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DEMONSTRATION TEST OF ELECTRICAL LIGHTING SYSTEMS FOR PLANT GROWTH IN HI-SEAS ANALOG MARS HABITAT

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Greenhouse modules and regenerative life-support systems are critical for long-duration space missions and future settlements on the Moon and Mars; understanding their mechanisms and issues on Earth in remote areas is a first step towards their space adaptation.

To follow up with studies performed in NASA‘s Deep Space Habitat and deployed at NASA Desert Research and Technology Studies test site in 2010 and 2011, and at NASA Johnson Space Center in 2012, three sole-source LED lighting systems – commercial-off-the-shelf “UFO” red and blue LED grow lights, AIBC’s super-slim whiteEx70Dim panels, and Heliospectra multispectral LX60 lamp – were tested during the four-month HI-SEAS (Hawaii Space Exploration and Analog Simulation) analog mission.

The primary objective of this study was to assess the effects of different wavelengths on lettuce and radish growth in a semi-controlled environment. Crew time required to take care of plants was also assessed.

A Biomass Production System for Education (BPSe) unit developed by ORBITEC and modelled after their Deployable Vegetable Production System was placed inside the habitat and available for crew interaction and recreational purposes. Preliminary results regarding psychological benefits of plants in remote areas during long-term isolation are presented.

I. INTRODUCTION

Long-duration space missions to the Moon and Mars will include greenhouse (plant production) modules and regenerative life-support systems, which will be critical to sustain the crew [1, 2], since resupplying to the Moon or Mars as is currently done on the ISS would not be an option due to high costs associated with sending payloads into space ($10,000 to Low Earth Orbit [3] and higher costs to more distant locations). Testing these systems on Earth in analog test sites and remote locations provides a deeper understanding of their mechanisms and issues and constitutes a first step towards their space adaptation.

Radiation levels on Mars will likely constrain future greenhouse modules to be under a thick layer of shielding, thus preventing the use of direct lighting from the Sun [4]. Sunlight can be gathered in parabolic collectors and then transmitted to the plant illumination system using fiber optics [5, 6]. But when a dust storm occurs on Mars this might not be enough. Therefore an efficient lighting approach would be a hybrid system providing electrical and natural lighting to the plants [7], mutually redundant systems and supplementing light when a single system cannot provide enough.

Implementation of hybrid lighting will require investigations of light spectrum for wavelengths to make plant growth under a hybrid lighting system as efficient as possible. One step in these investigations is to study plant growth efficiency under lighting systems composed of different color light emitting diodes (LED).

Indeed many studies have already showed that leaf conductance and stomatal opening react to different light wavelengths. Kim et al. in 2004 showed that light spectrum affects the diurnal changes of stomatal conductance [8]. In addition, blue light has important effects on stem elongation and leaf expansion [9, 10], as well as water relations [11].

Other important factors to take into account when growing plants in such a resource-limited environment are power requirements for lighting and water consumption of plants.

In a 1992 controlled-environment study on lettuce growth under fluorescent lights, Ikeda et al. showed that 45% of the total power in a plant factory was consumed by lights and 35% by air-conditioning – to remove the extra heat from these lamps [12].

This paper details a study of four different LED lighting systems on a small-scale plant production system, installed in the Hawaii Space Exploration Analog and Simulation (HI-SEAS) habitat (Fig. 1) during a 120-day simulation of mission on Mars from March to June 2014. The habitat is located in an abandoned quarry on the slopes of the volcano Mauna Loa, in Hawaii (USA). The first floor of the habitat is composed of a kitchen, a laundry area, and a living room and science laboratory where the plant experiments were conducted (Fig. 2).

It is surrounded by a string of cinder cones dotting a collapsed lava tube, resembling the Tharsis region of Mars and the habitat is isolated from any sign of animal, vegetal or human life activity. The simulation focused on psychological factors involving crew interaction and performance. This psychological study will have two follow-up missions of eight and twelve months using the HI-SEAS habitat.The simulation included a 20-minute one-way delay for communications with the outside to simulate the worst case scenario when the Earth and Mars are the furthest apart. For any outside activities the crew was required to wear analog space suits.

Earlier studies during missions on MIR or on the ISS showed that cultivating plants acts as a stress relief on the crew [13] and that the presence of plants in isolated or in extreme environments benefits human psychological state [14]. The small-scale plant production approach presented in this paper enabled a study of how plants influenced psychological well-being of the crew and how the crew interacted with plants during this long-duration isolation mission.

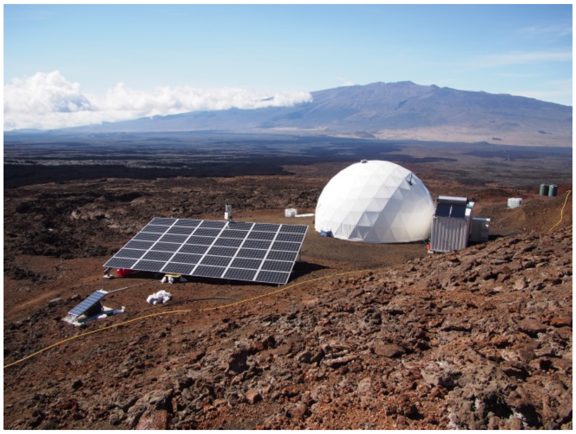

Fig. 1: HI-SEAS habitat on the slopes of Mauna Loa. Credits: Ross Lockwood.

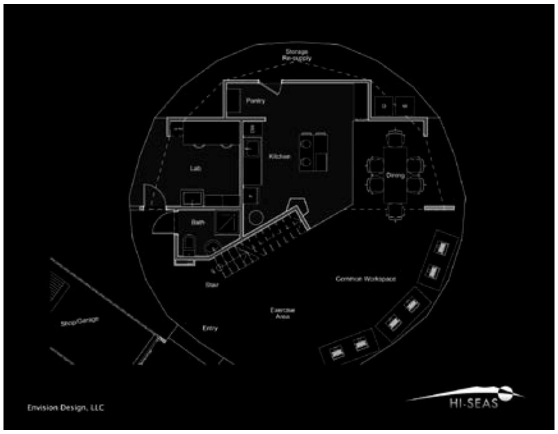

Fig. 2: Detailed schematic of the HI-SEAS habitat. Credits: HI-SEAS.

II. MATERIALS AND METHODS

II.I Lighting systems set-up

Lamps in the science laboratory

Three different kinds of lamp were set up in the science laboratory: two AIBC super-slim whiteEx70Dim panels (each with 216 cool white (6000K) LEDs, AIBC International, Ithaca, NY) positioned 22.5 cm and 17 cm above the plant trays (later referred in this paper as white panel #1 and #2 respectively), one commercial-off-the-shelf 50 W "UFO" red (630 nm) and blue (460 nm) LED grow lamp (AIBC-RB81-630, AIBC International, Ithaca, NY) positioned 25.5 cm above the plant tray, and one Heliospectra multispectral LX60 lamp red (660 nm), blue (450 nm) and white (5700K) positioned 19 cm above the plant tray (Fig. 3). These lamps allowed a study on the influence of wavelength on plant growth and morphology. The "UFO" red and blue lamp was tested in 2011 in the Deep Space Habitat (DSH) plant atrium during the NASA Desert Research and Technology Studies (DRATS) and both the UFO red and blue lamp and the white panels were tested in the DSH at NASA Johnson Space Center in 2012 [15].

Plants were grown in plastic trays provided by the Kennedy Space Center and also previously used in the Deep Space Habitat plant atrium [15].

Fig. 3: Set-up of the experiment in the science laboratory.

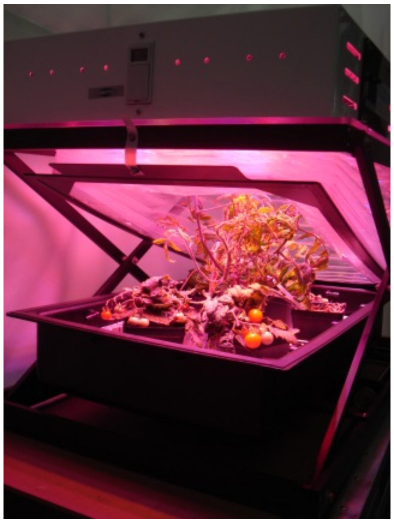

Fig. 4: Tomatoes growing in the ORBITEC BPSe.

Biomass Production System for education

The Biomass Production System for education (BPSe) provided by ORBITEC was located in the living room and served at studying crew interaction with plants (Fig. 4). The lighting system is composed of red (640 nm), blue (440 nm), and green (540 nm) LEDs.

II.II Plant species

Plants in the science laboratory

Lettuce *Lactuca sativa* L. cv. 'Waldmann's Green' (a green leaf lettuce) and cv. 'Outredgeous' (a red romaine lettuce) and radish, *Raphanus sativus* cv. 'Pink Beauty' and 'Rudolf' (Johnny's Selected Seeds, Winslow, Maine) were the plants grown to study the influence of light wavelength on plant growth.

Plants in the Biomass Production System for education

Plants grown in the BPSe varied from peas (*Pisum sativum* cv.'Earligreen', Utah State University) to green leaf lettuce (*Lactuca sativa* L. cv. 'Waldmann's Green', and 'Salanova', Rijk Zwaan) and red romaine lettuce (*Lactuca sativa* L. cv. 'Outredgeous'), radishes (*Raphanus sativus* cv. 'Pink Beauty' and 'Rudolf'), and tomatoes *(Solanum lycopersicum* cv. 'Microtina', Utah State University and 'Rutgers California Supreme', NASA seeds which were exposed to space in the LDEF satellite between April 6th 1984 and January 20th 1990).

II.III Soil and nutrient solution

The fertilizer solution used for both systems was BioThrive Plant Food from General Organics (NPK: 4-3-3). The nutrient solution was made diluting four teaspoons of the fertilizer into 1 gallon (3.8 L) of water. All plants were germinated in plant starters "Rapid Rooters" from General Hydroponics (genhydro, CA, USA).

Plants in the science laboratory

Plants in the science laboratory were grown in medium consisting of 200 mL of organic coco chips (Roots Organics by Aurora Innovations, Soilless Hydroponic Coco Media) and 250 mL of pre-wetted potting soil (Roots Organics by Aurora Innovations, Original Potting Soil).

Biomass Production System for education

Plants in the BPSe were grown in various combinations of medium: coco chips and potting mix, lava rocks (ejecta material about 1 cm diameter) from the surroundings of the habitat and potting mix, and lava rocks only.

II.VI Experiment description

Plants in the science laboratory: wavelength influence

This experiment was replicated twice. Each replicate lasted 27 days from seed to harvest for the lettuces and 20 days for the radishes.

During the first replicate, plants were watered every other day the first week and every day for the remaining duration of the experiment. Each watering consisted of 250 mL per tray. During the second replicate, they were watered every day during the whole length of the experiment and the amount of water varied between 250 and 500 mL per tray because signs of water stress were observed.

Light levels were set at 300 µmol/m^2/s during the first week and at 400 µmol/m^2/s until the end of the experiment, with a 16-hour photoperiod during the whole length of the experiment. An Apogee MQ200 quantum sensor enabled setting of desired levels. Since the lamps did not provide a uniform pattern, light was set so that the average on each tray would reach the desired value. Panda black & white plastic film (www.viagrow.biz) was set around each lamp and acted as reflective walls. The "UFO" lamp was non-dimmable and thus placed at 25.5 cm from the plants during the first week and at 22 cm during the remainder of the experiment. One of the white AIBC super-slim panels was placed at 22.5 cm and the other one at 17 cm from the plants. This difference comes from the fact that the second panel had some missing LEDs resulting in a lower light intensity at a given height. The Heliospectra LX60 was placed at 19 cm from the plants.

Four thermal and load-resistant fiberglass plant trays were used in this experiment, each measuring 44.5 cm L x 26.7 cm W x 10.5 cm H (Fiberglass Stacking Box, Product # 51058, www.usplastic.com). Eight plants were grown into each tray two of each cultivar (Waldmann's green, Outredgeous, Pink Beauty and Rudolf), positioned as indicated on Table 1.

Pink Beauty	**Waldmann's**
Outredgeous	**Rudolf**
Waldmann's	**Pink Beauty**
Rudolf	**Outredgeous**

Table 1: Plant organization within trays.

Fig. 5: Waldmann's green lettuce at harvest under each treatment on the second replicate of the experiment.

At the end of each growth period the following data were collected: images, measures of plant size (root, hypocotyl, and leaf length), plant fresh mass (leaves, hypocotyl and root), and leaf number (Fig. 5). Crew time was also measured for daily operations such as watering and temperature checking, as well as for operations such as sowing, transplanting and harvesting.

Biomass Production System for education

Each crew member was assigned a day to take care of plants growing in the BPSe. Plant care duties included watering, checking plant health, and harvesting.

Crew time was recorded for each activity and each crew member completed a survey before, during and after the mission, assessing their experience and their enjoyment of plant care and plant growth in the habitat as well as their commitment to it. Some questions asked for a rating on a scale from 0 to 10 (e.g. Please rate each of the following Food Production Activities), some were open questions (e.g., What effect did caring for the plant facility have on your mood?), and others a choice between two options (e.g., Would you prefer the amount of plants available to be smaller or greater?).

All plants harvested from both the lab studies and the BPSe were consumed by the crew.

II.V Environmental conditions

CO_2 levels were not controlled in the laboratory nor in the BPSe but values in the habitat varied between 600 and 1500 ppm (at 2500 m altitude and 75.3 kPa atmospheric pressure).

Temperature and humidity in the laboratory were not controlled, but readings were taken twice daily in the laboratory and under each light treatment using a digital thermometer/hygrometer from Growers's Edge (National Garden Wholesale, Sunlight Supply Inc.). Temperature differences between treatments were kept within 1.1°C on average.

Fig. 6 gives an overview of the temperature variation for each treatment during replicate 1 and replicate 2 of the experiment. The temperature in the laboratory was also monitored by a sensor of the built-in sensor network of the habitat.

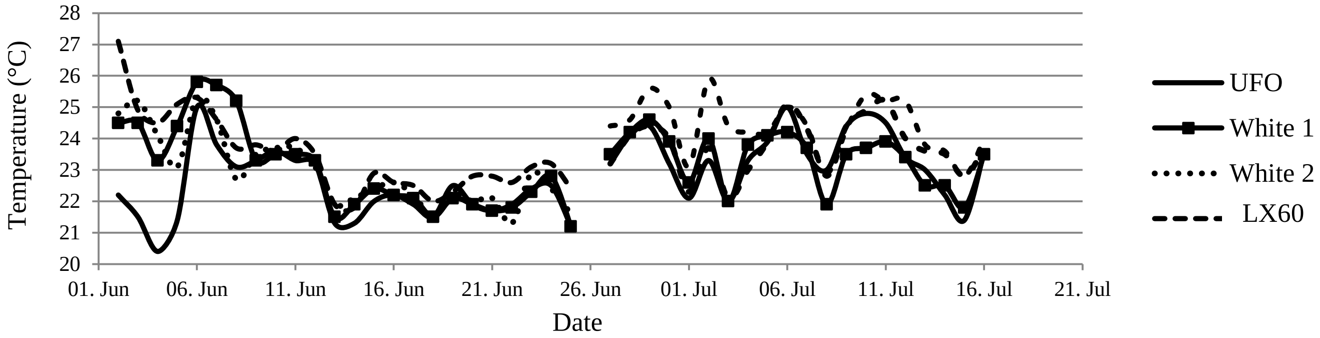

Fig. 6: Temperature variations in each treatment over the course of the experiment.

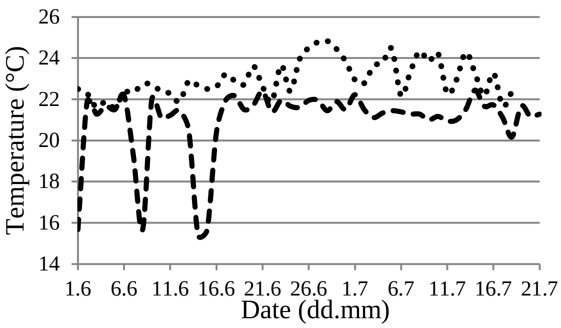

Fig. 7: Temperature in the lab at 08:00 (dashes) and 19:00 (points) over the experiment duration.

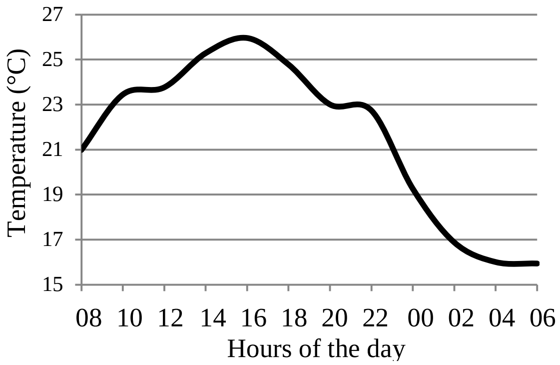

Fig. 8: Temperature in the lab over the course of one day.

Fig. 7 shows the temperature variations in the laboratory during replicate 1 and replicate 2 of the experiment at 08:00 (dashes) and 19:00 (points) and Fig. 8, the temperature in the laboratory over the course of one day on average during replicates 1 and 2.

III. RESULTS AND DISCUSSION

III.I Influence of wavelength on plant growth

Since results obtained in both replicates were similar, data of the two replicates are pooled and results for hypocotyl length, leaf fresh mass, and hypocotyl fresh mass (only for radishes; the hypocotyl is the edible portion of the radish) are presented below (Fig. 9, Fig. 10, and Fig. 11). Results are grouped per cultivar (PB= Pink Beauty, Ru= Rudolf; W= Waldmann's green; O= Outredgeous) and species (All R= All radishes and All L= All lettuces). Different light treatments are indicated with different colors (In blue, red and blue UFO; in red, white panel #1; in green, white panel #2; in purple, the multispectral LX60.). Each bar represents the average value for a given cultivar and a given light treatment over the course of the two replicates (4 plants).

The hypocotyl length of lettuces gives an indication on light quality and quantity. Insufficient blue light or total light will result in an elongated hypocotyl, which can be detrimental for young seedlings [16]. Here results showed some variations among cultivars for the hypocotyl length (Waldmann's Green hypocotyls were in average 44% longer than Outredgeous hypocotyls) but overall the different light treatments did not show notable differences on lettuce hypocotyl length.

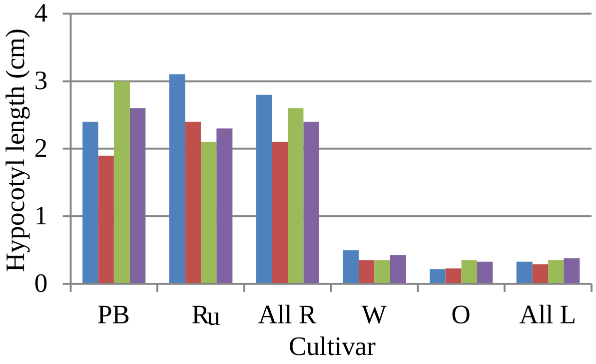

Fig. 9: Hypocotyl length per cultivar for each light treatment.

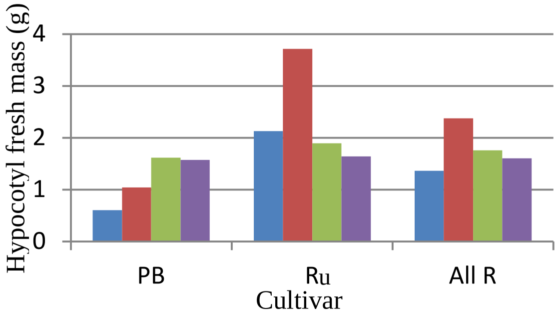

Fig. 10: Hypocotyl fresh mass per radish cultivar and for all radishes for each light treatment.

As mentioned earlier, the hypocotyl in radishes is the edible part. Results differ according to cultivars. First of all, there is a discrepancy between the two white treatments for Pink Beauty, showing two extreme results, the smallest and the longest hypocotyl. Overall, the red & blue treatment resulted in a longer hypocotyl compared to the three other treatments.

Examining the hypocotyl fresh mass of radishes gives more insight into the shape of the hypocotyl and its quality (Fig. 10). The cultivar Rudolf had on average among all treatments twice as much biomass for the hypocotyl than Pink Beauty. Although the red & blue treatment produced longer hypocotyls, it also yielded the least heavy ones, suggesting that the radishes looked long and thin, not ideal for consumption. These results indicate that white light or a combination of white, red and blue is more suited for the development of radish hypocotyls but differences between treatments will be further discussed.

Leaf fresh mass is the largest under the red & blue treatment for both radishes and lettuces, although differences between treatments are more notable in the case of lettuces than radishes.

In the case of radishes, the treatment which led to the smallest hypocotyl mass (red and blue light), also produced the largest leaf mass.

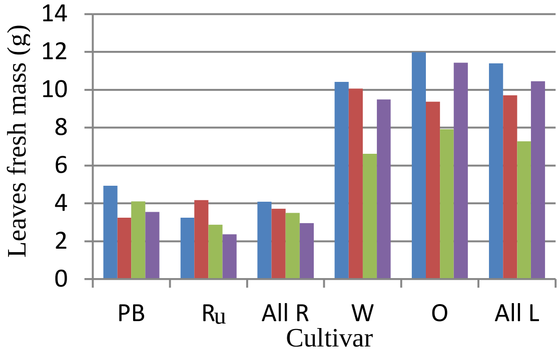

Fig. 11: Leaf fresh mass per cultivar for each light treatment.

On average the cultivar Outredgeous yielded more biomass than Waldmann's Green. Differences between treatments were more visible on Outredgeous. For both cultivars, the second white panel yielded less than the other treatments. This can be explained by the fact that some LEDs were missing on this panel, making the intensity on one side of the panel lower than in the rest of the panel and thus increasing the inhomogeneity of lighting.

For radishes, differences between treatments were not meaningful in the aggregate, but the two cultivars responded differently to light spectrum. Compared to the white light spectrum, the red & blue treatment yielded more leaf biomass and smaller hypocotyl mass for Pink Beauty. On the other hand, the white treatment triggered more leaf and hypocotyl mass in the Rudolf cultivar. All these conclusions are preliminary and more research in this direction could confirm or inform them. This could be critical information for future human space missions to Mars but also for controlled-environment agriculture on Earth.

As can be seen in Fig. 6, temperatures between treatments differed up to 4°C on some days due to poor temperature control in the habitat, resulting in a standard deviation on the two replicates of 0.6°C in average. Therefore it is very hard at this stage to conclude whether the differences observed between treatments were due to light or temperature difference or a mix of both.

III.III Surveys

The pre-mission crew survey indicated that two crew members had no experience with plants, one had experience in growing ornamental plants and herbs, and another one had a garden (vegetables and ornamental). It also showed that all crew members were used to eating fresh vegetables every day, with one person eating them multiple times per day. Thus, although this crew mostly was composed of beginners in plant growth, the all had an interest in growing vegetables.

The survey during the mission revealed that all crew members enjoyed consuming the plants grown in the habitat, as well as performing tasks such as potting, checking plants daily, or harvesting. The average level of satisfaction of having plants in the habitat ranked 8.75 on a scale from 0 to 10 (0 being not satisfied and 10 being very satisfied). All crew members reported that caring for plants gave them a feeling of productivity in plant growth - as well as providing them a calming effect and some change in their routine. Three out of four reported that it would be desirable to have a greater amount of plants in the habitat, though for different reasons: more plants means more time dedicated to take care of them and thus the activity would have been more engaging; more plants should be grown if they were to furnish a significant part of the diet. One crew member emphasized that the amount of plants grown during this mission made harvesting and consuming a special event and thus would like not to change it. Only one crew member perceived plant caring as recreational. For the rest it was perceived as work or a mix of work and recreation. Two crew members reported that the grow lights interfered with their daily activities: one because of light entering their room at night and the other because the electricity consumption was managed around the grow lamps. But they were all satisfied or indifferent to the light color and would not insist to have white light (and see green plants) instead of the purplish color displayed by the BPSe. Plant consumption was very appreciated among crew members who enjoyed the vegetable flavors as well as the change it made in the regular diet of dehydrated and freeze-dried food. All agreed that taking care of plants was worth the effort.

The post-mission survey showed that all crew members liked having plants in the habitat mostly because it provided them fresh food. They also reported that watching the plants growing was enjoyable. They all agreed that a future mission to Mars should include plants, mostly edible or utilitarian plants. They did not emphasize the need for ornamental plants. Two crew

	Watering	New Solution	Health check	Temp check	Harvest	Sowing	Transplant	Reorga	Cleaning	Thinning	Intensity raise	Photos	Total
Total (min)	232.6	27.7	71.4	106.6	415.7	79	153	58	37	24	193.2	49.7	1448
Avg (min)	1.6	2.1	0.7	2.1	50.2	16	38.3	0.6	37	7	22.9	2.3	15.6

Table 2: Total and average crew time per task and total crew time over the course of the experiment. Reorga = reorganization of plants in the tray; Avg = average time (mean) for each activity

members thought it would be beneficial to have ground experts guiding decisions on planting and harvesting plants unless one crew would have the necessary horticulture background. Another crew member thought these decisions should only be made by the crew, whereas the last one thought a mix of both would be beneficial. Crew members had the opportunity to add comments at the end of the survey and they all stated that this experience showed them the importance of plants in a space mission and opined that plant research in this direction should become a priority.

These survey results emphasize the psychological importance of the addition of fresh vegetables in astronauts' diet over long-duration missions. It confirms other results from previous studies that gardening provides crew members a calming effect as well as a break in their routine [13].

III.II Crew time

Total and average crew time for different operations of plant care is summarized in Table 2. The average time overall for plant care was 15.6 min per day. The longest task was the harvest, followed by transplanting and raising light intensity. The shortest tasks were watering, checking plant health, and reorganizing plants.

The high labor requirements documented here suggests that it would be beneficial to automate longer tasks like harvest and transplant of young seedlings during Mars missions, thus leaving more time to the astronauts to focus on the primary objectives of the mission. It should be noted however that the crew time results here should not be extrapolated to a crop production environment, since some of the time spent was invested in research tasks. According to the survey results, it would be good for the crew to be involved in plant growth (calming effect and sense of productivity), so not all the tasks should be automated in a Martian greenhouse module. Tasks like checking for water stress and plant health, which require human judgment, could be good ways to involve the crew the food production process.

IV. CONCLUSION

One way of improving lighting efficiency is to enhance plant growth by choosing specific wavelengths needed for photosynthesis and morphological development. More research is necessary on plant growth under different wavelengths in order to be able to fully understand the effects of light spectrum on specific crops and cultivars..

This study showed that crew members are willing to spend time taking care of plants during long-duration isolation missions and are willing to put in some efforts in order to eat fresh vegetables. We speculate that crew interest in plant-related tasks and in consuming fresh vegetables will increase with the mission length.

Increasing the amount of plants grown for future space missions will be achievable if some of the plant care is automated, enabling crew members to focus on their primary objectives.

IV. ACKNOWLEDGMENTS

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