EDEN ISS

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Objectives

Sustained human presence in space requires the development of new technologies to maintain environmental control, to manage wastes, to provide water, oxygen, food and to keep astronauts healthy and psychologically fit. Bio-regenerative life support systems, in particular the cultivation of higher plants, are advantageous from this regard due to their ability to be employed for food production, carbon dioxide reduction, oxygen production, water recycling and waste management. Furthermore, fresh crops are not only beneficial for human physiological health, but also have a positive impact on crew psychological well-being.

The EDEN ISS project [Zabel P, et al. (2015)] was a 4.5 M€ European Union Horizon 2020 project (reference number: 636501) supported via the COMPET-07-2014 - Space exploration – Life support subprogramme. It had its official kick-off in March of 2015 and ended in April 2019 after the completion of a year-long Antarctic deployment phase in which the EDEN ISS greenhouse system was installed and operated in the vicinity of the *Neumayer Station III*. The EDEN ISS consortium was comprised of leading European experts (in addition to Canada and the USA) in the domain of human spaceflight and controlled environment agriculture (CEA). The EDEN ISS scientific advisory board consisted of the top scientists in the field of space greenhouses from Russia, USA, Japan, Italy and Germany.

The EDEN ISS greenhouse, or Mobile Test Facility (MTF), has been designed to provide fresh produce for overwintering crews at the *Neumayer Station III* in the Antarctic while at the same time advancing the spaceflight readiness of a number of key plant growth technologies. The greenhouse also serves as a tool to develop operational procedures and select science aims associated with remote plant production. The greenhouse consists of two 20 foot high cube containers, which have been placed on top of an external platform located approximately 400 m south of *Neumayer Station III*. The actual system can be subdivided into three distinct sections:

- Cold porch/airlock: a small room providing storage and a small air buffer to limit the entry of cold air when the main access door of the facility is utilized.
- Service Section (SES): houses the primary control, air management, thermal control, nutrient delivery systems of the MTF as well as the full rack ISPR plant growth demonstrator.
- Future Exploration Greenhouse (FEG): the main plant growth area of the MTF, including multilevel plant growth racks operating in a precisely controlled environment.

The design of the EDEN ISS greenhouse is presented in detail in the following publications [Boscheri G, et al. (2016); Vrakking V, et al. (2017); Zabel P, et al. (2017)].

During the 2018 overwintering period, the EDEN ISS consortium tested essential CEA technologies using an International Standard Payload Rack (ISPR) cultivation system for potential testing on-board the International Space Station (ISS). Furthermore, the FEG was designed with a focus on larger scale bio-regenerative life support systems for planetary

surfaces (e.g. Moon, Mars). In addition to technology development and validation, food safety and plant handling procedures were, and will be, developed and tested in Antarctica. These are integral aspects of the interaction between the crew and plants within closed environments.

Due to the necessity of validating key technologies for space greenhouses under mission relevant conditions and with representative mass flows, the EDEN ISS consortium defined six objectives:

1. Manufacturing a space analogue Mobile Test Facility.
2. Integration and test of an International Standard Payload Rack plant cultivation system for future tests on-board ISS and a Future Exploration Greenhouse for planetary habitats.
3. Adaptation, integration, fine-tuning and demonstration of key technologies.
4. Development and demonstration of operational techniques and processes for higher plant cultivation to achieve safe and high-quality food.
5. Study of microbial behaviour and countermeasures within plant cultivation chambers.
6. Actively advancing knowledge related to human spaceflight and transformation of research results into terrestrial applications.

Although the project officially ended, the German Aerospace Center (DLR) and the Alfred-Wegener Institute agreed to continue operation of the EDEN ISS facility at the *Neumayer Station III* through 2020 and beyond.

Field work

ANT-Land 2019/20 Neumayer Station III summer field season

A detailed overview of EDEN ISS related activities carried out by members of the German Aerospace Center during the ANT-Land 2019/20 summer season has been documented in the previous year's ANT-Land report [Vrakking V, et al. (2020)].

Nominal Operations Phase – 2020/21 Neumayer III winter season

For the ANT-Land 2020/21 winter field season, operational activities were carried out by the regular overwintering crew. In the absence of a dedicated operator, scientific activities were reduced throughout the season, in an attempt to limit the required crew effort. Remote support was provided by the consortium partners to assist the overwinterers in the operation of the greenhouse.

The EDEN ISS greenhouse was in operation since the 2nd of January 2020, when the overwinterers, together with the summer season expedition crew members of the German Aerospace Center, carried out the initial sowing operations in the greenhouse. In contrast to previous years this enabled hands-on instruction of the overwinterers with respect to plant cultivation techniques and, furthermore, enabled the first harvests of fresh edible biomass already at the end of January, before the departure of the summer season expedition crew.

Once the summer season had ended, the overwintering crew took over all activities within the greenhouse, in addition to their regular scientific, and station maintenance, work load.

Most of the time needed for operations of the EDEN ISS greenhouse was dedicated to nominal operational and maintenance activities, such as:

- Seeding of various crops,
- Transferring juvenile plants from germination area to cultivation trays,
- Pruning/training of fruiting crops, such as tomatoes and cucumbers,

- Harvesting of various crops, starting with radish on the 25th of January 2020,
- Cleaning and disinfection of surfaces, filters and tanks,
- Exchange of consumables (e.g. filters, oxygen tablets, ozone cells),
- Regular (weekly) tele-cons with remote operations team in Bremen,
- Emptying waste water tanks and refilling fresh water tanks,
- Preparation and exchange of nutrient stock solutions,
- Preparation and exchange of acid and base supply,
- Sensor calibration,
- Repair and exchange of thermal control system actuators,
- Cleaning and repair of thermal control system piping leaks,
- Cleaning and exchange of misting nozzles in the aeroponic plant cultivation trays, and
- Repair and exchange of pumps.

In total 324,1 kg of fresh food was produced for the overwintering crew between January and December 2020, with the final harvest occurring on December 22nd. Valuable additional knowledge was gained about the operation of the greenhouse with non-specialists and non-scientific personnel. This resulted in improved operation procedures, communication and control software. Furthermore, technical issues were observed that need to be improved in order to optimize the operation of the greenhouse, so that more food can be produced with less resources.

In parallel to the operations on-site at Neumayer Station III data evaluation, documentation and publication of the scientific data from the previous winter season were continued by the EDEN ISS partners. Details are provided in a later section.

ANT-Land 2020/21 Neumayer Station III summer field season

During the 2020/21 summer season one project member from the German Aerospace Center, along with a dedicated EDEN ISS overwinterer from NASA, travelled to the Antarctic to carry out maintenance and repair work, and to install upgrades to the facility. Although the focus was primarily on routine activities, such as cleaning, sensor calibration, filter exchange and training of the overwinterers, a number of upgrades and changes were implemented as well.

In particular, two of the plant cultivation levels were removed from the Future Exploration Greenhouse to provide more space for tall-growing, fruit-bearing crops such as tomatoes and peppers. Furthermore, special plant cultivation hardware developed by NASA was installed in the Future Exploration Greenhouse (FEG) in order to test its performance throughout the 2021 experiment phase. New filters, developed by the University of Florida, were also installed on the multi-spectral plant imaging cameras as part of ongoing research into plant health monitoring systems.

Due to the CoViD-19 pandemic, the regular flights to the Antarctic were cancelled, and transport of the summer season expedition crew was carried out via ship with the *RV Polarstern*. The EDEN ISS team left Bremerhaven on the 20th of December 2020 and arrived at the *Neumayer Station III* on the 19th of January 2021. The summer season expedition crew, along with the 2020 overwintering crew, left *Neumayer Station III* on the 19th of March 2021. During the two months at *Neumayer Station III*, the following work was carried out with respect to the EDEN ISS project:

- Facility inspection and status documentation,
- Microbial sampling within the facility,
- Cleaning of the facility in preparation of maintenance and repair work,
- Cleaning of the Nutrient Delivery System (NDS) piping with hot water,
- Disinfection of the FEG using the TransMADDs system,
- Exchange of consumables (e.g. CO_2 canisters, filters),
- Replacement of the gas concentration measurement system of the EDEN ISS safety system,
- Testing of the EDEN ISS safety system (gas concentration and smoke sensors),
- Preparation of return freight, and documentation, for ship transport to Europe,
- Exchange of multi-spectral imaging camera filters,
- Preparation of nutrient solution for initial plant cultivation,
- Repair of a leak in the Thermal Control System (TCS) piping,
- Refilling of cooling fluid in the TCS piping,
- Preparation of plant scheduling for the summer and winter field seasons,
- Organization of newly arrived cargo,
- Initial teach-in of the 2020/21 winter field season overwinterers,
- Initial seeding of the FEG,
- Replacement of NDS high pressure pumps,
- Cleaning and reconfiguration of aeroponic plant cultivation trays,
- Replacement of NDS sensors and calibration of new sensors,
- Replacement of tubing and connectors for NDS acid and base supply,
- Inspection and cleaning of the Atmosphere Management System (AMS) cooling coil,
- Replacement of AMS condensate water recovery loop UV lamp,
- Preparation of nutrient salt mixtures for the winter field season,
- Replacement of the AMS cooling coil UV lamp,
- Inventory of consumables and equipment in the MTF, the multi-purpose laboratory and the various storage areas,
- Repair of insulation around the main entrance door
- Backup of data from the previous winter field seasons,
- Preparation of documents for the winter field season (e.g. procedures, task lists),
- Continued training of the winter field season crew,
- Fuse switch exchange in the Power Control and Distribution System with the aid of the AWI electrician, and
- Safety briefings for the winter field season crew.

For the ANT-Land 2020/21 winter field season, operational activities will be carried out by the dedicated EDEN ISS overwinterer from NASA. Remote support will be provided by the consortium partners to assist with EDEN ISS-related activities.

Preliminary (expected) results

Detailed analysis of the data and samples from the previous operations phases is still ongoing. However, some preliminary results have already been collected and are described below.

Aside from the data which had previously been published, such as the performance of the Plant Health Monitoring system [Zeidler C, et al. (2019)], the impact of plants on crew well-being [Schlacht I, et al. (2019)], crew time measurements [Zabel P, et al. (2019)], biomass production [Zabel P, et al. (2020)], microbiological measurements [Fahrion J, et al. (2019)], and ISPR plant cultivation system performance [Boscheri G, et al. (2019)], a number of new publications have been prepared based on results from the Antarctic operations phases.

General experience gained with respect to the greenhouse operations and the performance of the different technical aspects of the design was used, and will be used in the future, to develop the design concept for a greenhouse for Moon and Mars [Volker V, et al. (2020)]. With the aim to develop and build an improved greenhouse demonstrator by 2025, the failures and non-optimal design aspects of the EDEN ISS greenhouse will be reviewed and adjustments will be made to the various systems in order to improve performance and reliability, and reduce the amount of crew time needed for nominal and off-nominal operations.

Additional information on the Plant Health Monitoring system, specifically the multi-spectral cameras and the associated image processing, was published [Tucker R, et al. (2020)]. Furthermore, new research into the use of machine learning for Controlled Environment Agriculture was initiated. Initial results on image compression and plant classification have been published [Nesteruk S, et al. (2021)]. The ultimate goal is to implement an artificial intelligence which can autonomously analyse images taken by the Plant Health Monitoring system, identify the plant type and cultivar in the image and identify the health and age of the plant to then provide instructions to the crew with respect to horticultural activities.

Additional publications regarding crew time, crew work load and energy consumption, among other topics, are in various stages of the publication process.

Fig. 1: Germinating plants in the Future Exploration Greenhouse in January 2020

Biomass production

Table 1 shows the amount of biomass harvested each month during the 2020 operations phase. As mentioned previously, the facility was already put into operational mode at the beginning of January, with first sowing occurring on the 2nd of January. Figure 1 shows the

first germinating plants on the 12th of January First harvest occurred at the end of January and the last harvest occurred on December 22nd. Only part of the available cultivation area of the MTF was used during the months of October and November due to a lack of sufficient nutrient salts, as well as to reduce crew time demand in preparation of the upcoming summer field season. In total, around 324,1 kg of fresh edible biomass was harvested.

Tab. 1: Monthly fresh biomass harvest during the 2020 winter season

Month	Biomass Yield [kg]
January	2,86
February	26,00
March	38,27
April	41,08
May	31,96
June	51,24
July	20,31
August	25,86
September	28,92
October	31,96
November	11,57
December	14,05

Based on feedback from the first operations phase in 2018 and 2019, the variety of cultivars available for cultivation in the MTF had been greatly increased for the 2020 winter season. However, for many of these new cultivars no laboratory testing had been done to determine optimal growing conditions and as such some of the new crops did not yield significant edible biomass, thereby reducing the average yield per cultivation area. Additionally, it was found that the germination rate of the seeds, especially those which had been brought to the Antarctic during the first EDEN ISS summer season expedition in December 2017, was significantly lower than the germination rate in previous years. As a result, new seeds as well as a dedicated refrigerator for improved seed storage, were brought to the *Neumayer Station III* during the ANT-Land 2020/21 summer season.

Crew time and work load

For the 2020 mission, the overwintering crew of the Neumayer Station III was asked to track the amount of time which was spent on activities related to the operation of the MTF. These activities included regular communication with the project team at DLR, nominal operations in the facility such as cleaning, seeding and harvesting, as well as off-nominal activities in case of, for example, component failures. The maximum amount of time needed by the crew per month during the 2020 winter season was 108,5 hours in March. For the other months, the time was 75 hours or less either due to a reduced amount of plant handling activities and/or fewer off-nominal events.

Aside from crew time, members of the 2019 and 2020 winter field season crews were asked to complete an assessment of the work load related to their activities in the EDEN ISS greenhouse. The results of the crew time and work load investigations are currently going through the review process for two separate journal publications. Additional data will be collected during the 2021 winter field season.

Psychological investigations

Due to the limited winter crew size of 10 people, the psychological investigations, carried out in 2018, to determine the impact of the greenhouse and fresh produce on crew wellbeing did not yield statistically significant results. Based on anecdotal evidence the general impact of

the greenhouse was found to be positive, and in particular the olfactory experience within the greenhouse was explicitly mentioned as a positive aspect.

The ANT-Land 2019/20 winter field season crew participated in a number of psychological and medical investigations and studies. Results from these investigations should add to the data previously collected and allow for more accurate and significant determination of the impact of the EDEN ISS greenhouse on crew wellbeing. For 2021 the questionnaire for the psychological investigations has been reworked to align more closely with the questionnaires used by NASA for astronauts.

Data management

All data collected and generated by this project will be published in open access journals and/or submitted to a public database (https://zenodo.org/communities/edeniss).

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