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Summary of Research and Outreach Activities during the 2021 Season of the EDEN ISS Antarctic Greenhouse

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THE EDEN ISS greenhouse is a space-analogue test facility near the German Neumayer Station III (NM-III) in Antarctica. The greenhouse design, construction, and test phase began in 2015, and the facility was shipped to NM-III in January 2018. From 2018 until early 2022, the greenhouse was in continuous operation during every winter-over period, with the 2021 season being the latest to be completed. The purpose of the facility is to enable multidisciplinary research on topics related to plant cultivation on future human space exploration missions. Research on food quality and safety, plant health monitoring, microbiology, system validation, human factors, horticultural sciences, and resource demand was conducted. During the 2021 season, research and operation of the EDEN ISS greenhouse was done as part of a DLR-NASA collaboration with an American on-site operator. Part of this collaboration was testing new crops like chili pepper, broccoli, cauliflower, and beans, which had never been grown inside EDEN ISS. These crops were complemented by a variety of lettuces, mustard greens, herbs, tomatoes, cucumbers, radishes, and kohlrabi. In total, approximately 315 kg of fresh produce was harvested during the 2021 season, which was supplied to the NM-III wintering crew. Frozen and dried plant subsamples were collected and transferred back to Europe and the United States for further investigation. Additional samples were taken from the nutrient delivery subsystem and from surfaces inside the EDEN ISS facility in order to continue the microbiological research activities from previous years. Another research focus was capturing crew time for all activities inside the MTF and select support activities inside NM-III to increase the understanding of work time demand for future food production systems in space. DLR and NASA also continued the numerous outreach activities of the past years. This paper summarizes both the research and the outreach activities during the latest operational season of the EDEN ISS Antarctic greenhouse in 2021.

Nomenclature

AMS	=	Atmosphere Management System
AWI	=	Alfred Wegener Institute
DLR	=	German Aerospace Center
ISS	=	International Space Station
KSC	=	Kennedy Space Center
MTF	=	Mobile Test Facility
NDS	=	Nutrient Delivery System
NM-III	=	Neumayer Station III
TLX	=	Task Load Index

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I. Introduction

THE EDEN ISS project, which ran from March 2015 to April 2019, aimed to build and test a closed-loop greenhouse facility in a space-analogue environment, in order to investigate technologies and procedures for plant cultivation in future life support systems. The resulting design, called the Mobile Test Facility (MTF; Figure 1), was successfully deployed near the German Neumayer Station III (NM-III) in Antarctica at the beginning of 2018. Following the initial check-out phase, the facility began operating in February 2018. Following the official end of the project, operation of the greenhouse facility was continued through a partnership between the German Aerospace Center (DLR) and the Alfred-Wegener-Institute (AWI). The EDEN ISS project background, design of the MTF, the initial set-up phase, and data and operation information from the 2018 through 2020 seasons have been published previously[1,2,3,4,5,6,7,8].

In 2021 DLR and NASA expanded their collaboration on the utilization of the EDEN ISS greenhouse. A NASA scientist stayed in Antarctica as part of the 2021 wintering crew to manage the MTF operations and conduct scientific projects. The presence of a dedicated on-site operator, after the previous two years when tasks were split among the regular members of the NM-III winter crews, allowed for an increased scope of scientific activities.

Due to the ongoing pandemic, the logistics associated with travel to and from Antarctica had to be overhauled, which impacted the 2020/2021 Antarctic summer season. Instead of the typical flights from Cape Town to the Russian Novo Station, and then onward to NM-III, the summer crew were transported directly from Germany to NM-III by ship. After completing a hotel quarantine phase, the crew departed Bremerhaven, Germany, on the research vessel *FS Polarstern* on the 20th of December 2020 and arrived at NM-III on the 19th of January 2021. During the next two months, the summer team completed the required work to prepare the station and various scientific facilities, including the MTF, for the 2021 winter season, as well as to train the new winter crew in their respective responsibilities.

As part of the summer team, one person from DLR, along with the NASA on-site operator, travelled to NM-III to carry out maintenance on the greenhouse. Activities included replacing various pumps and filters, repairing a leak in the coolant lines, calibrating and testing sensors and safety equipment, and installing new hardware to address issues encountered in previous years of operation. Furthermore, a novel NASA plant cultivation system was set up for testing throughout the year.

On the 19th of March 2021, the summer crew, along with the 2020 winter crew, departed the station on *FS Polarstern*, with only the ten-member 2021 winter crew remaining at NM-III. The winter crew were isolated until November 2021 when the first flights with members of the 2021/2022 summer team arrived. The on-site operator worked through the 2021/2022 summer season to prepare the MTF for hibernation in 2022, with only key subsystems remaining active throughout the year, before leaving along with the rest of the 2021 winter crew in mid-February 2022.

Figure 1. The MTF exterior, July 2021.

II. Scientific Activities

Having a dedicated on-site operator during the 2021 Antarctic winter season enabled day-to-day operations, such as regular maintenance and plant handling activities, as well as a significant amount of data and biological sample collection. Although the data and samples collected throughout the year are still undergoing analysis, here we provide an overview of the different scientific activities and respective methodologies that were conducted during the 2021 season.

A. Horticultural & Nutrition Investigations

A total of approximately 315 kg of fresh edible biomass was harvested throughout the 2021 experiment phase, which ran from initial sowing on the 2nd of March 2021 until the final harvest from the aeroponic trays on the 15th of January 2022. Horticultural data collection was taken at each harvest at the plant level and included number of leaves or fruit, edible fresh biomass, inedible fresh biomass, and inedible root mass (final harvest only).

Subsamples from various crops were collected throughout the season for post-mission nutrition analysis. In total, 164 dried samples for nutrition analysis were collected. The subsamples were dried, vacuum sealed, and ultimately shipped to Germany on the vessel *Malik Arctica* in late 2021. The subsamples were transported in an environmentally controlled shipping container to limit sample degradation as the ship traveled across different global regions with vast temperature and humidity fluctuations. After arrival in Germany, the samples were then shipped to NASA's Kennedy Space Center (KSC) for analysis. An overview of the monthly harvest of fresh edible biomass can be found in Table 1 below. A more detailed analysis of the edible and inedible biomass, including breakdown per cultivar, is intended for a separate publication in the future.

Table 1: Monthly Fresh Weight Edible Biomass during the 2021 Experiment Phase

Month	Fresh Weight Edible Biomass [kg]
April	22.47
May	37.21
June	32.32
July	16.35
August	23.17
September	28.79
October	22.95
November	54.56
December	50.86
January	26.25

B. Microbiological & Molecular Investigations

A major area of investigation in plant cultivation systems for future space missions is to track the development of the microbiome within the system and to assess countermeasures to minimize the level of contamination. This concerns not just the crop surfaces and tissues but also the fluids and surfaces of the support systems, such as the nutrient solution and piping in the Nutrient Delivery System (NDS) and the ducts and dehumidifier in the Atmosphere Management System (AMS).

Plant tissue samples were collected from select crops throughout the season. The chosen cultivars have either been previously grown in the Veggie vegetable production system ('Outredgeous' lettuce, 'Waldmann's Green' lettuce, 'Amara' mustard, 'Mizuna' mustard, 'Toscano' kale) or the Advanced Plant Habitat facility ('Española Improved' pepper) on the International Space Station (ISS), or they are currently being studied at KSC as potential space crop candidates ('Red Robin' dwarf cherry tomato). Subsamples from all edible plant parts were collected at harvest; in the event of a multiple, "cut-and-come-again" harvest, the plants were sampled at the first and final harvests. Root subsamples were also collected at either the single harvest event or the final "cut-and-come-again" harvest. Anticipated statistical analysis will assess the microbiological and molecular load at the crop, time (across season), and harvest method levels.

Initial investigations on the microbiome in the MTF were conducted using samples taken during the 2018 operations phase, with results published in Fahrion et al. (2020). In 2021 the on-site operator collected surface and nutrient solution samples weekly for the first four months of the season, followed by monthly sampling for the remainder of the season. The locations of surface samples were chosen based on the results of the sampling during the

2018 season and aimed to include locations with a facility representative microbiome (Figure 2). Additional nutrient solution samples were collected before and after routine overhauls of the nutrient tanks.

Figure 2. The on-site operator collecting a microbial swab sample on the greenhouse wall. This sampling location was also used during the 2018 season.

To preserve the quality of the samples for testing, the probes were stored at -40 °C in two Liebherr LGT 2325 freezers. The freezers were encased in protective wood housing and shipped back to Germany in late 2021 on *Malik Arctica* (Figure 3). During transport from Antarctica to Germany, the freezers remained plugged in to either the ship or generators, and phase change material packs were used to maintain the cold chain during the periods where power was not available. Frequent checks during transport ensured the temperature of the freezers remained at the desired setpoint. In total, 139 edible plant tissue samples, 99 root tissue samples, 72 surface swabs, and 39 nutrient solution samples were collected for microbiological and molecular analyses.

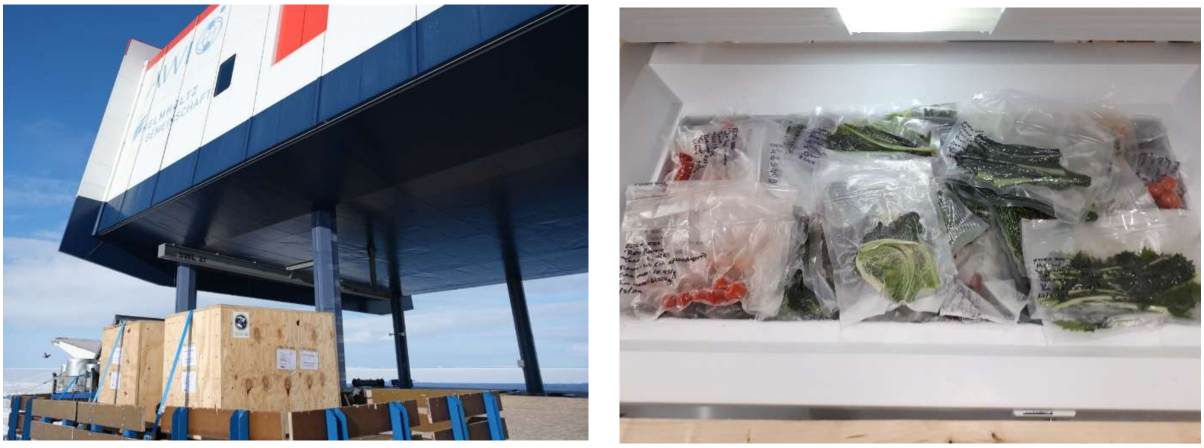

Figure 3: (Left) The two freezers filled with return biomass and swab samples shown packed in wooden cases and staged outside NM-III for loading onto *Malik Arctica*, December 2021. (Right) Freezer full of edible plant tissue samples for microbiological and molecular analyses.

A key area of focus concerning microbial contamination inside the MTF in 2021 was the AMS dehumidifier. During the 2020/2021 summer season, a thorough cleaning of the dehumidifier, in particular the droplet separator, was carried out to reduce or eliminate the microbial contamination on these surfaces. Additionally, a periodic inspection and cleaning procedure was implemented to monitor and control the recurrence of microbial contamination build-up on this cooling coil and within the AMS condensate recovery system.

To reduce contamination in the NDS piping for the 2021 season, the system was flushed with heated fresh water (~50°C) during the nutrient solution tank cleaning overhauls, roughly every 3-4 months. Visual inspections confirmed the system flushing removed biofilm and other biological buildup from the inside the piping. Plant root tissue samples and nutrient solution samples will be analyzed to quantitatively assess the microbiological load across the season and to determine the efficacy of the flushing events as a countermeasure for systems contamination and potential food-safety risks. Unfortunately, hotter water temperatures were not an option in the current MTF design due to hardware limitations. In future system designs, hardware that could withstand hotter water temperatures should be selected, or bypasses should be integrated for cleaning events to preserve temperature-sensitive hardware. Further investigations could then determine the optimal temperature and frequency of these cleaning procedures.

As the samples arrived in Bremen in March 2022 and then had to be distributed to the partners for analysis, the results of these microbiological and molecular analyses are not yet available at the time of publication of this paper. Separate publications are intended for the future to disseminate the data obtained from these samples.

C. New Hardware & Crop Testing

For the 2021 season, a novel plant cultivation system developed at KSC was brought to Antarctica for testing in the MTF. The goals of this hardware testing were to compare the performance of the system in the MTF and with an operator independent of the hardware development with performance of the system at NASA's facilities, as well as to compare biomass production in the NASA hardware with the same crops being cultivated in the aeroponic system of the EDEN ISS greenhouse. The NASA system is a passive porous tube nutrient delivery system, with a small water reservoir which is manually filled with nutrient solution. Once the system is primed (e.g. filled with nutrient solution and air having been vented from the system), the nutrient solution is taken up by the plant roots without requiring pumps. Throughout the year, three plant cultivation cycles were successfully completed: the first two grow-outs with 'Outredgeous' lettuce and the third grow-out with 'Red Robin' tomato (Figure 4). Plant tissue samples for microbiological, molecular, and nutrition analyses were collected during both 'Outredgeous' lettuce grow-outs in both the NASA system and concurrent aeroponic tray system.

Figure 4: Plant health monitoring camera system image of 'Red Robin' tomatoes growing in the NASA cultivation system.

In addition to the NASA hardware, the 2021 operations phase tested a number of new crops and cultivars in the EDEN ISS greenhouse. These included broccoli, cauliflowers, beans, peas, 'Amoroso' tomatoes, and new chile pepper cultivars like 'Española Improved' and 'Chimayo' (Figure 5).

Figure 5. New crops and cultivars tested during the 2021 season, including beans (left) and 'Española Improved' chile pepper (right).

The new crops and cultivars were grown to determine their performance in the closed-loop growth environment of the MTF, the crew time and effort required to grow them and, most importantly, to provide additional variety to the winter crew at Neumayer Station III. As for the crops grown in the NASA Hardware, and the comparison crops grown in the aeroponic trays, various samples were collected of these new cultivars to enable comparisons between the available options with the ultimate aim of selecting the most suited crops and cultivars for future space missions.

D. Crew Time Tracking

For mission planning, as well as for future design improvements, it is important to know how much time is needed to conduct the various routine and off-nominal activities for operating the greenhouse. Initial results of crew time investigations from the previous years of MTF operations are published in Zabel et al. (2019), Poulet et al. (2021), and Zeidler et al. (2021).

These previous investigations were limited in the accuracy of crew time tracking and the differentiation of crew time spent across multiple activities carried out within the greenhouse. To improve the data collection process in the 2021 season, the on-site operator recorded crew time with a Timeular Tracker device and software. The Timeular system allowed for straightforward monitoring of crew time for different activities by changing the orientation of an 8-sided tracking die. Depending on this orientation, and the activity assigned to each side of the die, time was automatically tracked and assigned to a specific task in the companion software application. The categories used on the Timeular system were Daily Check, Sowing, Pruning/Trellising, Harvesting, Cleaning, Repair, Maintenance, and Miscellaneous. Based on the experience of the on-site operator these categories did not fully cover all the different tasks which needed to be carried out. As such, a more detailed breakdown was established based on the monthly crew survey, with crew time assigned to 28 different tasks (ranging from environment monitoring to plant pollinating to produce cleaning) across 5 categories (Daily operations, Cultivation Operations, Routine Operations, Maintenance and Utilization).

Whenever multiple members of the winter crew were simultaneously active in the MTF, such as during larger harvests or off-nominal events, crew time was tracked manually for additional crew members.

An overview of the daily average crew time needed for the main categories of tasks is presented below in Table 2. Note that the time periods in the left column reflect the time period between two surveys.

The data presented in Table 2 reflects the crew time of the dedicated on-site operator and does not include the crew time of the other members of the winter crew.

Table 2: Crew Time Measurements from the 2021 Experiment Phase

Time Period	Daily Average Crew Time [min]				
	Daily	Cultivation	Routine	Maintenance	Utilization
March 24th – April 21st	26.5	22	43	91.1	36
April 22nd – May 15th	18.6	106.8	11.6	55.2	97
May 16th – June 17th	12.6	82	13	76.2	59.4
June 18th – July 16th	18.6	79.8	19.8	37.4	58.8
July 17th – August 13th	20.4	50.7	57	64.1	46
August 14th – September 13th	22.1	59.5	51.5	55.8	80
September 14th – October 13th	16.7	88.5	30.5	9.8	118.5
October 14th – November 16th	19.6	81.9	28.1	9.4	111.2
November 17th – December 7th	20.2	111	42.4	13.3	116.8
December 8th – January 20th	9	90.5	42.5	9	86.5

E. Crew Survey Questionnaires

As part of ongoing investigations into the effects of isolated, confined, extreme environments, as well as the influence of human-plant interactions on crew biobehavioral health, volunteering winter crew members completed a monthly survey from February 2021 through January 2022, plus a pre- and post-mission survey completed in November 2020 and March 2022, respectively. Questionnaires were previously completed by the 2018 winter crew, with results published in Schlacht et al. (2020). The questionnaire for the 2021 season was adapted from the Veggie questionnaire used by astronauts on the ISS. This updated survey was comprised of 11 areas that aimed to capture enjoyment and time spent conducting various plant-related activities, sensory stimulation, and the active and passive psychological effects of having live plants and available fresh food in an environment where no other source of either is available [14].

Additionally, the on-site operator completed NASA Task Load Index (TLX) surveys from October through December 2021. The TLX surveys, coupled with crew time reporting and pairwise comparison surveys, aimed to capture the relationship between crew time and workload and to identify which tasks should be conducted or prioritized with respect to workload, as well as identify where augmented reality could be integrated into future system designs to better support operators.

III. Outreach Activities

In addition to the operational and scientific activities, the on-site operator, with support from remote support teams in Bremen, Germany, and the United States, promoted the EDEN ISS project to the general public in order to increase awareness and enthusiasm for space research and closed-loop plant cultivation. An overview of the extensive dissemination and outreach program within the EDEN ISS project was presented in Zabel et al (2020). For the joint DLR-NASA mission in 2021, a number of these activities were used to share information about the project and related activities by DLR and NASA (Table 3).

Table 3: Overview of dissemination and outreach activities

	Social Media	Press	Physical Items
Activities	• Website • Facebook • Instagram • Flickr • Blog posts	• Press releases • Press conferences • Photo and video material	• Mission patch • Mission logo stickers

A. Social Media

Within the EDEN ISS project, a dedicated website (https://eden-iss.net) was developed to share information; highlight the consortium partners; and disseminate project publications, images, animations, and videos. Additionally, a special tool was developed to allow visitors to monitor the plants in the EDEN ISS container by accessing images taken daily by the 34 cameras within the MTF. Throughout the 2021 season, this tool continued to provide access to the plant health monitoring camera images, allowing the public to see the crops develop from sowing through to harvest.

Along with the images taken by the cameras inside the container, DLR and NASA also regularly released images and videos taken by the on-site operator showing the MTF, the Antarctic environment, and the various tools and tasks which made up the day-to-day work. These images and videos were sent by the on-site operator to the remote support team in batches and were subsequently released to the general public via Facebook (https://www.facebook.com/spaceedeniss), Instagram (user name: eden_iss_project), and Flickr posts (https://www.flickr.com/photos/dlr_de/sets/72157683682719480/).

Throughout the year the on-site operator also contributed to blog posts detailing the journey to Antarctica, life at NM-III, and working with the EDEN ISS greenhouse.

B. Press

Two press conferences were organized in 2021 – near the beginning (early May) and end (early December) of the growing season – to inform the public about the EDEN ISS project, the joint DLR-NASA mission, and the related work being carried out by both DLR and NASA. The general format of the press conferences involved statements from the two space agencies, from the Alfred Wegener Institute for Polar and Marine Research (AWI), which operates NM-III, and from the on-site operator in Antarctica. After these initial introductions, the press was invited to ask questions. Furthermore, the press conferences were livestreamed, and project members were available to answer questions from the general public in the corresponding online chat.

In addition to these press conferences, throughout the year numerous requests for interviews and information from the press were completed, resulting in a large number of articles. Over 250 distinct articles were published about the EDEN ISS project and mission during 2021, with noticeable spikes in activity after the press conferences as expected.

C. Physical Items

For the joint DLR-NASA mission, a new logo was developed based on the original EDEN ISS design. This new logo was used to make mission stickers and patches for the on-site operator and the other members of the winter crew. These items will also be used as promotional hand-outs at future conferences along with the material that was initially developed during the EDEN ISS project.

IV. Future Activities

Hibernation mode in 2022

During the 2021/2022 Antarctic summer season, the EDEN ISS on-site operator prepared the MTF for the remainder of the year before departing the Antarctic. Throughout the 2022 winter season, the facility will be in hibernation mode with most systems shut-off and only critical systems remaining in operation to allow monitoring of the internal conditions and to maintain the internal temperature at a sufficient level to prevent damage to any components. The 2022 winter crew will periodically check the MTF to confirm that there are no problems inside the greenhouse, but no plant cultivation is planned for the year.

Refurbishment in 2023

The reason for the hibernation phase in 2022 is to facilitate the planned return of the EDEN ISS MTF to Germany in 2023. Based on current planning, two people will travel to NM-III early during the 2022/2023 Antarctic summer season to prepare the greenhouse for transport by ship back to Bremerhaven.

Following arrival in Germany, the container structures will be checked and, if necessary, repaired, before the greenhouse is brought to DLR's Institute of Space Systems in Bremen. Once there, the internal subsystems will be overhauled with a particular focus on the Nutrient Delivery System and the cooling coil of the AMS.

There are a number of possibilities regarding the operation of the EDEN ISS following this refurbishment, with discussions regarding funding and timing currently ongoing.

Additionally, discussions are underway with AWI to replace the EDEN ISS MTF with a new Antarctic greenhouse, which would be integrated inside NM-III.

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