Implications of different plant cultivation techniques for food production in space based on experiments in EDEN ISS

Paul Zabel[1], Conrad Zeidler[1], Vincent Vrakking[1], and Daniel Schubert[1]
German Aerospace Center (DLR), 28359 Bremen, Germany

The EDEN ISS greenhouse is a space-analogue test facility near the German Neumayer III station in Antarctica. The facility is part of the project of the same name and was designed and built since 2015 and eventually deployed in Antarctica in January 2018. The first operational phase of the greenhouse started on February the 7th and continued until the 20th of November 2018. The purpose of the facility is to enable multidisciplinary research on topics related to future plant cultivation on human space exploration missions. Research on food quality and safety, plant health monitoring, microbiology, system validation, human factors and horticultural sciences was conducted. Part of the latter was an experiment to compare different plant cultivation techniques for lettuce and tomato plants. For lettuce two different harvest methods were applied, either batch harvesting of the fully grown lettuce heads or spread harvesting of mature leaves while leaving the plant alive to allow regrowth. The dwarf tomato plants were cultivated for three different durations. The short growth cycle ended right after the first set of fruits were harvested. The plants were then terminated and new plants sown. The longest duration cultivation involved several pruning events were old stems and leaves were removed from the plants allowing regrowth of new shoots. This paper compares the impact of the different cultivation techniques on the biomass output, the required crewtime and the required energy. The results show that depending on whether the goal is to optimize for highest biomass production, lowest energy demand or lowest crewtime demand some cultivation techniques are more favorable than others.

I. Introduction

The EDEN ISS Mobile Test Facility (MTF) was successfully deployed in Antarctica in January 2018 after three years of design, development and construction. The MTF is located 400 meters south of the German Neumayer Station III (70°40´S, 008°16´W) on the Ekström ice shelf in the vicinity of the Atka Bay. The station is operated year-round with a summer (November to February) crew of 50-60 people and a winter (February to November) crew of 9 people. During the winter period are no supply missions able to reach the station, which means that all supplies (e.g. food, spare parts, tools) need to be delivered during the few summer months. This remoteness makes the Neumayer Station III an excellent test area for human space exploration test missions.

In 2018 a tenth person complemented the wintering crew to operate the MTF. The operation started in February 2018 and was continued throughout the whole winter-over season 2018. The first plants were sown on February 7 and subsequently transferred to the cultivation trays in the following weeks. The plants developed very well and the first harvest occurred on the March 20. This harvest included lettuces, radishes, Swiss chard and other leafy greens. The first harvest of cucumber (March 29) and tomatoes (May 16) followed soon after. The last harvest of the 2018 winter season was executed on November 20. Until then a total edible fresh biomass of 67 kg cucumbers, 46 kg tomatoes, 19 kg of Kohlrabi (a type of cabbage), 8 kg of radish, 15 kg herbs, 56 kg of lettuce, 51 kg of leafy greens and 1.5 kg of sweet pepper was harvested from the plants grown inside the FEG. Most of the produce was consumed by the wintering crew except for a small portion that was set aside for measurements and sampling.

Furthermore, a large number of experiments and measurements have been conducted by the on-site operator (Paul Zabel) which included research in the fields of food quality and safety, microbial environment, horticulture, greenhouse subsystem validation, plant health monitoring, impact of the greenhouse on the crew, electrical energy demand, remote operation and crewtime demand[1].

[1] Research Associate, Institute of Space Systems, Robert-Hooke-Str. 7, 28359 Bremen, Germany.

II. Cultivation Techniques for Space Greenhouses

There are different ways in how plants can be treated during the cultivation in a space greenhouse. Typically plants are grown on a flat surface with the light source above the cultivation area. However, different concepts such as the cultivation on angled surfaces[2] or in a kind of spiral growth chamber [3, 4]. All these concepts aim to optimize the space required for plant cultivation during the different development stages of the crops.

The cultivation techniques used for the experiments presented in this paper are different, because the treatments are directly used on the plants.

A. Lettuce

The cultivation techniques used on lettuce are different harvesting methods. Normally, once the lettuce plant has reached a certain size the full lettuce is harvest by cutting the whole plant from the roots. This is meant by full harvest throughout the paper. The second method is called spread harvest. Using this method, only the oldest respectively largest leaves of the lettuce plant are harvested, while the youngest leaves stay on the plant. This means the plant stays alive and can grow more leaves. Because the largest leaves are harvested, the lettuce plants using spread harvest generally take less space compared to a full lettuce head. This in turn means that the plant density can be increased which should lead to an increase in productivity. This method was already applied in the crop selection experiments for the EDEN ISS project[5].

For the experiments presented in this paper the plant density could be doubled for lettuce grown with the spread harvest technique. This means that instead of 6 plants per tray (600 x 400 mm), 12 plants were cultivated.

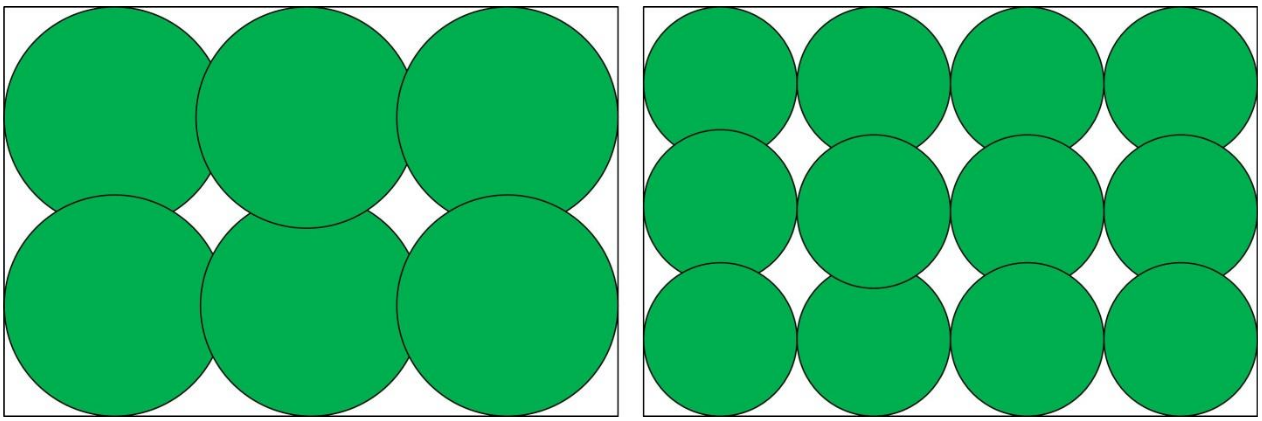

Figure 1. Idealized schematic of lettuce cultivation techniques used in the experiment. Left side: Full harvest, 6 plants per tray. Right side: Spread harvest, 12 plants per tray. Green circles represent one lettuce plant.

B. Dwarf tomato

The varieties of dwarf tomato cultivated for this experiment are indeterminate crops, which means that the plants continue growing and developing fruits as long as the environmental conditions are suitable. When keeping the plants for a long time it is necessary to cut withered side shoots in order to allow the plant to develop need side shoots with new leaves and flowers.

During the experiments the dwarf tomato crops were grown for different time periods before replacing them with new seedlings for the next cycle. The idea behind that technique was to determine whether it is more effective to let the plant inside the greenhouse for a long time with regular pruning after harvesting tomato fruits compared to terminating the plant after the first harvest of ripe tomatoes and replacing it with a new seedling.

III. Materials and Methods

A. Experiment setup

The experiments described in this paper were conducted inside the EDEN ISS MTF in Antarctica during the wintering season of the year 2018. The MTF houses the Future Exploration Greenhouse (FEG), which is a space greenhouse test facility with a cultivation area of 12.5 m² and a Service Section which contains the subsystem necessary to run the FEG and a work desk including a sink. A detailed description of the design process of the MTF and its components, plant selection and project development can be found elsewhere [6–13].

B. Crop species cultivated for the experiment

1. Lettuce

The two lettuce (*Lactuca* sativa) varieties used for the experiments are:

- Othilie - supplier: Rijk Zwaan
- Waldmann's Green - supplier: Johny's Selected Seeds

Figure 2. Lettuce Othilie (left photo) and Waldmann's Green (right photo) growing inside the EDEN ISS FEG.

2. Dwarf tomato

The two dwarf tomato (*Lycopersicon esculentum*) varieties used for the experiments are:

- Cherry tomato (F1 1202) - supplier: Vreugdenhil
- Orange tomato (F1 3469B) - supplier: Vreugdenhil

Figure 3. Dwarf tomato plants growing inside the EDEN ISS FEG: Cherry tomato (left photo), Orange tomato (right photo).

C. Cultivation conditions

1. Illumination

Lettuce was cultivated with around 330 µmol/(m²*s) and dwarf tomatoes with 300-400 µmol/(m²*s) at canopy level. The spectrum was a mixture of red (650 nm), blue (450 nm), white and far red. A detailed description of the illumination subsystem can be found elsewhere[14]. The photoperiod inside the FEG consisted of 15 hours of full illumination per day and 1hour of reduced light intensity (50% of nominal intensity) before and after the full illumination period. Consequently, the dark period was 7 hours per day.

2. Irrigation

The irrigation system is a hybrid of aeroponic and nutrient film technique[14].

Lettuce and dwarf tomatoes were cultivated with slightly different settings in the irrigation system. The pH of both nutrient solutions was around 6.00, but the EC value for lettuce was set to 2.20 mS/cm and for the dwarf tomatoes to 3.49 mS/cm.

Composition of the nutrient solution can be found in Table 20 in the Appendix.

3. Climate

The temperature inside the EDEN ISS FEG was set to 21 °C during the photoperiod and 19 °C during the dark period. Relative humidity was set to 65% and CO_2 concentration to 1000 ppm.

Due to frequent human activities inside the FEG, the carbon dioxide concentration had strong variation and was on most of the days higher than 1000 ppm reaching up to 2000 ppm or even 4000 ppm for short periods of time.

D. Plant treatment

The crops were sown in rockwool blocks of 2x2x4 cm (LxWxH) and were first put into a nursery tray for 10 days in terms of lettuce or 14-20 days in terms of tomato. Small amounts of nutrient solution were added manually to this tray in order to keep the rockwool blocks moist. Following the period in the nursery tray, the young plants were moved to the plant cultivation trays for maturation. Tomato plants required regular pruning of withered side shoots when cultivated for a long period.

Dates for sowing, transfer, pruning and harvest events per cultivation tray were tracked continuously. Plant density can be determined from the type of cultivation tray which was used. Upon harvest fresh edible and inedible biomass was measured. The latter was measured separately for roots and stems/leaves. Sometimes plant material was dried using lyophilisation in order to determine the dry biomass ratio which is the ratio of the dried biomass weight to the original fresh biomass weight. Drying plant material was limited due to the sizing of the equipment and due to the fact that dried material was required for each crop species.

Plant development was monitored by several cameras. From each plant cultivation tray, one photo from the top and one photo from the side were taken every day and send to a FTP server where all project partners could access the images. This way the horticulture scientists in the project team could advise the on-site operator on improvements for the cultivation of the crops. An image processing algorithm checked the photos automatically to detect issues with plant development. A multi-wavelength imaging system was setup in two positions to test whether this system can detect plant stress during growth.[15]

IV. Results

A. Biomass production

The following biomass production data was collected in the 2018 wintering season between February and November 2018. The full harvest data for lettuce and the long cycle data for the dwarf tomato plants are also available elsewhere together with the data of all the other crops cultivated in that season[19].

1. Lettuce

The lettuce cultivars were grown under the same conditions inside the EDEN ISS FEG. The normal production cycle was performed with the full harvest procedure, while the spread harvest procedure was performed as an experiment to increase productivity. Consequently, there are more cycles for the full harvest cultivation compared to the spread harvest one. In total Othilie has 15 and Waldmann's Green 11 valid growth cycles with the full harvest method. Spread harvest was conducted for one cycle with Othilie and 2 cycles with Waldmann's Green.

The full harvest growth cycle was around 38 days for both cultivars, while the spread harvest cycle for Othilie was 78 days and for Waldmann's Green around 58 days. The spread harvest growth cycle for Waldmann's Green was shorter compared to Othilie because of elongation of the stem, which is described in more detail in the discussion chapter of this paper.

Table 2 gives the production values for the full harvest and spread harvest method based on one tray, which refers to the production unit used in the FEG. One tray has a cultivation area of 0.328 m². Waldmann's Green had the higher productivity with the full harvest method compared to Othilie, but also compared to Expertise and Outredgeous lettuce[19]. These two varieties were also grown with the full harvest technique, but not with spread harvest. The spread harvest results are contrary to the full harvest. Here Othilie had a higher productivity than Waldmann's Green.

Table 1 shows the productivity values converted to kg/(m²*d) for comparison of the two varieties and cultivation techniques. When comparing full harvest and spread harvest, the latter has a higher productivity per cultivation area and time for both cultivars. Waldmann's Green performs better with full harvest and Othilie with spread harvest, which indicates a cultivar specific response to spread harvest.

Table 1. Time normalized average edible fresh weight of lettuce varieties in kg/(m²*d).

Cultivar	Full harvest	Spread harvest
Othilie	0.043	0.111
Waldmann's Green	0.080	0.097

Table 2. Edible biomass production of lettuce varieties. Standard Error (SE) is given for the measurements.

Cultivar	Number of valid cycles	Average cycle length [d]	SE on average cycle length [d]	Average edible FW [g/tray]	SE on average edible FW [g/tray]	Time normalized average edible FW [g/(tray*d)]	SE on time normalized FW [g/(tray*d)]
Full harvest							
Othilie	15	38.00	0.53	512.53	39.71	13.44	0.94
Waldmann's Green	11	37.91	0.71	907.49	99.08	24.91	2.39
Spread harvest							
Othilie	1	78.00	n.a.	2846.40	n.a.	36.49	n.a.
Waldmann's Green	2	58.50	1.50	1854.00	73.20	31.69	2.07

2. Dwarf Tomato

The dwarf tomato cultivars were grown under the same conditions inside the EDEN ISS FEG. Three different cycle lengths were investigated. The long cycle went on for 286 which is the full season length. The medium cycle was around 200 days long and short cycle only around 120 days. The short cycle was terminated after the first sets of fruit were ripe and harvested. Although the average number of harvests is six for the short cycle, all these harvests were performed in quick succession within a few days of each other. Each of the cycles was performed two times for each cultivar. The two valid cycles of each cycle length and cultivar were cultivated in parallel in two different trays.

Table 3 shows the production values with standard error applied for the three different cycle lengths and two cultivars. The values are given on a per tray basis because one tray is the production unit inside the FEG. One tray equals to a cultivation area of 0.328 m².

Table 3. Edible biomass production of dwarf tomato varieties. Standard Error (SE) is given for the measurements.

Cycle name	Cultivar	Number of valid cycles	Average number of harvests	SE of average number of harvests	Average cycle length [d]	SE of average cycle length [d]	Average edible FW [g/tray]	SE of average edible FW [g/tray]	Time normalized average edible FW [g/(tray*d)]	SE on time normalized FW [g/(tray*d)]
Long	Orange	2	20.50	2.50	286.00	0.00	4285.30	1.50	14.98	0.01
	Cherry	2	24.00	1.00	286.00	0.00	4888.20	604.60	17.09	2.11
Medium	Orange	2	15.50	0.50	203.00	0.00	3152.95	473.05	15.53	2.33
	Cherry	2	9.00	0.00	193.00	0.00	3383.55	178.95	17.53	0.93
Short	Orange	2	6.00	0.00	119.00	0.00	1804.55	100.85	15.16	0.85
	Cherry	2	6.00	0.00	121.00	0.00	1786.30	75.00	14.76	0.62

Table 4 shows the productivity per cultivation area and time for the six combinations of cycle length and cultivar converted to kg/(m²*d). In general the cherry tomato produces slightly more edible fresh biomass compared to the orange tomato. No clear difference in production between the three cycle lengths can be identified from the experiments performed for this paper. However, only a small amount of growth cycles were available for the analyses of this paper. The conclusion stated above is therefore not final yet, additional experiments with larger data sets are recommended to establish a final conclusion.

Table 4. Time normalized average edible fresh weight of dwarf tomato varieties in kg/(m²*d).

	Long	Medium	Short
Orange	0.046	0.047	0.046
Cherry	0.052	0.053	0.045

B. Resources required

The biomass production is only one criterion to evaluate cultivation techniques. One also needs to take into account the resources required to produce a certain amount of fresh edible biomass. In terms of a space greenhouse these resources are water, nutrients, carbon dioxide, electrical energy and labor (crewtime).

Only the electrical energy and crewtime was tracked for the experiments presented in this paper. The water used for plant cultivation can be recovered to a large degree (~95 %) from the transpiration emitted by the plants. This recovery is to some degree factored into the evaluation because of the electrical energy required for the cooling system. It is assumed that the influence of nutrient and carbon dioxide use is minimal compared to the electrical energy and crewtime demand of the different cultivation techniques.

1. Crewtime

The crewtime measurements of the EDEN ISS 2018 wintering campaign are available elsewhere in detail [16]. These include the crewtime required for full harvest cultivation of lettuce and long cycle cultivation of the dwarf tomato cultivars. The crewtime demand for lettuce spread harvest and the medium and short cycle of dwarf tomato cultivation were measured with the same method. This means that the crewtime was measured for six maintenance tasks and four crop cultivation tasks such as sowing, transferring, pruning and harvest.

Table 5. Crewtime for crop cultivation tasks of lettuce[16].

Cultivation technique	Sowing [h:mm:ss]	Transferring [h:mm:ss]	Pruning/Thinning [h:mm:ss]	Harvest EB [h:mm:ss]	Harvest IB [h:mm:ss]
Full harvest	0:01:35	0:01:15	0:00:00	0:01:18	0:02:54
Spread harvest	0:01:35	0:01:15	0:00:00	0:07:16	0:04:45

Table 6. Crewtime for crop cultivation tasks of dwarf tomatoes[16].

Cultivar	Sowing [h:mm:ss]	Transferring [h:mm:ss]	Pruning/Thinning [h:mm:ss]	Harvest EB [h:mm:ss]	Harvest IB [h:mm:ss]
Orange	0:01:00	0:01:00	0:16:05	0:04:26	0:10:00
Cherry	0:01:00	0:01:00	0:13:15	0:05:38	0:10:00

Table 7. Number of crop cultivation tasks performed per growth cycle on average.

Crop	Cultivation technique	Sowing	Transferring	Pruning/ Thinning	Harvest EB	Harvest IB
Lettuce (both cultivars)	Full harvest	1	1	0	1	1
	Spread harvest	1	1	0	5	1
Orange	Short	1	1	0	6	1
	Medium	1	1	1	9	1
	Long	1	1	6	20.5	1
Cherry	Short	1	1	0	6	1
	Medium	1	1	1	15.5	1
	Long	1	1	5	24	1

Table 8 shows the crewtime for maintenance tasks for the whole EDEN ISS FEG in the wintering season 2018. The total crewtime per is then around 36 minutes for the whole FEG and 00:02:56 per square meter per day[16].

Table 8. Crewtime for maintenance tasks for the whole EDEN ISS FEG[16].

	Daily system and plant check	Illumination Subsystem	Atmosphere Management Subsystem	Nutrient Delivery Subsystem	Fresh and waste water	Cleaning tasks
Crewtime per day [hh:mm:ss]	00:14:10	00:00:25	00:00:40	00:12:17	00:06:55	00:02:06

When combining the values for the crop cultivation tasks and the maintenance tasks, the total crewtime values for each crop and cultivation technique as shown in Table 9 and Table 10 are the results.

Table 9. Total crewtime per square meter cultivation area and per kilogram of edible produce for the two lettuce cultivars.

Cultivar	Full harvest	Spread harvest
Othilie	2:11:25/m²	6:02:41/m²

Waldmann's Green	2:10:55/m²	5:05:30/m²
Othilie	1:24:14/kg	0:41:48/kg
Waldmann's Green	0:47:26/kg	1:04:10/kg

Table 10. Total crewtime per square meter cultivation area and per kilogram of edible produce for the dwarf tomato cultivars.

Cultivar	Long	Medium	Short
Orange	24:06:33/m²	13:22:33/m²	7:46:39/m²
Cherry	24:49:26/m²	15:09:09/m²	8:14:28/m²
Orange	0:46:32/kg	0:21:34/kg	0:21:24/kg
Cherry	0:43:40/kg	0:33:15/kg	0:25:37/kg

2. Electrical power demand

Inside the EDEN ISS FEG the electrical power demand is measured with a system installed inside the power distribution box of the MTF. Voltages and currents are measured and the power and energy demand is calculated by the measurement system based on these values. Voltage and current are measured on a subsystem level, but also on some specific components (e.g. selected LED lamps).

Table 11 shows the electrical power demand per cultivation area for four of the five major subsystems. The power demand of those four subsystems is accounted for on a per square meter basis. For the fifth subsystem, which is the illumination subsystem, crop specific power demand values are taken into account. This is done because of the different illumination settings for lettuce and dwarf tomato, which lead to different power demands.

Lettuce requires for illumination 0.121 kW/m² whereas dwarf tomato requires 0.279 kW/m² has a time normalized average over one day including photo period and dark period.

In total, all subsystems together, the lettuce cultivars have a power demand of 0.532 kw/m² and dwarf tomato 0.690 kW/m².

Table 11. Power demand per cultivation area in kW/m².

Nutrient delivery subsystem	Atmosphere management subsystem	Thermal control subsystem	Control & data handling & operations
0.013	0.268	0.080	0.049

The ESM works with electrical power values in its equation, but it is also important to understand the amount of electrical energy which is required to grow a kilogram of fresh edible produce. The power values shown in Table 11 combined with the length of the cultivation period and the yield do lead to the electrical energy demand per kilogram of the different cultivation techniques as shown in Table 12 and Table 13.

Table 12. Electrical energy demand per kilogram of edible produce for the two lettuce cultivars.

Cultivar	Full harvest	Spread harvest
Othilie	310.51	114.76
Waldmann's Green	174.95	132.15

Table 13. Electrical energy demand per kilogram of edible produce for the dwarf tomato cultivars.

Cultivar	Long	Medium	Short
Orange	362.43	349.64	358.11
Cherry	317.73	309.76	367.85

C. Weighting of results

In order to quantify the effectiveness of the different cultivation techniques, the biomass production values and the required resources need to be weighted in order to understand whether it is beneficial to invest more resources to increase the productivity of the crops. The weighting is best done using a modified version of the Equivalent System Mass evaluation tool for life support systems.

1. The Equivalent System Mass evaluation tool

The Equivalent System Mass (ESM) is an evaluation tool for life support systems and is used to determine which of several system options with the same performance has the lowest launch mass for a defined mission. For the evaluation, different performance values such as volume (V), power demand (P), cooling demand (C) and crew time (CT) are converted by being multiplied with mission specific constants (V_{eq}, P_{eq}, C_{eq}, CT_{eq}) to a mass value and added to the actual system mass (M) to form the ESM value (see equation 1). The crew time calculation also includes the mission duration (D) [17].

$$ESM = M + V * V_{eq} + P * P_{eq} + C * C_{eq} + CT * D * CT_{eq} \quad (1)$$

The following analysis assumes a Mars surface mission as defined by Anderson et al. [18] with the conversion parameters shown in Table 14. There are also reference values for ESM values as shown in Table 15. However, since most of the values were measured in the EDEN ISS project. The values shown in the second row of Table 15 are used for the ESM calculation.

Table 14. Mars and moon surface mission ESM mass penalties [18].

	V_{eq} [kg/m³]	P_{eq} [kg/kW]	C_{eq} [kg/kW]	CT_{eq} [kg/h]
Moon	133.1	76.0	102.0	1.500
Mars	215.5	87.0	146.0	0.465

Table 15. Performance values for plant growth chambers.

	Mass (M) [kg/m²]	Volume (V) [m³/m²]	Power (P) [kW/m²]	Cooling (C) [kW/m²]	Crew time (CT) [h/(m²*y)]
NASA BVAD[18]	101.5	1.03	2.6	2.6	13.1
Values used in this paper	101.5	0.40 for lettuce 1.07 for dwarf tomato	Values from section B 2)	Same as power values	Values from section B 1)

2. Weighting spread versus full harvest

Combining the production values from section A, the resources demand from section B with the aforementioned ESM method one can calculate a mass equivalent. This value can be used to determine the effectiveness of the different cultivation techniques.

Table 16 and Table 17 present the ESM values for mass (M), power demand (P), volume (V), cooling (C) and crewtime (CT) for a moon and a Mars surface mission. The values are given in kg_ESM per kg fresh edible biomass per day. Therefore, the value is a ratio per the biomass production and time normalized over the different growth cycle lengths.

Table 16. Relative ESM value in kg_ESM per kg fresh edible biomass per day [kg_ESM/kg/d] for a lunar surface mission.

Moon	**Cultivation technique**	**M**	**P**	**V**	**C**	**CT**
Othilie	Full harvest	2387.43	951.05	1252.29	1276.41	77.27
Othilie	Spread harvest	912.30	363.42	478.53	487.75	81.50
Waldman's Green	Full harvest	1276.53	508.51	669.58	682.48	41.16
Waldman's Green	Spread harvest	1050.48	418.46	551.01	561.62	79.05
Tomato - Orange	short	2195.42	1134.02	1151.57	1521.98	252.34
Tomato - Orange	medium	2143.48	1107.19	1124.32	1485.97	423.71
Tomato - Orange	long	2221.90	1147.70	1165.46	1540.33	791.65
Tomato - Cherry	short	2255.13	1164.86	1182.89	1563.37	274.65
Tomato - Cherry	medium	1899.00	980.91	996.09	1316.48	425.24
Tomato - Cherry	long	1947.86	1006.15	1021.71	1350.35	714.59

Table 17. Relative ESM value in kg_ESM per kg fresh edible biomass per day [kg_ESM/kg/d] for a Mars surface mission.

Mars	**Cultivation technique**	**M**	**P**	**V**	**C**	**CT**
Othilie	Full harvest	2387.43	1088.70	2027.55	1827.01	23.95

Othilie	Spread harvest	912.30	416.02	774.78	698.15	25.26
Waldman's Green	Full harvest	1276.53	582.12	1084.11	976.88	12.76
Waldman's Green	Spread harvest	1050.48	479.03	892.13	803.89	24.50
Tomato - Orange	short	2195.42	1298.16	1864.49	2178.52	78.22
Tomato - Orange	medium	2143.48	1267.44	1820.37	2126.97	131.35
Tomato - Orange	long	2221.90	1313.81	1886.97	2204.79	245.41
Tomato - Cherry	short	2255.13	1333.46	1915.19	2237.76	85.14
Tomato - Cherry	medium	1899.00	1122.88	1612.75	1884.38	131.82
Tomato - Cherry	long	1947.86	1151.77	1654.24	1932.86	221.52

The total ESM values for the two lettuce cultivars are shown in Table 18 for both cultivation techniques and for moon and Mars surface missions. One can see, that the spread harvest technique is in general more effective compared to the full harvest method. The Mars values are slightly higher than the moon values which comes from the different penalty values of the ESM method for both destinations. However, the ratio between full and spread harvest stays almost the same independent of the location.

Table 18.Total ESM value in kg_ESM per kg fresh edible biomass per day [kg_ESM/kg/d] for the lettuce cultivars.

	Moon		Mars	
Cultivar	**Full harvest**	**Spread harvest**	**Full harvest**	**Spread harvest**
Othilie	5944.5	2323.5	7354.7	2826.5
Waldmanns' Green	3178.3	2660.6	3932.4	3250.0

The total ESM values for the two dwarf tomato cultivars, the three growth cycles lengths and the two destinations are presented in Table 19. In general the values are very similar independent of the method and the destination. However the orange tomato cultivar has the lowest ESM for the short cycle on the moon and the medium cycle on Mars. The cherry type tomato on the other hand has the lowest ESM for the medium cycle on the moon and medium cycle on Mars. Overall the cherry type performs slightly better than the orange type, due to the higher productivity.

Table 19. Total ESM value in kg_ESM per kg fresh edible biomass per day [kg_ESM/kg/d] for the dwarf tomato cultivars.

	Moon			Mars		
Cultivar	**Long**	**Medium**	**Short**	**Long**	**Medium**	**Short**
Orange	6867.0	6284.7	6255.3	7872.9	7489.6	7614.8
Cherry	6040.7	5617.7	6440.9	6908.3	6650.8	7826.7

V. Discussion

The goal of the presented experiment was to determine whether different plant cultivation techniques can be used to increase the effectiveness of plant cultivation in a future space greenhouse. The experiments were performed in the first season (2018) of the highly successful EDEN ISS space analog greenhouse in Antarctica in the vicinity of the German Neumayer Station III. A modified version of the ESM evaluation method was used to compare the productivity and resource demand of the different cultivation techniques.

A. Lettuce

The results of the experiment show that the biomass productivity of lettuce can be drastically increased with the spread harvest method. This is mainly achieved by the higher plant density which is possible with this technique. In numbers the biomass productivity is almost 3 times as high as for the full harvest method (for Othilie). Even when taking into account the larger energy and crewtime demand the ratio of the ESM value for Othilie spread versus full harvest is still 2.5. This is a substantial increase in effectiveness with basically the same hardware, just by implementing a different cultivation technique.

However, there are differences between the two cultivars tested. While Waldmann's Green has the highest performance for full harvest, it is performing less good with spread harvest compared to Othilie and only 1.2 times better compared for spread harvest versus full harvest. This is mainly caused due to the different morphology of the cultivars themselves. Waldmann's Green is forming relatively large leaves with a larger vertical distance between leaf pairs. Othilie on the other hand is growing smaller leaves with shorter vertical distance between leaf pairs and is in general more compact compared to Waldmann's Green.

When growing lettuce for a long period of time a central stem develops from which the leaves are growing. For Waldmann's Green this stem is elongated at the end of the growth cycle when using spread harvest, see Figure 4 left photo. The 20 days shorter growth cycle using spread harvest with Waldmann's Green compared to Othilie are caused by this elongation of the stem. The growth cycle is shorter, because the plants reached the lamps above them, basically touching the lamp and getting burned by the illumination. Othilie does not have such a strong elongation of the stem, see Figure 4 right photo. Consequently, the cultivar can be grown for a longer cycle which increases the productivity.


Figure 4. Elongation of stems of Waldmann's Green (left photo) and Othilie (right photo) lettuce.

B. Dwarf tomato

The dwarf tomato cultivars were cultivated with different growth cycle lengths. There is only a small difference between the three growth cycles investigated. The biomass productivity is very similar independent of the cultivation technique. Even when factoring in the advantage of having a mature plant growing new side shoots after a harvest to form new fruit compared to sowing new plants which need to reach maturity before forming fruit, there is no real difference in ESM values. This is mainly caused by the much larger crewtime demand of the medium and long cycle techniques. The crewtime increase comes from the time consuming pruning events after each set of fruit is harvested. Figure 5 gives an impression on what pruning of dwarf tomato means and why it takes around 15 minutes per tray. The left photo shows mature plants in the middle of flowering. The right photo shows a plant that was harvest and pruned a few days before. All side shoots that carried fruit were cut from the plant and new side shoots are already visible.

While the cherry tomato performs slightly better than the orange type, the latter was more favored by the crew because of its taste and texture. Furthermore, the orange type had less but larger fruit while the cherry type had more but on average smaller fruit.


Figure 5. Dwarf tomato plants in a mature state when flowering, left photo, compared to plant which was pruned a few days before, right photo.

C. Summary

In general the experiment presented in this paper shows the potential of cultivation techniques to increase the effectiveness of space greenhouse. While the hardware and cultivation conditions were not changed, but only the method of how the plant is cultivated brings a substantial increase in the productivity of lettuce. Here lettuce can be seen as a representative of leafy greens in general. It is therefore important to also investigated other leafy greens which are candidate crops for space greenhouse systems such as Mizuna, Red Mustard and similar crops in future experiments. There is a potential of greatly increasing the effectiveness of space greenhouses which would also make them more competitive when compared to other life support systems.

However, the experiments also showed that there is a strong influence of the cultivars and how these react to the different cultivation techniques. Furthermore, not all types of crops are suitable for the same methods and crop specific methods need to be investigated. There is a strong demand for further experiment in this area in order to determine the best cultivation technique for space greenhouse candidate crops.

Appendix

Table 20: Nutrient concentration in 100 liters bulk solution in NDS tanks during the experiment phase. Note that the composition of the fruit crop solution was adapted during the mission. Adjusted values are shown in italic. (The adjustment was necessary because a calcium deficit could be observed on the tomato plants, which most likely was the result of a bad K:Ca ratio.)

Nutrient compound	Leafy crop solution concentrations	Fruit crop solution concentrations
NH4	0.122 mol	0.226 mol
K	1.028 mol	1.503 mol / *1.378 mol*
Ca	0.419 mol	0.597 mol / *0.711 mol*
Mg	0.135 mol	0.226 mol
NO3	1.785 mol	2.347 mol / *2.450 mol*
Cl	0.068 mol	0.104 mol
SO4	0.109 mol	0.332 mol
P	0.189 mol	0.267 mol
Fe	3.795 mmol	5.161 mmol
Mn	0.189 mmol	2.059 mmol
Zn	0.244 mmol	0.825 mmol
B	2.840 mmol	4.321 mmol
Cu	0.068 mmol	0.164 mmol
Mo	0.041 mmol	0.103 mmol

Acknowledgments

The EDEN ISS project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 636501.

References

[1]Zabel, P., Zeidler, C., Vrakking, V., Dorn, M., and Schubert, D., "Crewtime in a Space Greenhouse based on the Operation of the EDEN ISS Greenhouse in Antarctica," *49th International Conference on Environmental Systems,* Boston, Massachusetts, 2019.

[2]Schroeder, F.-G., Domurath, N., Brohm, D., and Schubert, D., "ADVANCED GREENHOUSE MODULES AND RESEARCH FOR USE WITHIN PLANETARY HABITAT," *Acta Horticulturae, No.* 1004, 2013, pp. 53–62.

[3]Berkovich, Y. A., Krivobok, N. M., Krivobok, A. S., and Smolyanina, S. O., "Advanced nutrient root-feeding system for conveyor-type cylindrical plant growth facilities for microgravity," *Life sciences in space research*, Vol. 8, 2016, pp. 14–21.

[4]Erokhin, A. N., Berkovich, Y., Smolianina, S. O., Krivobok, N. M., Agureev, A. N., et al., "A cylindrical salad growth facility with a light-emitting diodes unit as a component for biological life support system for space crews," *Advances in Space Research*, Vol. 38, No. 6, 2006, pp. 1240–1247.

[5]Dueck, T., Kempkes, F., Meinen, E., and Stanghellini, C., "Choosing crops for cultivation in space," *46th International Conference on Environmental Systems,* Vienna, Austria, 2016.

[6]Bamsey, M., Zabel, P., Zeidler, C., Poulet, L., Schubert, D., et al., "Design of a containerized greenhouse module for deployment to the Neumayer III Antarctic Station," *44th International Conference on Environmental Systems,* Tucson, Arizona, 2014.

[7]Bamsey, M., Zabel, P., Zeidler, C., Vrakking, V., Schubert, D., et al., "Early Trade-offs and Top-Level Design Drivers for Antarctic Greenhouses and Plant Production Facilities," *46th International Conference on Environmental Systems,* Vienna, Austria, 2016.
[8]Vrakking, V., Bamsey, M., Zabel, P., Zeidler, C., Schubert, D., et al., "Service Section Design of the EDEN ISS Project," *47th International Conference on Environmental Systems,* Charleston, South Carolina, 2017.
[9]Zabel, P., Bamsey, M., Zeidler, C., Vrakking, V., Johannes, B.-W., et al., "Introducing EDEN ISS - A European project on advancing plant cultivation technologies and operations," *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.
[10]Zabel, P., Bamsey, M., Zeidler, C., Vrakking, V., Schubert, D., et al., "The preliminary design of the EDEN ISS Mobile Test Facility - An Antarctic greenhouse," *46th International Conference on Environmental Systems,* Vienna, Austria, 2016.
[11]Zabel, P., Bamsey, M., Zeidler, C., Vrakking, V., Schubert, D., et al., "Future Exploration Greenhouse Design of the EDEN ISS project," *47th International Conference on Environmental Systems,* Charleston, South Carolina, 2017.
[12]Dueck, T., Kempkes, F., Meinen, E., and Stanghellini, C., "Choosing crops for cultivation in space," *46th International Conference on Environmental Systems,* Vienna, Austria, 2016.
[13]Schubert, D., Bamsey, M., Zabel, P., Zeidler, C., and Vrakking, V., "Status of the EDEN ISS Greenhouse after on-site installation in Antarctica," *48th International Conference on Environmental Systems,* Albuquerque, New Mexico, 2018.
[14]Zabel, P., Bamsey, M., Zeidler, C., Vrakking, V., Schubert, D., et al., "Future Exploration Greenhouse Design of the EDEN ISS project," *47th International Conference on Environmental Systems,* Charleston, South Carolina, 2017.
[15]Zeidler, C., Ceriello, A., Fortezza, R., De Simone, D., Stanghellini, C., et al., "The plant health monitoring system of the EDEN ISS space greenhouse in Antarctica," *Front. Plant Sci.* 10:1457, 2019.
[16]Zabel, P., Zeidler, C., Vrakking, V., Dorn, M., and Schubert, D., "Crewtime in a Space Greenhouse based on the Operation of the EDEN ISS Greenhouse in Antarctica," *49th International Conference on Environmental Systems,* Boston, Massachusetts, 2019.
[17]Levri, J. A., Fisher, J. W., Jones, H. W., Drysdale, A. E., Ewert, M. K., et al., "Advanced Life Support Equivalent System Mass Guidelines Document," *NASA,* NASA/TM-2003-212278, 2003.
[18]Anderson, M. S., Ewert, M. K., Keener, J. F., and Wagner, S. A., "Life Support Baseline Values and Assumptions Document," *NASA,* NASA/TP-2015–218570, 2015.
[19]Zabel, P., Zeidler, C., Vrakking, V., Dorn, M., Schubert, D., "Biomass Production of the EDEN ISS Space Greenhouse in Antarctica during the 2018 experiment phase," *Front. Plant Sci.* 11:656, 2020.