

Gravitational and Space Research

Design, Build and Testing of Hardware to Safely Harvest Microgreens in Microgravity

Haley O. Boles¹, Lucie Poulet^{2,3}, Christina M. Johnson^{3,4}, Jacob J. Torres⁵, Lawrence L. Koss⁵, LaShelle E. Spencer⁵, Gioia D. Massa⁶

¹University of Florida, Florida, USA; ²Université Clermont Auvergne, Clermont Auvergne INP, CNRS, Institut Pascal, Clermont-Ferrand, France; ³NASA Postdoctoral Program, NASA Kennedy Space Center, Florida, USA; ⁴KBR, Moffett Field, California, USA; ⁵Amentum Services Inc, Kennedy Space Center, Florida, USA; ⁶NASA Kennedy Space Center, Florida, USA

Abstract

In long-duration space missions, crops will supplement the astronaut diet. One proposed crop type is microgreens, the young seedlings of edible plants that are known for their high nutritional levels, intense flavors, colorful appearance, and variety of textures. While these characteristics make microgreens promising for space crop production, their small size presents a unique challenge within the microgravity environment. To address this challenge, a microgreen planting box was developed to improve microgreen harvest techniques both in 1 g and in microgravity without concern for contamination by roots. Using this microgreen planting box, three parabolic flights were conducted where two different bagging methods (attached and manual) and three different microgreen cutting methods (Guillotine, Pepper Grinder, Scissors) were tested. In flight, the microgreens were contained within a glovebox and footage of all microgreen harvests was recorded. Statistical and trade analyses revealed that the combination of Cutting & Bagging method that performed the best was the Pepper Grinder with attached bagging. This was based on the following criteria: (1) average execution time, (2) microgreen debris, (3) biomass yield, (4) root debris, (5) microgreens left on the hardware, (6) number of seedlings growing under the lids, (7) hardware failure, and (8) perceived ease of use. This process allowed us to identify weaknesses and strengths of all hardware types and helped us identify major points of improvement within the hardware design to harvest microgreens in microgravity. Future directions include microgreen harvests in analog environments and further development of microgreen Cutting & Bagging method.

Keywords

microgreens • human factors • harvesting • parabolic flight • microgravity • space agriculture

Introduction

In long-duration space missions, crops will supplement the astronaut diet (Johnson et al., 2021). For long-duration missions, the current spaceflight diet has been shown to be deficient in certain key nutrients, including vitamin K, vitamin C, potassium, and calcium (Cooper et al., 2017). Crops can supplement these nutritional losses. One such proposed crop type is microgreens (Poulet et al., 2022), the young seedlings of edible herbs and vegetables (Teng et al., 2022) that are known for their intense flavors (Caracciolo et al., 2020), colorful appearance, and variety of textures (Chloe et al., 2018). Microgreens contain high concentrations of vitamins and minerals (Xiao et al., 2012 and 2016). Calcium, vitamin K, potassium, phosphorus, and manganese improve bone health (Tylavsky et al., 2008; Rondanelli et al., 2021; Alonso et al., 2023) while β -carotene and vitamin E improve ocular health for astronauts (Tanito, 2021). Microgreens also contain

vitamin C, which mitigates radiation damage (Mortazavi et al., 2014).

While these characteristics make microgreens a great candidate for space crop production, they also present many unique challenges within the microgravity environment. Microgreens are grown with a high planting density (Hummerick et al., 2022), which can become difficult to handle when harvesting large quantities. Traditional methods of harvesting microgreens for small-scale operations include harvesting with scissors or a knife, both of which can be time intensive and expose the operator to an open blade (Riggio et al., 2019). Crew time is a limited resource in space, and astronauts need to be able to operate quickly and easily to ensure an efficient workflow (Zeidler et al., 2021). Also, microgreens are grown in contact with water and fertilizer, leading to a high microbial load in the root zone (Turner et al., 2020). A high microbial load presents food safety concerns

[†] Corresponding author: Lucie Poulet
E-mail: lucie.poulet@uca.fr

(Yeargin et al., 2023), so for the purposes of spaceflight only microgreen shoots are to be eaten.

To ensure astronauts will be able to harvest microgreens in microgravity with ease while avoiding the introduction of debris to the spacecraft cabin, multiple harvesting methods were developed by the Space Crop Production Team at NASA's Kennedy Space Center. These harvesting methods were separated into three different microgreen cutting methods (Pepper Grinder, Guillotine, and Scissors) as well as two different bagging methods (attached and manual). These harvesting methods were then evaluated on three parabolic flights conducted in November and December 2021. The hardware in which the microgreens were grown for the parabolic flight testing ensured separation between the root and the shoot zones, likely limiting microbial contamination. In each parabolic flight, the microgreens were contained inside of a glovebox and footage of all the harvests was recorded. This paper presents the post-flight analyses conducted to determine which method was the most suitable (under multiple criteria) to harvest microgreens in microgravity as well as the benefits and drawbacks of the different approaches.

Materials and Methods

Plant Preparation

Daikon radish, *Raphanus sativus* var. longipinnatus (True Leaf Market, Salt Lake City, Utah) were grown on bamboo VegBed Microgreen Mats (Hackensack, NJ). Preliminary studies were conducted to select varietal and substrate. Daikon radish was chosen because it grew quickly and had reliable, even growth (Figure 1). The chosen substrate, a soft grow mat, had higher yields than other fiber-based substrates, with the added benefit of being autoclavable, which will be useful for future flight applications.

Plants were grown in a controlled environment chamber at NASA Kennedy Space Center with conditions set to 1,000 ppm CO₂, 70% relative humidity, and 23°C. Light was provided by Biomass-Production-Systems-for-Education (BPSe) (ORBITEC, now Sierra Space, Madison, WI) or Phytify® RL (OSRAM GmbH Munich, Germany) lighting arrays throughout the growth cycle (7 days). The light intensity under the BPSe was on average 255 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, with 40% red (630 nm), 25% blue (455 nm), and 35% green (530 nm). The light intensity under the Phytify® RL arrays was on average 400 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, with a light spectrum 31.1% blue (450 nm), 34.4% red (660 nm), and 34.5% green (521 nm). Approximately 150 mL of half-strength Hoagland solution was used in each hardware unit.

Due to the nature of the mission, plants did not remain in their closely controlled environment for the last 2–3 days of growth. Instead, plants were transported by car in trays covered with plastic domes (Greenhouse Megastore, Danville, IL)

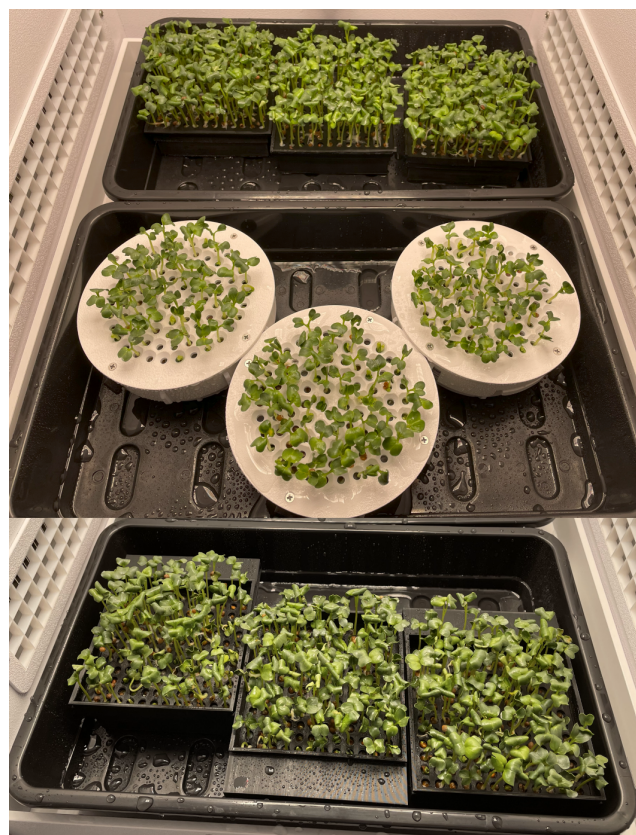


Figure 1. Scissors (top), Pepper Grinder (middle), and Guillotine (blade removed) (bottom) planting boxes with young Daikon radish microgreens.

and maintained in suboptimal growing conditions (i.e., no environmental control, no grow lights) the night(s) before the parabolic flights. Before each flight, 24 planting boxes were chosen that had ~100% germination and uniform growth.

Parabolic Flight

Three parabolic flights were performed over two separate research flight campaigns in November and December 2021 aboard Zero-G Corporation's modified Boeing 727 aircraft. Each flight consisted of 30 parabolas, separated into six groups of five parabolas. The first group of parabolas helped operators to get used to reduced gravity and was comprised of two parabolas in Martian gravity (0.38g) followed by three parabolas in Lunar (0.16g) gravity, which did not count for our study. The following five groups were all in microgravity (< 0.01g). Each parabola lasted in total approximately 60 seconds, starting with 20 seconds of 1.8g, followed by 15 to 20 seconds of microgravity, and finishing with 20 seconds of 1.8g (Figure 2). Between each group of parabolas, an approximate 3-minute break at 1g was given, which allowed for resetting of hardware.

The experimental setup inside the aircraft consisted of a glovebox (University of Louisville) equipped with two video cameras (Sony HDR-CX 260A and Nikon KeyMission 170), an accelerometer (custom-made from the University of Louisville), microgreen planting boxes, and harvesting bags (Figure 3). The glovebox's purpose was to contain any fluids or materials that may become airborne during the reduced gravity sections of the parabolic flight. Underneath the glovebox, microgreen planting boxes and harvesting bags for

subsequent parabolas were stored. The microgreen planting boxes, scissors, harvesting bags, and waste bags were secured inside the glovebox using VELCRO®, with planting boxes and scissors secured to the floor, and other supplies secured to walls.

On each parabolic flight, three operators participated in a harvest in one of three roles: harvester, assistant, or coordinator. Operators were cross-trained for each role and rotated positions after every parabola group. During the ~3-minute break between parabola groups, the glovebox was cleaned of any microgreen debris and the used microgreen planting boxes as well as used harvesting bags were exchanged for new sets. Freshly harvested microgreens were left in their harvest bags and were placed in the drawer beneath the glovebox for ground-based analysis. During each parabola, the harvester was tasked with cutting and bagging the microgreens. The assistant helped the harvester by handing them necessary supplies such as the harvest bag or scissors as well as cleaning the glovebox between harvests. (See harvest videos on the supplemental materials tab on the article page). The coordinator was responsible for ensuring that harvests were performed within the altered gravity window and that the harvests were performed in the correct order to avoid bias. The operator in the harvester role also filled out an in-flight survey on each of the Cutting & Bagging method used in that parabola group. If any team members became indisposed the assistant also assumed coordinator responsibilities.

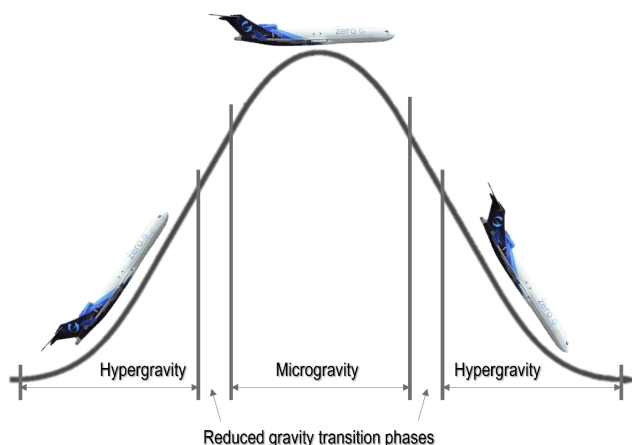


Figure 2. Parabolic flight phases. Hypergravity was experienced during ascent, microgravity at the inflection point, and hypergravity upon descent. Airplane image courtesy of Zero Gravity Corporation.



Figure 3. Experimental setup within the ZeroG aircraft. Left: overview of the glovebox in its flight configuration within the aircraft. Right: a view inside the glovebox showing one of the two cameras filming the inside.

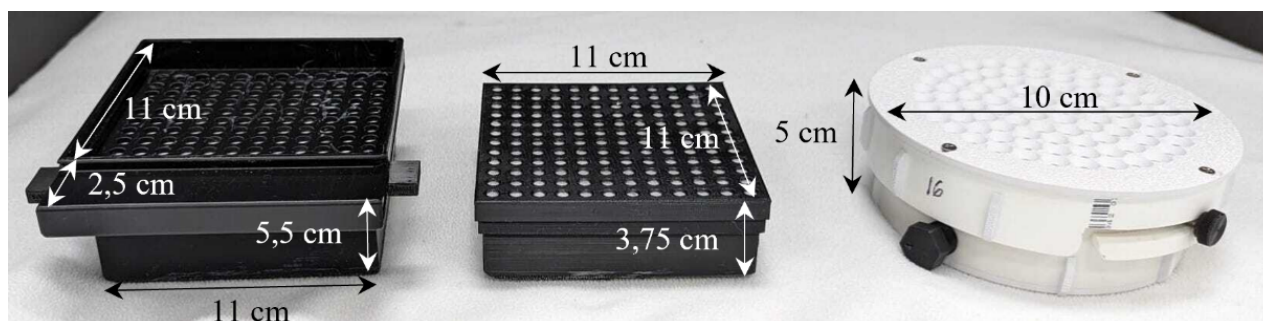


Figure 4. Photograph showing (left) Guillotine, (center) Scissors, and (right) Pepper Grinder microgreen planting boxes.

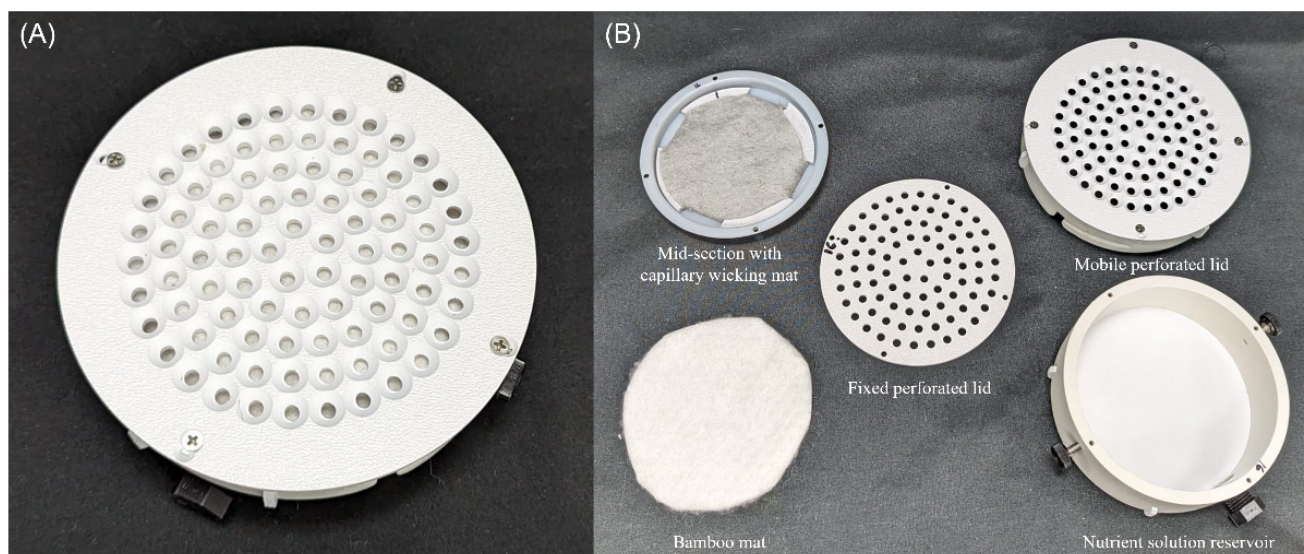


Figure 5. Pepper Grinder hardware. (A) Top view of the assembled hardware. (B) Top view of the different pieces of the hardware.

Growth Hardware and Cutting Methods

Figure 4 shows the three different microgreen cutting methods tested in parabolic flight, known as Guillotine, Scissors, and Pepper Grinder. Microgreens were seeded in microgreen planting boxes with the cutting hardware integrated (except Scissors), grown, and then harvested during flight. Planting boxes are composed of shells as well as inner textile components. The planting density differs between the Pepper Grinder (1.13 holes / cm²) and the Guillotine/Scissors growing hardware (1.44 holes / cm²). A combined cutting & bagging method where the bag was directly attached to the scissors was tested during the first parabolic flight but was found to be unsuitable due to its difficulty of operation and high debris generation. Therefore, it was discarded in later flights.

Pepper Grinder

The growth and cutting hardware called “Pepper Grinder” was in-house machined hardware composed of a reservoir for the

nutrient solution (250 mL), a midsection where a capillary wicking mat and a bamboo mat were placed, a fixed perforated lid (10 cm diameter), and a mobile perforated lid (Figure 5). The seeds were placed within the 89 holes of the lid, and the seedlings then emerged, with their roots attached to the bamboo mat below. During the harvest, the mobile lid rotated while the rest of the hardware remained fixed (like a pepper grinder), cutting the stalks of the microgreens all at once. The Pepper Grinder was fabricated from stainless steel screws, PVC pipe, and ABS plastic sheet. When fully assembled, the hardware dimensions were 10 cm diameter and 5 cm in height.

Guillotine

The growth and cutting hardware called “Guillotine” was 3D-printed hardware composed of a lid (11 cm x 11 cm) with 144 holes for the microgreens to grow out of, a midsection that snapped onto the lid, and a hydroponic basin (Figure 6). The midsection contained a bamboo mat (10 cm x 10 cm)

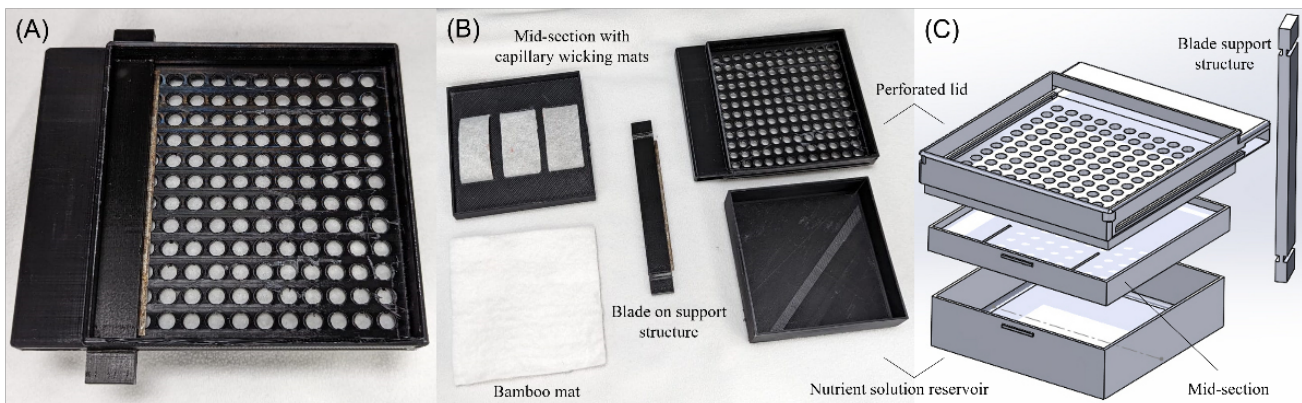


Figure 6. Guillotine hardware. (A) Top view of the assembled hardware, (B) Top view of the different pieces of the hardware, (C) CAD drawing of the different hardware elements.

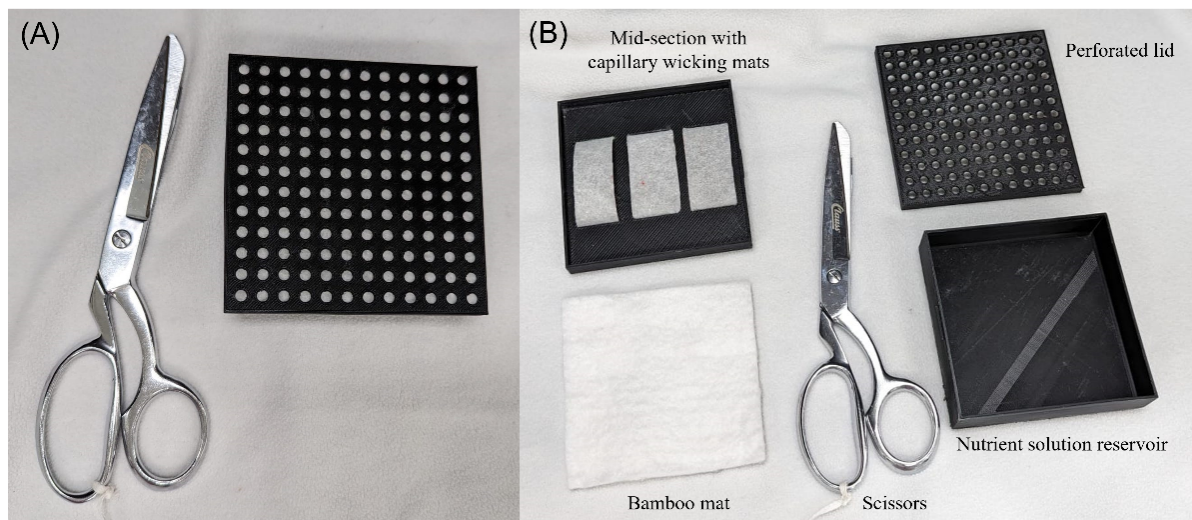


Figure 7. Scissor and growth hardware. (A) Top view of the scissors and growth lid. (B) Top view of the different pieces of the growth hardware and scissors.

and three capillary mats that extended down below into the hydroponic basin (210 mL), which contained the nutrient solution. The seeds were placed within the holes of the lid, and the seedlings then grew out, attaching their roots on the bamboo mat below. A razor blade was glued to a supporting structure, which could be inserted in the lid when it was time to harvest. To harvest microgreens, the blade was pulled from one side of the lid to the other, cutting the microgreen stalks as the blade passed. The Guillotine hardware was manufactured from poly lactic acid (PLA) and the dimensions of the fully assembled hardware were 13.5 cm x 11 cm x 5.5 cm.

Scissors

Microgreens are often harvested with scissors on Earth, so a similar approach was used as a control for these flight

experiments. The growth hardware used with the scissor-cutting method was made from 3D printed PLA like the Guillotine (210 mL basin volume, 11 cm w 11 cm lid, 144 holes), except there was no space in the lid for the blade support structure to be inserted (Figure 7). During all three parabolic flights, the scissors (carbon steel, 8"/20.32 cm, Clauss) were tethered inside the glovebox using a string and VELCRO®, to prevent them from free flying within the glovebox. When fully assembled, the hardware dimensions were 11 cm x 11 cm x 3.75 cm.

Bagging Methods: Manual, Attached bag

Two different bagging methods, manual bagging and attached bagging, were tested to contain the microgreens in microgravity (Figure 8).



Figure 8. Bagging methods. Left: attached bag. Right: zip-top bag.

Manual Bagging

The operator gathered the microgreens at the surface of the cutting hardware with one hand, cut the microgreens with their other hand, and deposited the microgreens into an open zip-top bag. The zip-top bag (15.1 cm x 23.1 cm) was then closed to avoid having microgreens escape into the glovebox (See harvest videos on the supplemental materials tab on the article page).

Attached Bagging

The attached bag was a 1-gallon paint strainer (Home Depot, HDX Model #11572/36WF) modified with a drawstring inserted 11 cm above the elastic base, enabling the bag to be closed. The attached bag was placed on the cutting hardware via the integrated elastic band (Figure 9). Once the microgreens were cut, the cutting hardware and attached bag were shaken in a rotating motion, enabling the microgreens to be directed upward within the bag. The operator then pulled the drawstring, thereby closing the bag, and then removed the attached bag from the cutting hardware (See harvest videos on the supplemental materials tab on the article page).

Collected Data

During the flight, two video cameras installed in the glovebox filmed the operators' actions. This enabled the retrieval of quantitative data and data on any hardware anomalies via post-flight video analysis. After each group of parabolas, the operator within the harvester role completed a survey with questions on their perception of the ease of use for the cutting hardware and on the bagging methods.

Immediately after landing, all harvest bags were weighed (Sartorius L 420 P lab balance, Range + 0.000 to 300.000 g) and contamination from roots within them was visually assessed. All harvested boxes were also photographed

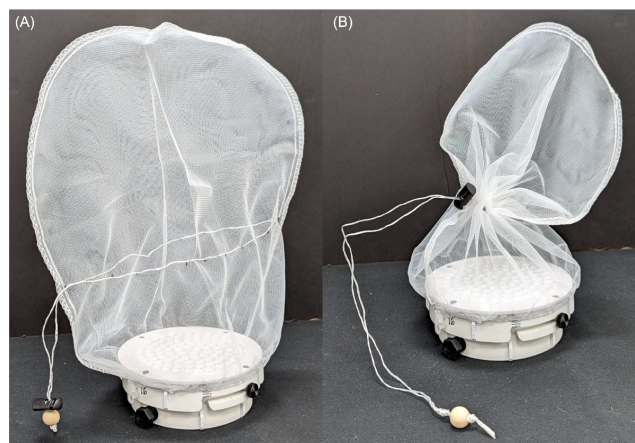


Figure 9. Attached bag on Pepper Grinder hardware. (A) Loose string, position while cutting the microgreens. (B) Tied string, position after harvesting complete.

(Canon 250D DSLR (lens: 50 mm)) enabling the assessment of the cleanliness of cuts, as well as the success of germination emergence and separation (Table 1).

Statistics and Trade-Analysis

Prior to conducting a trade analysis to compare the six different cutting & bagging combinations (Pepper Grinder with attached bag, Pepper Grinder with manual bagging, Guillotine with attached bag, Guillotine with manual bagging, Scissors with attached bag, and Scissors with manual bagging), the mean, standard deviation and outliers were computed for the seven quantitative criteria detailed in Table 2. Additionally, ANOVA analyses were performed on each of these criteria to determine the influence of the following factors: flight, parabola group, the three operator roles, parabolic experience of the harvester, and the Cutting & Bagging method.

Time of execution refers to the average time across all operators needed to perform the harvesting, from cutting to bagging. This started at the beginning of the microgravity phase and stopped when the bag was closed. Approximately 31% of the time, the bag was closed during the microgravity phase (0g to 0.1g); 33% of the time, the process of harvesting and bagging exceeded the microgravity phase and had to be finished during the reduced gravity transition phase (0.1g to 1g); and 35% of the time, the harvest was finished at the beginning of the hypergravity phase (1g to 1.8g). Microgreen debris refers to pieces of microgreens that were cut but did not make it into the harvesting bag. They would end up free-floating in microgravity and could constitute a hazard in a spacecraft. During this experiment, they corresponded to the average number of microgreen debris left in the glovebox after harvesting. Yield is the average biomass harvested by each hardware and adjusted for the planting density (1.44 holes/cm² for the Guillotine and Scissor hardware, 1.13 holes/cm²

Table 1. Quantitative and qualitative data collected in-flight and post-flight.

	Quantitative Data	Qualitative Data
In-Flight	- Time needed for harvesting - <i>Video Analysis</i> - Duration of the reduced gravity phase - Cutting - Containment (bagging) - Stowing bag - Microgreens contamination within the glovebox - <i>Video Analysis</i>	Harvester questionnaire - <i>Spreadsheet</i>
Post-Flight	- Harvest bags weights - <i>Spreadsheet</i> - Root contamination within harvest bags - <i>Spreadsheet</i>	Photos of harvested boxes - <i>Photos</i>

Table 2. Criteria and associated weights used for the trade analysis, along with justification for each criterion.

Criteria	Evaluation Data	Data Collection	Justification	Weight
Time of Execution	Average total harvest time across all operators	Flight video analysis	Crew time needs to be minimized	1
Microgreen Debris	Average debris counts across all operators	Flight video analysis	Loss of food and environmental safety hazard—needs to be minimized	2
Yield (edible biomass)	Fresh mass adjusted by planting density	Post-flight weighing	Biomass production needs to be maximized	2
Root debris	Average root debris counts across all operators	Post-flight count	Food safety hazard needs to be minimized	2
Percentage of microgreens left on the hardware	Ratio between microgreen plants remaining on hardware and total plants	Post-flight count	Loss of food—needs to be minimized	1.5
Number of seedlings growing under the lids	Average number across all units of a given hardware	Post-flight photo analysis count	Loss of food—needs to be minimized	1.5
Percentage of no failures of the hardware	Ratio between number of hardware failure and total runs	Flight video analysis	Severe loss of food, potential food safety hazard—needs to be minimized	2
Perceived ease of use	Average score across all operators	In-flight surveys	Mental health of crew—needs to be maximized	1

for the Pepper Grinder), excluding microgreen debris. Root debris refers to the average amount of roots found in the harvest bag post-harvest. The percentage of microgreens left on the hardware was evaluated post-flight, and it is the ratio of the number of individual microgreen plants left on the hardware to the total number of microgreen plants initially grown on the hardware (144 for Guillotine and Scissors—89 for Pepper Grinder). The number of seedlings growing under the lid refers to the number of plants, which did not manage to adequately grow through the holes in the lids and remained trapped underneath. The percentage of no failure of the hardware refers to the average number of times the hardware did not fail during the harvesting process. Perceived ease of use was evaluated based on in-flight questionnaires filled in by the operator in the harvester role, using a subjective scale from 1 (very easy) to 10 (very hard).

Collected data for each criterion were normalized by percentage of maximum to allow grouping into a final score. Data on values to be minimized were first reversed, to allow normalization. The reversed value is equal to the sum of the minimum and maximum values, minus the raw value. After all data were normalized, each value was multiplied by its weight. Ordinal ranking coupled to a pairwise comparison of each criterion was used for weight attribution. A weight of 2 was attributed to the most important factors, which are in

direct link with the project objective of building a hardware that can be used for easy and safe microgreen food production: microgreen debris, yield, root debris, and percentage of no failure. In comparison, the percentage of microgreens staying on hardware after harvest and the number of microgreens growing under the lid are less important and can be improved on later iterations. Therefore, a weight of 1.5 was attributed to these factors. Finally, time of execution and perceived ease of use are the least important factors in this study and were given a weight of 1. Indeed, time of execution will be somewhat important in future space missions but will not have to be within 20 seconds—this was a particularity of the parabolic flight. Regarding the perceived ease of use, since this was a subjective parameter, it was decided not to amplify it. The sum of each individual criterion score gave a final score for each combination of cutting & bagging.

Results

Source Data

Table 3 gives a summary of the average data collected for each criterion and each combination of cutting & bagging. For the execution time, it was not possible to get the effects of all seven factors (flight, parabola group, the three operator

roles, parabolic experience of the harvester role, and the Cutting & Bagging method) with a seven-way ANOVA analysis because of unbalanced sets of data. To study the effects of these factors, we performed three five-way ANOVA analyses on the four factors: parabola group, the harvester role, the assistant role, and the Cutting & Bagging method, against the fifth factor being flight, the coordinator role, or the parabolic experience of the role of the harvester. These analyses showed no significant effect of the flight, the role of coordinator, or the parabolic experience of the harvester on execution time. A four-way ANOVA analysis on the factors of parabola group, the role of the harvester, the role of the assistant, and the Cutting & Bagging method showed that only the role of the harvester ($p=0.00022$) and the Cutting & Bagging method ($p=0.00052$) had a significant effect on execution time. After removal of one outlier and running a two-way ANOVA test for the factors of the Cutting & Bagging method and the harvester role, the only factor with significant influence on execution time was the Cutting & Bagging method ($p=0.0142$). A two-way ANOVA analysis on the cutting method and the bagging method showed that only the cutting method has a significant effect on time of execution ($p=0.006$). A one-way ANOVA test on the Cutting & Bagging method revealed a p value of 0.0186, where the Pepper Grinder with attached bagging exhibited a significantly faster time of execution than the Scissors with attached bagging (Table 3). Looking only at cutting methods, the Pepper Grinder cutting method had the fastest execution, Scissors the slowest, with the Guillotine in-between. Manual

bagging led to a slower overall execution time for Pepper Grinder and Guillotine compared to attached bagging, but not for Scissors.

The same approach was used for the yield. After removal of the outliers, the five-way ANOVA tests showed no significant effect of the flight, parabola group, the role of operators, or the parabolic experience of the harvester on yield but did show significant effect of the Cutting & Bagging method on yield. A two-way ANOVA test showed no significance of either cutting or bagging method. A one-way ANOVA on the Cutting & Bagging method showed a significance of $p=0.0054$, with the Pepper Grinder with Manual bagging yielding significantly less microgreens mass than the Guillotine with Manual bagging and the Scissors with attached bagging (Table 3).

Regarding microgreen debris, hardware failure, microgreens left on the hardware, and root debris, the same approach as previously mentioned was used. For microgreen debris, the factors of flight, parabola group, the role of operators, or the parabolic experience of the harvester had no significant effect. However, a two-way ANOVA test showed an interaction between the bagging method and cutting method ($p=0.0105$), and that the bagging method ($p=3.5 \times 10^{-6}$) was the main influence on microgreen debris generation. A one-way ANOVA on Cutting & Bagging method gave a p value of 2.5×10^{-5} and showed that manual bagging methods generated significantly more microgreen debris than attached bagging methods. The Cutting & Bagging method combination that introduced the lowest amount of microgreen debris was

Table 3. Average and standard deviation for eight different criteria and the six combinations. The letters indicate the different significance between means of the different groups following a one-way ANOVA test on the given criterion, for the factor Cutting & Bagging method. *N=9 for the yield computation of Pepper Grinder with attached bagging. N=8 for the yield computation of Pepper Grinder with manual bagging. N=9 for the time of execution computation of Scissors with attached bagging. **For this criterion, only differences in the growth hardware were evaluated with no effect on the cutting or bagging method and this was only done on two flights and N numbers were, respectively, 6, 8, 7, 6, 7, and 6. *** For this criterion, the survey questionnaires did not single out differences between bagging methods, only differences in the perceived ease of the cutting method.

Cutting & Bagging Method	Number of Cases	Mean Time of Execution (s) +/- Standard Deviation	Microgreen Debris (number)	Yield (g of edible biomass)	Root Debris (number)	Microgreens left on Hardware (%)	Seedlings Growing under Lid (number)**	No Hardware Failure (%)	Perceived Ease of Use***
Guillotine Attached	9	ab 18.00 +/- 4.4	ab 7.78 +/- 7.0	ab 19.39 +/- 5.7	a 1.89 +/- 2.4	a 12.56 +/- 8.0	ab 13.14 +/- 10.7	a 100 +/- 0	4.03
Guillotine Manual	11	ab 19.27 +/- 3.7	a 8.82 +/- 4.3	a 23.42 +/- 7.0	a 2.55 +/- 2.7	a 4.91 +/- 3.4	ab 13.14 +/- 10.7	a 100 +/- 0	4.03
Pepper Grinder Attached	10*	a 13.20 +/- 4.7	b 2.60 +/- 1.8	ab 15.24 +/- 2.6	a 0.90 +/- 1.4	a 0.40 +/- 0.5	a 16.00 +/- 5.3	ab 80 +/- 40	1.87
Pepper Grinder Manual	9*	ab 16.89 +/- 5.0	a 11.00 +/- 5.9	b 12.36 +/- 3.0	a 0.89 +/- 1.6	a 0.67 +/- 0.67	a 16.00 +/- 5.3	a 100 +/- 0	1.87
Scissors Attached	10*	b 20.89 +/- 5.7	b 2.00 +/- 1.7	a 22.68 +/- 7.7	a 0.90 +/- 1.4	b 30.20 +/- 16.7	b 6.54 +/- 3.7	b 60 +/- 49	4.77
Scissors Manual	9	ab 19.56 +/- 3.9	a 12.11 +/- 4.3	ab 21.42 +/- 9.1	a 1.67 +/- 1.9	a 11.2 +/- 7.6	b 6.54 +/- 3.7	a 100 +/- 0	4.77

the Scissors with attached bagging (2.00 particulates on average per harvest), closely followed by the Pepper Grinder with attached bagging (2.60 particulates on average per harvest). However, the Scissors with attached bagging may have introduced fewer particulates into the glovebox because on average; 30.2% of the microgreens were never cut using the Scissors method, so there were fewer particulates generated overall (Table 3).

For hardware failure, there was no significant effect of the harvester role, and a two-way ANOVA test showed no interaction between the bagging method and the cutting method, but the Bagging method was the main influence ($p=0.0084$) on hardware failure. A one-way ANOVA on the Cutting & Bagging method gave $p=0.0073$ and showed that Scissors with attached bagging exhibited a significantly higher number of hardware failures than other combinations of Cutting & Bagging method. Common failures observed included the 3D printed lids falling off when the attached bags were removed and the attached bag itself ripping (Table 3).

For the number of microgreens left on the hardware, both Cutting & Bagging method showed significant effect and interaction between the two. A one-way ANOVA test on the Cutting & Bagging method showed that Scissors with attached bagging left significantly more microgreens on the hardware than all the other methods ($p=1.8 \times 10^{-9}$) (Table 3). For root debris, the role of the harvester was significant, but not the Cutting & Bagging method. A two-way ANOVA test on these two factors gave a p value of 0.0043 for the role of the harvester (Table 3). The Pepper Grinder generated the smallest levels of root debris, regardless of the bagging method. The Pepper Grinder also led to the smallest percentage of microgreens left on the hardware. This is linked to the cleanliness of the cut performed by the Pepper Grinder and further elaborated upon in the discussion, section 4.1.1. The Guillotine cutting method generated two to three times more root debris than the Pepper Grinder, for both bagging methods. The Scissors generated twice as much root debris when the microgreens were manually bagged compared to when the bag was attached to the hardware. This can be explained in two different ways, the first being that when the microgreens were collected for manual bagging, the microgreens remaining on the hardware that were not cut were torn out of the growth media, bringing the roots with the hypocotyls. The second explanation is that there were twice as many microgreens remaining on the hardware with the attached bagging method than with the manual bagging, providing less opportunity for roots to be mixed with the edible biomass. The fact there are about 2.5 times more microgreens remaining on the Guillotine with attached bagging than on the Guillotine with manual bagging suggests that operators were in fact tearing the microgreens out of the hardware as they were gathering them for bagging.

Regarding the last criterion, microgreens growing under the lid, the study was only made on the last two flights. ANOVA tests revealed that the significant factor was the Cutting method ($p=0.0106$), and the Pepper Grinder had significantly more microgreens growing under the lid than the Scissors growing hardware (Table 3).

In terms of user experience, the Pepper Grinder was perceived as the easiest to use (1.87), far in front of the Scissors (4.77) and the Guillotine (4.03), which were ranked toward the middle of the scale (1–10).

Results of the Trade Analysis

Table 4 presents the results of the trade analysis performed between the six combinations of Cutting & Bagging method across the eight factors previously presented.

The trade analysis found the Pepper Grinder with attached bagging to be the highest ranked Cutting & Bagging method combination, followed by the Scissors with attached bagging, and the Pepper Grinder with manual bagging right behind (Figure 10). The cutting & bagging combination that ranked lowest was the Scissors with manual bagging, followed by the Guillotine with manual bagging.

Bagging Comparison

Looking at the overall scores within the trade analysis, the attached bagging outperformed the manual bagging for the Pepper Grinder (10.9 vs. 9.5) and for the Scissors (9.7 vs. 9.1).

Looking at specific data categories within the trade analysis, cutting & bagging combinations that used attached bagging generated lower levels of microgreen debris than methods that used manual bagging. However, while there was no difference in performance between the different bagging methods paired with the Guillotine in terms of the frequency of failures, fewer failures were seen in the Pepper Grinder with manual bagging combination as well as the Scissors with manual bagging combination.

Discussion

Hardware Validation for Future Spaceflight

Different areas of improvement needed to validate a microgreen harvest system for spaceflight applications are detailed below.

Attached Bag

The Scissors with attached bag was significantly slower than the other methods. The attached bag worked very well for hardware where the cutting mechanism was integrated, but it was not faster for the Scissors method, likely because the Scissors had to be inserted in a slit in the attached bag,

Table 4. Normalized and weighted data for each criterion of the six combinations of Cutting & Bagging method. *For this criterion, only differences in the growth hardware were evaluated with no effect on the cutting or bagging method. ** For this criterion, the survey questionnaires did not single out differences between bagging methods, only differences in the perceived ease of the cutting method.

Cutting & Bagging Method	Time of Execution (s)	Microgreen Debris (number)	Yield (g of edible biomass)	Root debris (number)	Microgreens left on Hardware (%)	Seedlings Growing under the Lid (number)*	No Hardware Failure (%)	Perceived Ease of Use**	Total	Rank
Guillotine Attached	0.77	1.05	1.66	1.21	0.90	0.88	2.00	0.55	9.01	5
Guillotine Manual	0.71	0.87	2.00	0.70	1.28	0.88	2.00	0.55	8.98	6
Pepper Grinder Attached	1.00	1.90	1.30	1.99	1.50	0.61	1.60	1.00	10.91	1
Pepper Grinder Manual	0.82	0.51	1.06	2.00	1.49	0.61	2.00	1.00	9.49	3
Scissors Attached	0.63	2.00	1.94	1.99	0.02	1.50	1.20	0.39	9.67	2
Scissors Manual	0.70	0.33	1.83	1.39	0.96	1.50	2.00	0.39	9.10	4

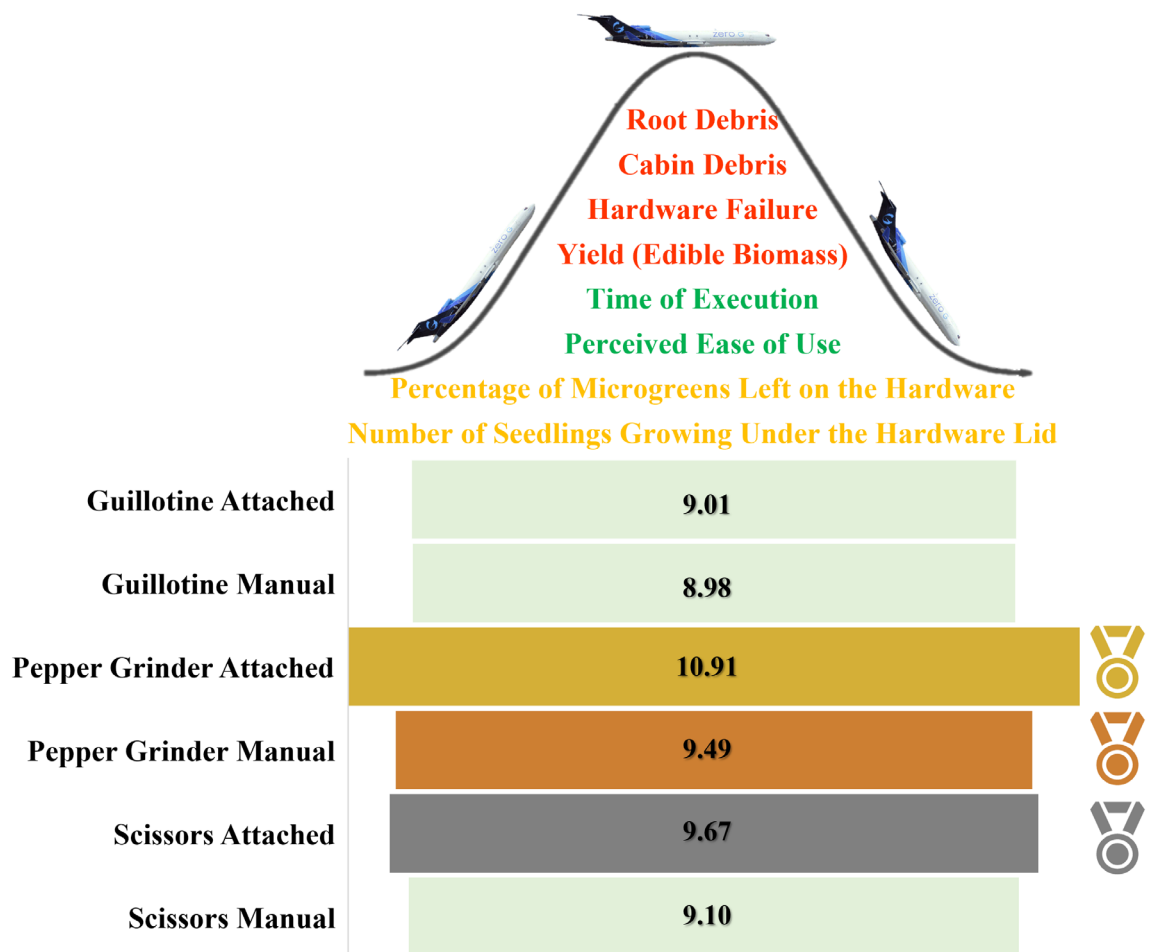


Figure 10. Graphical representation of the trade analysis results, giving the scores of each Cutting & Bagging combination. The evaluation criteria are indicated, their color indicate their weight: red = 2, yellow = 1.5, green = 1.

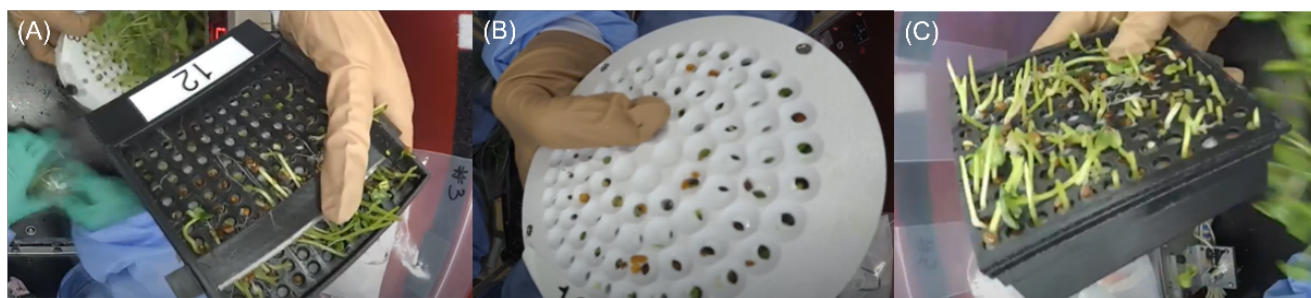


Figure 11. Photos of the three types of growth hardware after harvesting. **(A)** Guillotine. **(B)** Pepper Grinder. **(C)** Scissors.

perhaps slowing down the overall process (See harvest videos on the supplemental materials tab on the article page). Some hardware issues experienced in flight were due to the bag not securing correctly on the hardware lid, which led to challenging bag installation or microgreens escaping after harvesting. The round lid of the pepper grinder made it easier for operators to put on the attached bag compared to the square lid of the Guillotine and Scissors growth hardware. Since bagging the microgreens is part of the harvesting process, it will need to be thoroughly considered for spaceflight operations.

Cleanliness of Cuts

When evaluating the performance of the different cutting methods, it was observed that some cutting methods cut the hypocotyls of the microgreens more cleanly than others (Figure 11).

The Guillotine tended to pin the last half of the microgreens under the Guillotine blade rather than cutting them to be harvested (Figure 11). This was not considered a hardware failure but could be due to several factors, such as the blade not being sharpened, the blade collecting microgreen debris thereby dulling it, or the track that the blade moves down not being smooth enough to make it easy for the blade to travel across the hardware ensuring a clean cut. This is shown in the Table 4 data with a larger number of microgreens left on the hardware.

The Pepper Grinder cutting method left very little plant material behind on the hardware except for bits of seed coat, which was illustrated with 0.4 % and 0.67 % of microgreens left on the Pepper Grinder hardware, with the attached and manual bagging respectively.

The Scissors method left a significant amount of the microgreen hypocotyls on the hardware post-harvest (translating into 11.2% and 30.2% of microgreens left on the hardware with the manual vs. attached bagging, respectively). This could be due to procedural issues where harvesters found it awkward to cut close to the top lid of the hardware or were unable to clearly see where they were cutting due to the bagging method.

Altogether, the remaining plant matter on the growth hardware leads to an overall smaller yield and affects the reusability of the different growth hardware options due to microgreen residue. Also, the jagged nature of the cuts that were made could have implications on the organoleptic attributes of the microgreens, overall quality of the produce, and produce shelf life.

Additionally, when gathering microgreens before manually bagging, if the hypocotyl was not cleanly cut, the harvester might grab the remains, dislodging the roots, which would introduce root debris among the harvested edible biomass. This is reflected in the results where the attached bagging method gave less root debris for both the Guillotine and the Scissors. This is also reinforced with the fact that both the root debris and the number of microgreens left on the hardware were smaller for the Pepper Grinder.

Reusability

When considering these different methods for harvesting microgreens in space flight, one area of consideration is reusability. Within the designs of each of the microgreen planting boxes, some items are reusable, such as the box shell and the capillary wicks, while other items are consumable, such as water, seeds, and growth mats. However, even items that are reusable, such as the wicks and shells, are not infinitely reusable and will eventually degrade. There are degrees of reusability for all the items used.

To address this, future designs will aim to optimize material selection to avoid degradation if possible, such as using high-grade stainless steel for the shells or by changing the percentage of infill when 3D printing. But it should be noted that some items, such as wicks and growth mats, should only be reused when food safety standards can be maintained via sanitization between grow outs. A lifecycle assessment of hardware designs should be conducted in the future. The cleaning process will also need to be considered in the design of this hardware and included in the life cycle assessment. Antimicrobial coatings and/or material selection may be used to help maintain food safety.

Total Hardware Mass

When considering different methods for harvesting microgreens in space flight, one factor that should be taken into consideration is the total mass of the harvesting set up. While the cost per kilogram of launching a payload to the International Space Station has decreased in recent years, mass and volume are still important considerations within the spaceflight environment (Zabel, 2021; Audas et al., 2022). Each of these different approaches had varying masses, and as previously mentioned, there are degrees of reusability to all the items, so replacement parts should also be considered when evaluating the total hardware mass (Levri et al., 2000; Brunet et al., 2010; Audas et al., 2022). In this study, hardware mass was not factored in because the different solutions were not designed for mass optimization and thus introducing hardware mass as a factor would have been misleading.

For spaceflight applications, it will be important to determine and mature the potential yield (edible biomass) vs. total hardware mass ratio in later designs. To create a better ratio, future designs may use different materials.

Robustness

In addition to improving the hardware performance with cleaner cuts and addressing system mass and reusability, the hardware robustness will need to be evaluated as part of validation for future spaceflight. In this section, we discuss the robustness of the different hardware approaches, as experienced during the flight campaigns, as well as during two analog missions at the University of North Dakota's Inflatable Lunar Mars Analog Habitat (ILMAH) and at the Hawai'i Space Exploration Analog and Simulation (HI-SEAS) habitat. Both analog missions lasted for one month, offering perspective on the hardware's operational performance over several weeks of use.

As noted during the flights, the Guillotine blade became stuck several times during the HI-SEAS mission. The hardware made of 3D-printed material (Guillotine and Scissor units) was lighter but more fragile than the Pepper Grinder. Parts of the Guillotine lids as well as the Guillotine tabs broke, leaving the hardware unsealed in the first case, and the blade difficult to operate in the second case. In one analog mission, it was reported that the 3D-printed hardware partly melted under the grow lights, making them unusable afterwards. Although the Pepper Grinder hardware was sturdier, it lost its water tightness over time due to wear on the fastenings in this design.

As for hardware mass, robustness was not included in analysis at this stage of the study because it was not one of the requirements when building the hardware.

Yield

The Pepper Grinder yielded a lower mass of microgreens compared to the other designs, even after adjustment for

planting density. An explanation could be that the seedlings had to grow through an additional layer of material because of the mechanism of the Pepper Grinder, and that led microgreens to be trapped at germination, as indicated by a significantly higher number of seedlings growing under the lid (Table 3).

Recommendations for the Future

Recommendations on Data Collection—Lessons Learned

Both quantitative and qualitative data were collected throughout this study, each offering different benefits and limitations. Questionnaires were easy for operators to fill out and faster to analyze than video analysis, but these were subjective. Video analysis was more precise, but it was time-consuming. Video analysis of the operators interacting with the hardware offered the opportunity to revisit the time of data collection multiple times, allowing for the collection of additional data points and a more accurate measurement of the length of a harvest. However, the key to good video analysis is making sure that there are time indicators in the physical footage itself so that once the video is processed, footage is not missing, and time points are not manipulated. Also, high-definition footage was paramount to being able to achieve detailed observations. Video analysis also offered the opportunity of discovery of data that may not have been initially considered at the start of the experiment.

Recommendations on the Hardware

Upon evaluating the performance of the different harvesting methods in parabolic flight, ideas for improving the next iteration of hardware came to light.

Throughout different points in all three parabolic flights, the VELCRO® on the bottom of the planting boxes securing them to the floor of the glovebox peeled off the hardware, impacting the progress of the experiments. Future designs will need a more secure method of attaching the hardware to the glovebox or growth chamber floor in microgravity.

Throughout the different flights, harvesters and assistants were also seen occasionally struggling to put the attached bag onto the Scissors and Guillotine hardware. The attached bag would pin microgreens under the lip of the bag or fall off once the harvester rotated the hardware to move the cut microgreens farther into the bag. Adding a groove into the hardware design for the lip of the bag to sit in may remedy this issue.

In the first parabolic flight, the harvesters would occasionally struggle to push the blade of the Guillotine across the hardware, cutting the microgreens as it passed. It was determined after the flight that the tracks that the blade travels down should be broken in before actual use to run smoothly. Future iterations will need to ensure that blades are properly broken in before

use, with, for instance, a higher quality print, different filament selection (e.g., polycarbonate instead of PLA), and sanding of the track.

Harvesters using the Guillotine hardware also had trouble throughout all three flights with the blade not moving parallel across the hardware and instead skewing at an angle, leaving the microgreens at the end of the tray uncut or causing the harvesters to readjust the blade and cut again trying to keep the blade horizontal. Future design iterations will include improved blade management, allowing for better blade movement.

While the Pepper Grinder showed high operational efficiency throughout the experiment runs, it had a lower planting density than the Guillotine or Scissors growth hardware. Future iterations will aim to achieve a higher planting density, possibly through hybridization of design with the Guillotine or Scissors growth hardware. The Pepper Grinder also saw a higher number of microgreens trapped under the lid of the growth hardware, so future iterations will also aim to improve this issue.

Finally, one advantage of using 3D printing to build the hardware is that once it wears out, it can be recycled, and the filament reused to print new growth and harvesting hardware. This type of research is currently ongoing at NASA Kennedy Space Center.

Conclusions

Microgreens still present a strong potential for space crop production, though there are challenges that must be overcome before they are ready for space utilization. These tests on harvesting microgreens in parabolic flight enabled us to identify one Cutting & Bagging method—the Pepper Grinder with attached bagging—which ranks higher for most of the criteria we have defined. Many aspects of the hardware and the harvesting procedure can still be improved, but this assessment is one of the critical first steps before growing microgreens on the International Space Station. Parabolic flight has proven to be a valuable tool in developing technology for future use in microgravity, and post-testing video analysis is a highly effective way of evaluating the technology performance.

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