life on earth calls for innovative ideas and space research provides an diverse platform for creative solutions. Continuing to develop food production systems for space will provide more knowledge of how to maintain a continuous food supply while minimizing the inputs that are required to grow food. For this reason, space research will most likely continue to aid in the development of sustainable development earth.

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