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*Research article*

## MEPHI: A CubeSat biological payload for hydroponic food production demonstration

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**Abstract:** Biological research on small satellite platforms is hindered by stringent mass, volume, and power constraints, which often compromise environmental control or complicate operations. In this paper, we documented part of the feasibility study for MEPHI (Space Module for Hydroponic Production), a 2U CubeSat-compatible payload designed as a technology demonstrator for orbital plant growth. It features a compact, autonomous architecture capable of regulating critical developmental variables within a restricted volume. The system integrates active atmospheric control, closed-loop spectral lighting, and a water-free cultivation medium, achieving high-fidelity environmental regulation under strict resource limitations. Our purpose of this work was to register the high level requirements, assumption, constraints and design decisions as part of the Pre-Phase A of this payload project.

**Keywords:** space farming; vegetables; plant growth chambers; microgravity; CubeSat

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### 1. Introduction

Argentina possesses a robust food production sector, underpinned not only by its fertile soil but also by extensive research into genetic improvements to withstand adverse climate conditions. The country's climates have necessitated a network of agricultural experimental stations tailored to the requirements of each region. Notably, laboratories within Argentine scientific stations in Antarctica have served as essential testbeds for optimizing food production in extreme environments. The Marambio, Esperanza, and Belgrano II bases house the Antarctic Hydroponic Production Modules (MAPHI), a landmark biotechnological development arising from the collaboration between the National Institute of Agricultural Technology (INTA), the National University of Southern Patagonia (UNPA), and the Joint Antarctic Command (CCA) (see [1, 2]). Figure 1 shows the production facility in Antarctica, with a 28 days crop cycle for the *Lactuca Sativa* var. *Grand Rapids* (see [3]).



**Figure 1.** MAPHI-1 production facility in Antarctica, reproduced from [3].

Seeking to reach new frontiers, we propose a demonstrator for plant growth in space within an actively controlled environment. We hypothesize that understanding the impact of microgravity on plant physiology will be fundamental for enabling astronauts to cultivate their own food during long-term missions; a challenge being addressed across experimental platforms [4]. An orbital platform is selected to meet the duration requirements of the experiment, which exceeds the short microgravity windows provided by suborbital or parabolic flights. Consequently, MEPHI (Módulo Espacial de Producción Hidropónica) is introduced as a CubeSat-compatible 2U biological payload. Developed by the School of Engineering of the University of Buenos Aires (FIUBA) in collaboration with INTA and UNPA, and supported by the Argentine Space Agency (CONAE), MEPHI represents a strategic effort to strengthen national space technology capabilities. This payload is designed for ground-based testing under pseudo-microgravity conditions and in-orbit validation.

Biological experimentation on small satellite platforms is inherently limited by stringent mass, volume, and power constraints, which often compromise environmental regulation or increase operational complexity (see [5]). Here, the objective is to maintain a fully regulated, autonomous biological environment within a 2U volume, integrating comprehensive atmospheric control, closed-loop spectral lighting, and a water-free cultivation medium under rigorous energy and mass limitations.

Our purpose of this work is to present this proposal as the initial phase of the space project following the guidelines in [6]. We start in Section 2 with the identification of the main challenge given by the microgravity effect on the root oxygenation: This generates root hypoxia [7], which we consider has not been satisfactorily resolved at the moment. First, we review some of the solutions for this problem [8, 9] and propose an alternative using the matrix structure provided by hydrogels to mitigate the microgravity effect, adding nutrients and necessary oxygen. Moreover, we identify the experimental platforms to conduct the testing, including a clinostat for ground testing (which will be developed for this project in our facilities) and a payload compatible with a CubeSat LEO satellite [10] on an appropriate orbit. We also determine the objectives, constraints, and first level requirements. The mission metrics and evaluation criteria are given in Section 3, while in Section 4 we provide the main associated rationals, constraints, and assumptions. The system is defined in Section 5, with the main tree-decompositions

and associated block diagrams to define the proposed architecture and associated interfaces, including a brief description of the main elements. In Section 6, we detail the operational scenarios and the main milestones for each of them, including some details on the payload development. The paper ends with conclusions and future work discussed in Section 7.

## 2. Motivation & objectives

### 2.1. Motivation

The production of horticultural crops in microgravity faces a fundamental hurdle: Root hypoxia caused by the absence of buoyancy-driven convection [7]. Experiences with ISS systems like Veggie [8] and the Advanced Plant Habitat (APH) [9] have utilized porous calcined clay and capillary irrigation to manage fluids. However, persistent issues with water stagnation and fungal biofilms [11] suggest a need for more autonomous solutions. Building on these lessons, we propose using stratified, nutrient-enriched hydrogels as a stable soil analog, while analyzing ozone micro-bubble oxygenation as a promising alternative for enhancing rhizosphere gas exchange.

In this approach, ozone micro-bubbles serve as an internal oxygen source via kinetic decomposition directly within the root zone [12]. High and stable photosynthetic rates are maintained through continuous root-zone oxygenation, which prevents premature stomatal closure during LED cycles [13]. Such carbon fixation efficiency is critical for CubeSat platforms, where maximizing edible biomass per unit volume is the key metric for bioregenerative life support. Furthermore, improved oxygenation stimulates nitrate reductase, reducing harmful nitrate accumulation and enhancing nutritional quality [14, 15, 16].

However, the integration of ozone introduces significant chemical safety risks and open engineering problems. As a powerful oxidant, ozone may cause the oxidative degradation of the hydrogel's polymer chains, leading to matrix liquefaction and potential liquid leakage. Moreover, any unreacted ozone escaping into the cabin presents a respiratory hazard to the crew, requiring fail-safe decomposition mechanisms. The long-term viability of this technique is also limited by potential gel degradation caused by plant nutrient uptake and ionizing radiation, both of which can deteriorate the polymeric structure and alter nutrient release capacity [17, 18]. As mitigation, we will evaluate alternatives without adding ozone, or keeping it at the minimum feasible concentration.

Despite these challenges, the transition toward biological gels with active oxygenation represents a definitive step toward mission autonomy for long-duration transit, such as those envisioned for Mars [19, 20]. Therefore, we propose to validate this approach first in pseudo-microgravity ground tests, for future orbital validation using a CubeSat payload format.

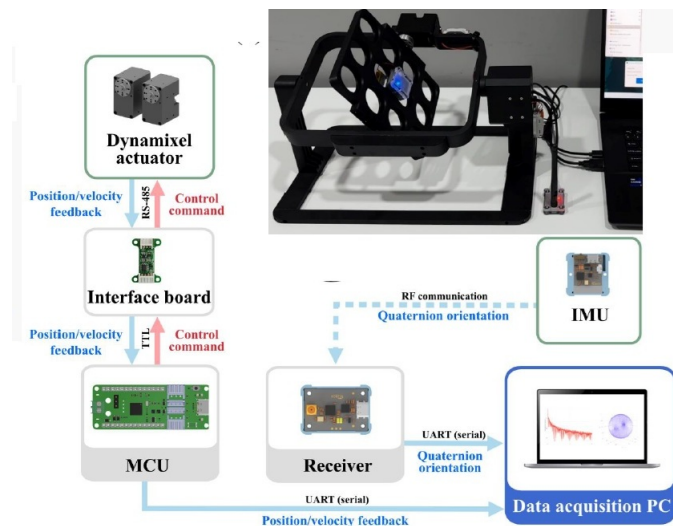
### 2.2. Experimental platforms

Gravity stimulation is a vital component for the growth and development of plants on Earth, but the associated mechanism is not well known [21, 22]. Even less is known about the adaptation of plants in a microgravity environment [4]. Various experimental and technical platforms have been proposed to study plant adaptations to microgravity. Using these platforms, molecular signaling pathways have been discovered, which will further help decipher the processes driving plant microgravity responses (see [23]). We consider two experimental platforms, excluding parabolic flights (which combines

hypergravity with microgravity, not realistic) and suborbital rockets (limited to a few minutes, while cultivation requires several days in microgravity).

### 2.2.1. ClinoStats and Random Positioning Machines (RPM)

Since the 19<sup>th</sup>-century, clinostats are used to test plant growth in microgravity conditions [24]. Time-averaged simulated microgravity does not provide actual microgravity at any given moment, but it continuously alters the direction of gravity such that its time-averaged value converges below a certain threshold ( $10^{-2}$ – $10^{-3}g$ ) over an extended period (see [25]). Clinostat experiments are physically distinct from true microgravity; nevertheless, some cell and plant experiments have shown that its biological effects resemble those observed onboard the ISS. A two-axis ClinoStat, also known as Random Positioning Machines (RPM), serves as an alternative that can continuously change the direction of gravity and simulate microgravity conditions by time-averaging the gravity vector over the three dimensions. However, its structural characteristics inevitably produce poles where gravity is unevenly concentrated. A quantitative analysis and comparison of pole formation across four representative clinostat control strategies were made in [25], leading to the evaluation of several deterministic and random profiles. This was tested in the setup shown in Figure 2.



**Figure 2.** Two axes motion simulator behavior verified with an inertial measurement unit (IMU). Reproduced from [25].

### 2.2.2. Spacecraft

CubeSats are recognized as suitable platforms to test plant growth in space [26], as it enables:

- Launching a small satellite enables “failing and learning” quickly.
- It is a closed and controlled environment that can be dedicated to this test.
- The low cost missions enables us to avoid the use of propulsion, providing true microgravity over extended time.

On the other hand, due to space limitations, it is more difficult to achieve proper radiation shielding, and the resources available to build the experiments are very constrained. There are several examples

of CubeSats testing these experiments, such as the O/OREOS [29], CultCube [30], Spacebean [31], ARCHER [32], and BioSentinel [33]. In LatinAmerica, the SUCHAI swarm developed by the Space and Planetary Exploration Laboratory (SPEL) at the University of Chile included the PlantSat 3U CubeSat, shown in Figure 3, with several biological experiments tested in Low Earth Orbit (see [27, 28]).



**Figure 3.** 3U PlantSat, part of the SUCHAI swarm of CubeSats developed by Universidad de Chile.

### 2.3. Objectives

Considering previous motivations, the high level capability to be developed is *an orbital payload able to test food production in space*. The primary objectives are:

- **PO-01:** Provide the conditions for plant cultivation during one month in orbit.
- **PO-02:** Report automatically the main variables necessary to evaluate the plant's health.
- **PO-03:** Validate a new substrate for plant cultivation in microgravity.

The following objectives are desirable but not strictly required for mission success:

- **SO-01** Characterize the environmental dynamics of the biological chamber during the experiment.
- **SO-02** Generate datasets that may support future improvements in environmental regulation strategies for biological payloads.

The following high-level constraints are identified:

- **CN-01:** The operation in orbit shall not require human intervention.
- **CN-02:** The payload envelope shall be compatible with CubeSat format with 2U size.
- **CN-03:** The seeds and cultivation medium shall survive the pseudo-microgravity condition as a precondition to be tested in orbit.
- **CN-04:** The total cost of the development shall be lower than \$1 million.
- **CN-05:** The orbital demonstration shall be made in 2029 or before.

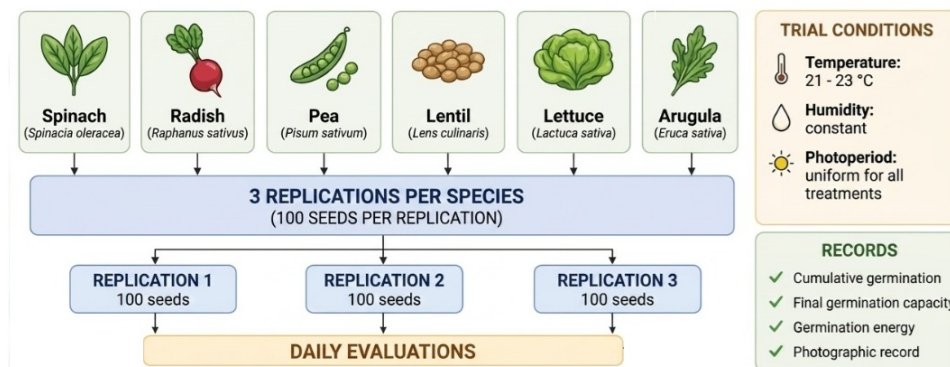
The high-level requirements are derived as follows:

- **R1-01** The payload shall test the growth of a plant and associated cultivation substrate to be defined in the development stage.

- **R1-02** The payload shall measure and report the concentration of  $CO_2$ .
- **R1-03** The payload shall measure the infrared spectrum of the plant, relative to an appropriate reference.
- **R1-04** The germination chamber volume shall be 1 liter or greater.
- **R1-05** The orbit shall be near circular LEO and dawn-dusk.
- **R1-06** The attitude shall guarantee at least one face pointing toward a cold sky.
- **R1-07** The germination chamber shall have pressure limits between 0.7atm and 1.2atm.
- **R1-08** The germination chamber shall have a temperature between 15° and 30°, modulated as function of light intensity.
- **R1-09** The germination chamber's relative humidity shall be between 50% and 90%.

#### 2.4. Biological candidates

The biological candidates to be evaluated for the microgravity experiment are detailed in Figure 4, with a brief description of the trial conditions and output variables, including cumulative germination, germination capacity, and germination energy, and associated photographic records.



**Figure 4.** Biological candidates and initial selection process.

### 3. Mission metrics

#### 3.1. Evaluation criteria & decision matrix

According to [9], crop selection is one of the most critical biological decisions in designing space agriculture systems. Because space agriculture must operate with minimal space, energy, water, and crew time, crops must be chosen for nutritional value and compatibility with controlled-environment systems such as controlled environment agriculture (CEA) chambers and closed-loop life support systems. The following evaluation criteria are considered to select the best candidate, provided that all previous requirements and constraints are obeyed.

- **EV-01** The plant health data from clinostat testing in pseudo microgravity.
- **EV-02** The food quality and safety generated by the selected plant, for human consumption.
- **EV-03** The time needed to harvest the plant (faster is better).

- **EV-04** The rusticity of the plant to environmental changes and conditions of the germination chamber (higher is better).
- **EV-05** The amount of water absorption (the less, the better).

During the conceptual study phase, multiple architectural alternatives may be evaluated for the implementation of the MEPHI payload. To support systematic trade studies, a weighted decision matrix will be used to compare candidate solutions across a set of predefined evaluation criteria. The evaluation criteria and associated weighting factors are defined as follows(see table 1):

**Table 1.** MEPHI implementation evaluation criteria and weights.

| Evaluation Criteria | Weight |
|---------------------|--------|
| Reliability         | 0.40   |
| Versatility         | 0.30   |
| Power efficiency    | 0.20   |
| Simplicity          | 0.10   |

Architectural options will be evaluated against these criteria during trade-off analyses conducted throughout the study. In the event of equivalent technical scores between two candidate solutions, the final decision will be taken jointly by the Study Manager and the Systems Engineer.

### 3.2. Preliminary technology assessment

An initial identification of critical technological challenges that may affect mission feasibility included the following:

- **TC-01** Environmental gas sensing and mitigation of cross-sensitivity effects between gas sensors.
- **TC-02** Autonomous environmental control within the strict resource constraints of a 2U CubeSat payload.
- **TC-03** The seed deployment mechanism required to initiate the biological experiment.
- **TC-04** The gel-based cultivation substrate used to support plant growth under microgravity conditions.

A preliminary Technology Readiness Level (TRL) assessment will be conducted for the main subsystems during the study. At present, most subsystems remain at an early development stage, although partial progress exists in pressure control systems and associated electronic subsystems.

A technological gap exists in the availability of compact, autonomous biological experimentation platforms capable of sustaining plant growth while operating within the severe resource constraints of CubeSat missions. The MEPHI payload addresses this gap by proposing a compact biological experimentation platform capable of autonomously regulating environmental conditions within a 2U CubeSat-compatible volume. The mission integrates aerospace systems engineering and agricultural science to explore the feasibility of sustained plant growth experiments in microgravity using highly resource-constrained platforms. Key technological elements explored by the mission include:

- **TE-01** Autonomous environmental regulation within a CubeSat payload.
- **TE-02** Active monitoring of atmospheric variables such as CO<sub>2</sub>.
- **TE-03** Controlled illumination tailored to plant growth.
- **TE-04** Gel-based cultivation substrate enabling plant growth without free water management.

- **TE-05** Integrated sensing architecture for environmental monitoring and experiment supervision.

The selected mission duration of approximately 30 days is driven by biological and observational considerations. This timeframe is expected to enable the observation of multiple stages of plant development while remaining compatible with the operational constraints of a CubeSat-class payload. A mission duration of this scale enables meaningful biological observations while maintaining a manageable level of system complexity and resource consumption. Additionally, the experiment duration is aligned with the objective of observing the early growth phases of the selected plant species while maintaining continuous monitoring of environmental conditions.

Most existing CubeSat biological payloads rely on simplified environmental control or passive biological systems due to the difficulty of integrating atmospheric regulation, sensing, illumination control, and biological support within extremely limited volumes. MEPHI aims to explore the feasibility of integrating these capabilities into a compact and autonomous system, contributing to the development of new technological approaches for small-scale biological experimentation in space.

### 3.3. *Mission success criteria*

Mission success is evaluated according to measurable indicators describing scientific and technological outcomes. The mission will be considered successful if the following conditions are achieved:

- **SC-01** Successful deployment of the seed activation mechanism.
- **SC-02** Autonomous operation of the biological experiment for approximately 30 days.
- **SC-03** Acquisition of environmental monitoring data during the mission.
- **SC-04** Acquisition of visual imagery documenting plant development.
- **SC-05** Completion of the plant growth process within the environmental conditions defined for the experiment.

If the plant fails to complete the expected biological cycle but the payload operates correctly and provides valid environmental telemetry, the mission may be considered a technological success, although with partial biological results.

### 3.4. *Measures of effectiveness*

Measures of Effectiveness (MOEs) evaluate the mission from the perspective of the stakeholders and the scientific objectives. The primary MOEs for the MEPHI mission include:

- **MOE-01** Days of survival and development of the plant during the experiment.
- **MOE-02** Observation data of plant growth stages during the mission.
- **MOE-03** Correlation between environmental conditions and observed plant development.
- **MOE-04** Metrics for validation of the gel-based cultivation method under space conditions.

Detailed quantitative thresholds for environmental parameters and scientific measurements will be defined in collaboration with INTA during later phases of the project.

## 4. Rationale on constraints and assumptions

In this section, we refine and provide rationals for the main constraints and assumptions adopted for the MEPHI Pre-Phase A study [6].

### 4.1. *Rationale of technical constraints*

#### 4.1.1. CubeSat volume constraint

The payload is constrained to a maximum envelope compatible with a 2U CubeSat volume. This constraint has been adopted as a study-level design boundary to maintain compatibility with common CubeSat payload accommodations and to increase the probability of future integration into an actual host mission. The use of a 2U envelope also represents a reasonable balance between the required compactness of the payload and the minimum internal volume needed to accommodate environmental regulation subsystems, sensing elements, and the biological experiment chamber.

#### 4.1.2. Launch environment compatibility

The payload shall comply with the mechanical and environmental conditions typically associated with CubeSat launch and deployment standards. Accordingly, the system will be designed and tested to withstand the launch vibration environment, launch loads, and deployment-related stresses associated with CubeSat-class missions, using CONAE's integration and testing laboratories, radiation testing capabilities in University of Buenos Aires labs, and seed dormancy/activation strategies to be tested on INTA laboratories, using also the clinostat capability to be developed for this project. Environmental testing consistent with CubeSat qualification and acceptance practices will therefore be considered during later development stages.

#### 4.1.3. Mass compatibility

The payload mass shall remain compatible with typical CubeSat mass density limits, approximately 2.6kg for two units. Although the final allowable mass will depend on the selected mission opportunity, this preliminary constraint is adopted as a critical design driver during the conceptual study.

#### 4.1.4. Development approach

This project follows a predominantly in-house development strategy, based on the technical capabilities available within the participating institutions. Subsystem development, prototyping, and integration activities are expected to be carried out primarily within FIUBA laboratories, with scientific validation support from INTA and technical guidance from CONAE.

### 4.2. *Operational assumptions*

#### 4.2.1. Orbital/Attitude environment

The mission is assumed to operate in a dawn dusk Low Earth Orbit (LEO). This provides the best thermal stability, with one face pointing to cold sky and another face aligned with the orbit normal vector, pointing to daylight. This keeps one face pointing to nadir (communication) and one lateral face (normal to nadir/zenith) always protected from sunlight. We assume also the availability of an infrared

horizon sensor, which guarantees the nadir pointing, and Sun sensors to guarantee that one lateral face always points to the daylight.

#### 4.2.2. Experiment activation

The biological experiment is assumed to be activated by a command transmitted from ground operations after orbital insertion. A water pump can be considered to be able to activate the substrate (or gel) in orbit, while the seeds shall be stored separately in inert environments previous to activation.

#### 4.2.3. Mission duration

The biological experiment is assumed to operate for approximately 30 days following activation of the seed deployment mechanism, which shall be made on the period of the year when the dawn dusk orbit does not have eclipse.

#### 4.2.4. Attitude stability

The payload external faces shall not be stabilized pointing towards daylight. One face shall be stabilized and pointed to the cold sky.

### 4.3. *Biological/Fluids safety*

A triple contention shall be guaranteed for fluids and biological elements. Leakage tests shall be conducted to guarantee no outgassing or bursting.

### 4.4. *Interface assumptions*

#### 4.4.1. Electrical power interface

The payload is assumed to receive electrical power directly from the host spacecraft bus. Rather than assuming a dedicated regulated payload input voltage, the MEPHI payload architecture assumes that raw spacecraft bus power will be internally conditioned by payload electronics in order to generate the voltages required by the subsystems. At the current stage of the study, the internal electronic architecture is expected to use voltage levels on the order of 3.3 V and 5 V.

At this stage, no fixed payload power budget is imposed. A more detailed analysis will be required in later phases to determine the average and peak power requirements of the payload over the orbital cycle. This study therefore assumes that the host spacecraft will be capable of providing an average energy budget sufficient to support payload operation, including eclipse periods typical of LEO missions.

#### 4.4.2. Data interface

The communication interface between the payload and the host spacecraft is assumed to be a standard serial interface typical of CubeSat payload architectures. For the purposes of this study, protocols such as I2C or UART are taken as reasonable baseline assumptions until the host spacecraft interface is formally defined.

#### 4.4.3. Data handling

The payload is assumed to operate using a store-and-forward data handling strategy. Environmental measurements and experiment observations will be stored locally in non-volatile memory within the payload and transmitted to the host spacecraft when communication opportunities become available. This assumption reduces dependency on continuous bus-level data availability and simplifies early interface assumptions.

#### 4.5. *Biological assumptions*

##### 4.5.1. Initial sterility condition

The biological chamber is assumed to begin the mission in a sterile state. This assumption is necessary to define a controlled initial condition for the experiment and to reduce uncertainty associated with unwanted biological contamination during the early phases of the mission.

##### 4.5.2. Contamination control during mission

It is assumed that contamination growth within the biological chamber will be actively mitigated during mission operations. At the current stage of the concept, this is expected to be supported by an ozone-generation function intended to suppress fungal growth that may develop in the gel-based cultivation medium. The detailed implementation and operational constraints of this function will be addressed in later design phases.

##### 4.5.3. Seed dormancy

Seeds are assumed to remain in a dormant biological state during launch and early orbital operations. This assumption avoids premature biological activity prior to experiment activation and simplifies the definition of launch and early mission conditions.

There are two conditions that are instrumental to obtain the seed dormancy objective:

1. Low temperature.
2. Low and constant humidity.

The first condition must be achieved by the cooling of the germinative chamber, which enables long time dormancy and can be achieved by separation of the chamber from the rest of the payload. Once this external ambient is changed to normal launch conditions and the chamber is integrated to the rest of the payload, the biological sample will maintain the necessary germinative energy to obey the orbital tests schedule. This condition can be held during months with this strategy provided that low and constant humidity conditions are maintained. This will be achieved by physical separation of the seed from the gel, in a separate container.

##### 4.5.4. Experiment initiation

The biological experiment is assumed to begin only after activation of the seed deployment mechanism. From that point onward, the seeds are exposed to the cultivation environment, and biological activity is expected to begin.

A seed activation command will ensure that the seed is integrated on the gel to start the germination with enough humidity. We evaluate different methods to implement this activation, which may include combining a pressure feed system to inject the seed on the gel, keeping the seed in a sealed compartment before this activation. The gel will have the necessary humidity, so it might not be necessary to include additional water, but we do not discard this alternative. This mechanism will be tested first in ground dynamic tests.

#### 4.5.5. Autonomous experiment operation

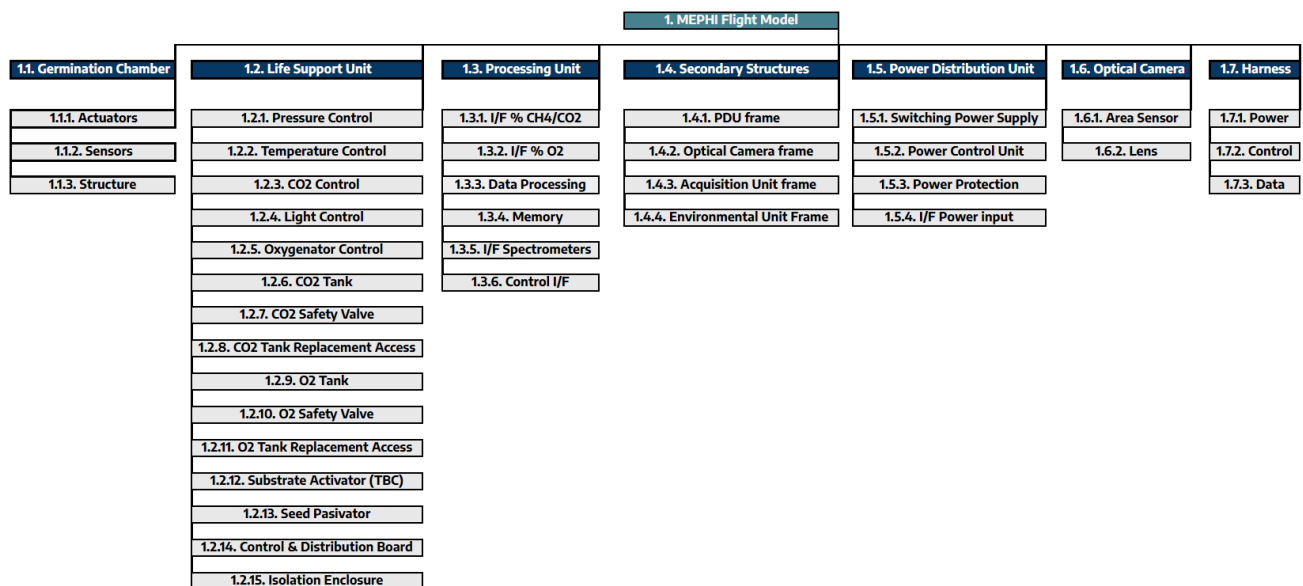
Following activation, the biological experiment is assumed to operate autonomously for the full planned mission duration. The payload is therefore assumed to maintain the environmental conditions required for the experiment through its internal sensing, supervision, and control architecture, without the need for continuous human intervention. The final design of the operation and supervision will depend on the selected species and illumination design.

## 5. System definition

The system is defined by a breakdown and an architecture shown through using block diagrams, at the high level and for two of the main units: the germination chamber and the life support units.

### 5.1. System breakdown

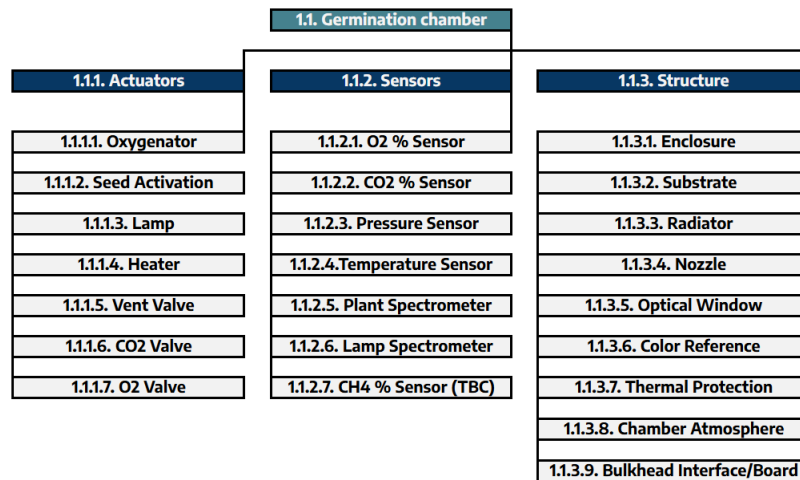
The proposed System Breakdown Structure (SBS) is shown in Figure 5 for the payload. The most challenging units are the germination chamber and the life support units.



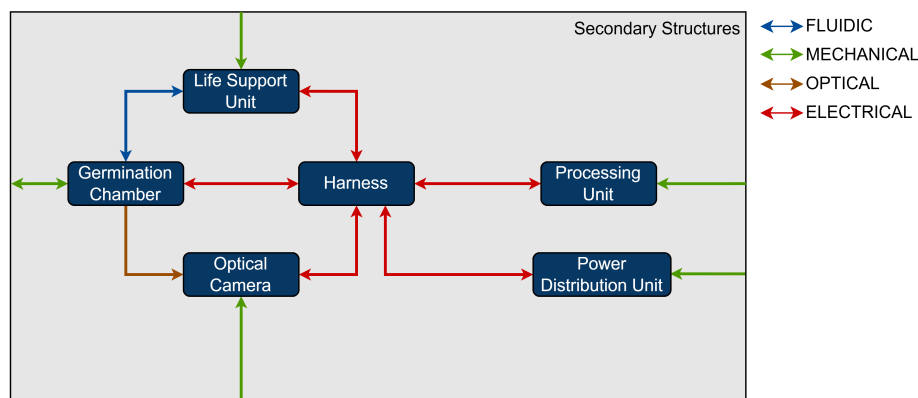
**Figure 5.** System breakdown structure.

A detailed view of the germination chamber is shown in Figure 6. To make the system description more general, we refer to *oxygenator* in the germination chamber and *oxygenator source* in the life

support unit, as there are other possible solutions to be considered as a trade-off.



**Figure 6.** Germination chamber decomposition.



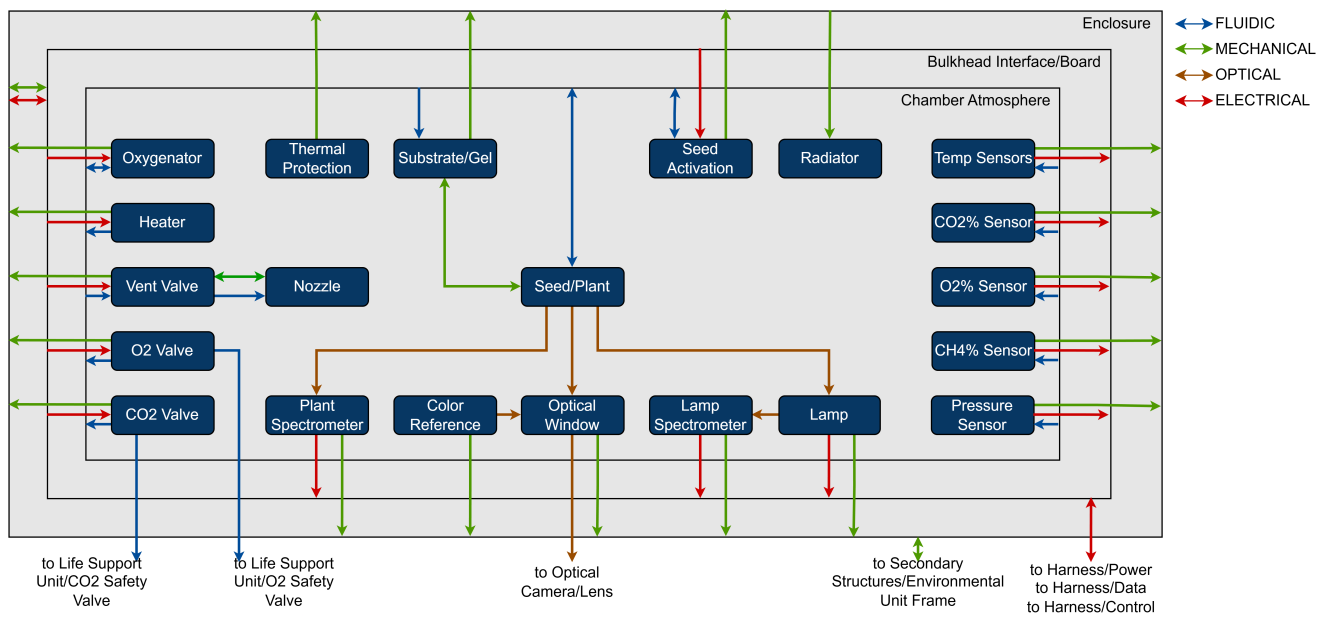
**Figure 7.** MEPHI system high level block diagram and interfaces.

A high level block diagram is shown in Figure 7. Some aspects of the design are described below.

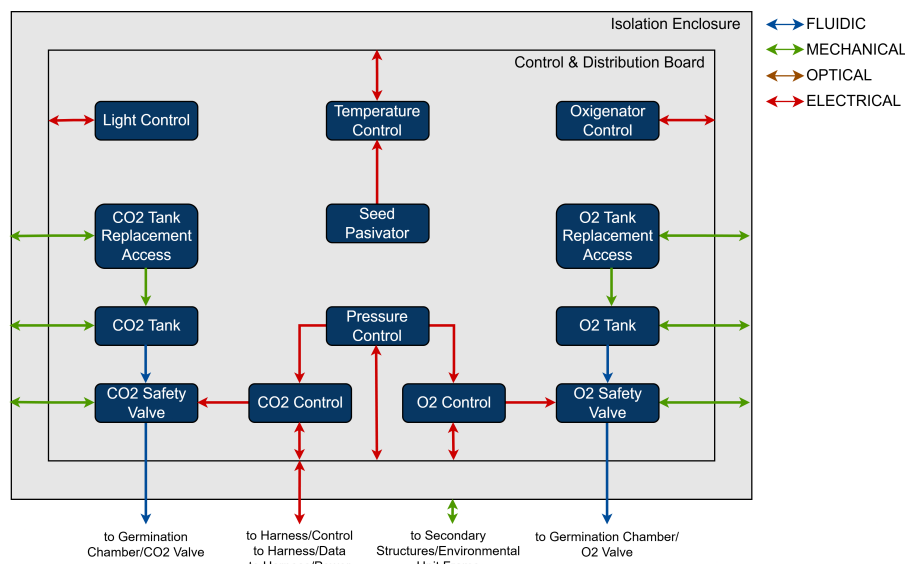
## 5.2. Block diagrams

A block diagram of the germination chamber is shown in Figure 8. Three concentric frames are used to simplify the interface definitions: the external enclosure, bulkhead interface/board, and the chamber atmosphere (the enclosed gas provides fluid interfaces). The seed activation mechanism is not defined at this moment: A seed activation block is included with electrical interface with the bulkhead board, fluid interface with the atmosphere, and mechanical interface with the enclosure, which gives enough degrees of freedom to define possible solutions.

Figure 9 shows a block diagram for the life support unit concept. This unit can be understood as the centralized control layer of the system. The control and distribution board contains the pressure, temperature, gel oxygenation, CO<sub>2</sub> and O<sub>2</sub> controllers. A set of tanks are included for the supply of CO<sub>2</sub> and O<sub>2</sub>. The associated sensors and actuators to complete these loops can be found in the germination chamber model.



**Figure 8.** Germination Chamber Block Diagram.



**Figure 9.** Life Support Unit Block Diagram.

## 6. Operational scenarios

The design of the payload is driven by the required reliability and environmental constraints, including the evaluation component's MTBF and environmental ranges, to guarantee the long-term stability of the critical elements as electromechanical subsystems and organic materials (hydrogels). These design drivers determine requirements that must be verified progressively along the development phases. The operational scenarios of the biological mission are detailed below and depicted in Figure 10:

| Phase       | Static Tests                                | Dynamic Tests                                        | Environmental Tests                                       | Launch Activities      | Commissioning                                                              | Operation                                       |
|-------------|---------------------------------------------|------------------------------------------------------|-----------------------------------------------------------|------------------------|----------------------------------------------------------------------------|-------------------------------------------------|
| Activities  | Germination Baseline<br>Sensors Calibration | Gravitropism<br>Stress Response Monitor              | Vibration&Shock<br>Thermo-Vacuum<br>EMI/EMC<br>Leak tests | Biological Dormancy    | Life Support Activation<br>Hydration Initiation<br>Subsystems Health Check | Growth Rate Mapping<br>Subsystem Health Monitor |
| MEPHI Model | Development Model                           | Engineering Model                                    | Flight Model                                              | Flight Model           | Flight Model                                                               | Flight Model                                    |
| Output      | Substrate Validation<br>Seed Candidates     | Seed and Substrate Selection<br>Clinostat Validation | MEPHI FM Qualified                                        | MEPHI flight readiness | Health baseline<br>Day 0 image                                             | Image Sequence<br>Data Trends                   |



**Figure 10.** Sequence of operational scenarios and proposed MEPHI models (images generated using IA tools).

- **Static Testing**

*Germination Baseline:* Establishing the standard rate of seed germination in Earth gravity to compare against orbital data. *Nutrient Delivery Validation:* Testing the efficacy of the hydroponic or agar-based delivery system in a controlled, 1G environment.

*Sensors Calibration:* Verifying that CO<sub>2</sub>, O<sub>2</sub>, temperature, and humidity sensors provide accurate readings before integration.

- **Dynamic Testing (ClinoStat)**

*Gravitropism Observation:* Using a 2D or 3D clinostat to randomize the gravity vector, observing if the plant's roots and shoots lose their directional orientation.

*Stress Response Analysis:* Monitoring for biochemical signs of stress caused by the constant rotation and lack of a fixed sedimentation point.

- **Environmental Testing**

*Vibration & Shock Survival:* Ensuring the biological container, lighting rigs, and structural seals remain intact during simulated launch loads.

*Thermal Vacuum (TVAC):* Testing the life-support system's ability to maintain a habitable internal temperature while the exterior faces the extreme gradients of space.

*Electromagnetic Compatibility (EMC):* Confirming that the growth lights and pumps do not interfere with the satellite's radio communications.

*Radiation:* A radiation testing will be considered to verify the shielding design (see [33]).

- **Launch Phases**

*Biological Dormancy:* Maintaining seeds in a dry or cold state to prevent premature germination during launch delays or "late-load" procedures.

- **Commissioning**

*Life Support Activation:* Powering on the internal heaters and fluid circulation to stabilize the environment.

*Hydration Initiation:* Executing the first command to inject water or nutrient solution into the growth chamber to trigger germination.

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*Subsystem Health Check:* Verifying that the imaging system can capture and transmit a clear "Day 0" baseline photo.

- **In-Orbit Demonstration**

*Growth Rate Mapping:* Utilizing time-lapse photography to measure leaf area expansion and stem elongation in true microgravity. We consider the use of an overhead camera to monitor crop coverage. This might be complemented with a lateral camera if necessary to view the stem elongation separately, as a function of the selected species.

*Circadian Rhythm Monitoring:* Observing how the plant responds to artificial light cycles.

*Closed-Loop Atmosphere Control:* Analyzing how the plant interacts with the internal atmosphere (O<sub>2</sub> production vs. CO<sub>2</sub> consumption) in the sealed volume.

### 6.1. MEPHI Electrical design

A preliminary design of the payload's electrical systems is made by students of the School of Engineering of the University of Buenos Aires, as their engineering final projects, with different levels of advancements.

The design of the payload is aimed to integrate active CO<sub>2</sub> concentration control through compensated and linearized sensing, chamber pressurization management, thermal control coordinated with illumination, and a seed deployment mechanism activatable in orbit or during ground validation campaigns. Illumination is regulated under closed-loop control at the spectral band level, enabling dynamic adjustment of specific wavelength ranges under energy constraints. The chamber controls internal atmospheric composition as an integrated system, while the gel-based rearing substrate provides structural anchoring and embedded water-nutrient supply without free-water handling, reducing fluid management complexity and enabling integration with the environmental control architecture. The seed deployment mechanism is integrated within the supervisory logic, enabling programmed activation without external intervention. The integrated sensing and supervisory architecture enables continuous data acquisition of environmental and growth parameters.

### 6.2. MEPHI mechanical design

To evaluate feasibility, an initial mission architecture is proposed based on the constraints of a potential satellite bus. By adopting a dawn-dusk Sun-synchronous orbit (approximately 06:00 LTAN) with Local Vertical Local Horizontal (LVLH) stabilization, an 8U CubeSat configuration (units) becomes viable. In this layout, four units on the sunward side house the solar arrays and primary bus subsystems, while the remaining four units on the anti-sunward side accommodate two MEPHI modules within a stable thermal environment. The zenith-facing surface, shared with the payloads, facilitates heat rejection via a radiator toward deep space. Since the sunward face receives near-continuous solar radiation, interrupted only by brief eclipses during a single solstice, the four external payload faces remain oriented toward nadir, zenith, and the dawn/dusk albedo directions.

### 6.3. MEPHI embedded systems

The onboard software architecture is evaluated between a bare-metal implementation and a lightweight real-time operating system (RTOS). The payload comprises multiple embedded subsystems

for control and telemetry acquisition under strict constraints in mass, power, memory, and processing resources.

A bare-metal approach minimizes software overhead and memory footprint, enabling deterministic execution with direct control of hardware resources. This is suitable for simple scheduling scenarios with limited concurrency and fixed timing requirements. However, as system complexity increases (e.g., multiple asynchronous data sources, prioritized tasks, and timing constraints), maintaining determinism and scalability becomes non-trivial, typically requiring custom schedulers and interrupt-driven designs.

The baseline approach foresees the inclusion of a hardware watchdog timer to autonomously recover from software faults, complemented by a remote reset capability via ground command using the satellite C&DH subsystem. To increase robustness against non-recoverable faults, the use of a dual firmware image (nominal and fallback) with basic integrity verification is considered. In line with SUCHAI recommendations, interface isolation between critical subsystems (sensors and actuators) is also identified as a key design driver to prevent fault propagation. Given resource constraints, only selective redundancy is envisioned, focused on critical variables for the life-support function (e.g., temperature sensing). The overall design philosophy prioritizes operational simplicity, restricting functionality to essential operations to reduce failure probability. These elements are under trade-off analysis and will be refined in subsequent mission phases.

#### 6.4. Development tests



**Figure 11.** Three-Axes motion simulator (CETT-CONAE).

A ClinoStat must be used to test the microgravity condition at a laboratory level to select and validate the biologic system. There are very limited references on the use of ClinoStats on national laboratories, with one particular exception presented in [34]. Other approaches may involve the development of the equipment based on existing capabilities, which are similar to inertial tables used for navigation systems calibration. A three-axes inertial table available at Centro Espacial Teófilo Tabanera (CETT) in CONAE is shown in Figure 11, which could be oversized for the project needs: The maximum mass capability is 90kg with maximum velocities up to 80rpm per axis. There are professional laboratory equipment that are used for space agencies, as the RPM 2.0 produced by Yuri Gravity (see [35]) for samples up to 1.5kg and compatible with incubators and radiation testing. Other researchers implement ad-hoc ClinoState/RPM solutions as shown in [25] and [36], mainly to reduce the cost. Our approach will start using the inertial table for the first experiments, while an ad-hoc two-axes clinostat is developed, to be used for the dynamic tests campaign.

## 7. Conclusions

Biological experimentation in space is essential for the advancement of long-duration human space exploration and the development of space-based agriculture. This initial work is part of a feasibility analysis to develop a payload that can test the growth of plant using a CubeSat format, with associated restrictions. The main challenge identified to reach efficient food production in space is to solve the microgravity effects on root hypoxia, which is proposed to be achieved with a specific hydrogel formulation, and verified first on a ClinoStat and in orbit using a CubeSat. The high level objectives, restrictions, and assumptions have been defined, with a preliminary decomposition of the system, block diagrams, and main interfaces. This study must be completed with a more detailed technical description of the system, including a programmatic evaluation of cost, risk, and schedule. On the other hand, pseudo-microgravity testing with the best seed and hydrogel candidates will be conducted soon to validate the approach and to define the lower-level requirements for the MEPHI payload design.

## Author contributions

Conceptualization: FS, FF, JB; Methodology: FS, SB, JB, PS; Formal Analysis: FS, SB, PS; Investigation: FS, SB, FF, JB, PS; Writing Draft: FS, SB, JB, PS; Writing Review & Editing: FS, SB, JB, PS.

## Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

## Conflict of interest

The authors declare no conflict of interest. Pablo Servidia is the Guest Editor and was not involved in the editorial review or the decision to publish this article.

## References

1. Alonso IA, Alvez-Rolo RH, Birgi JA, et al. (2025) Cultivar Soberanía: Producción Hidropónica y Gobernanza Antártica. *Revista Párrafos Geográficos* 24: 97–119.
2. Diaz B, Birgi JA, Gargaglione V, et al. (2024) Calidad del agua para consumo humano y producción hidropónica en Bases Antárticas Conjuntas de Argentina. *Inf Cientif Tecn UNPA* 16. <https://doi.org/10.22305/ict-unpa.v16.n1.1096>
3. Birgi JA, Gargaglione V, Peri P, et al. (2023) Módulo Antártico de Producción Hidropónica: primeros resultados del cultivo en la Antártida Argentina. *Inf Cientif Tecn UNPA* 15: 348–364. <https://doi.org/10.22305/ict-unpa.v15.n3.993>
4. Baba AI, Mir MY, Riyazuddin R, et al. (2022) Plants in Microgravity: Molecular and Technological Perspectives. *Int J Mol Sci* 23: 10548. <https://doi.org/10.3390/ijms231810548>
5. Ricco A, Parra M, Nielsen D, et al. (2011) PharmaSat: Drug dose response in microgravity from a free-flying integrated biofluidic/optical culture-and-analysis satellite, In: H. Becker & B. L. Gray (Eds.), *Microfluidics, BioMEMS, and Medical Microsystems IX*, 7929. <https://doi.org/10.1117/12.881082>

6. Ryschkewitsch M (1991) *Mission Design Process Guide*. NASA.
7. Poulet L, Fontaine JP, Dussap CG (2016) Plant's response to space environment: a comprehensive review including mechanistic modelling for future space gardeners. *Bot Lett* 163: 337–347. <https://doi.org/10.1080/23818107.2016.1194228>
8. Fazayeli H, Gholami M, Nazifi S, et al. (2025) Space Agriculture: A Comprehensive Systems-Level Review of Challenges and Opportunities. *Agriculture* 15: 2541. <https://doi.org/10.3390/agriculture15242541>
9. Monje O, Richards JT, Dimapilis DI, et al. (2020) Hardware Validation of the Advanced Plant Habitat on ISS: Canopy Photosynthesis in Reduced Gravity. *Front Plant Sci* 11: 673. <https://doi.org/10.3389/fpls.2020.00673>
10. Johnstone A (2020) CubeSat Design Specification Rev. 14.1. *The CubeSat Program*, Cal Poly SLO.
11. Yuliana T, Prihastanti E, Nurchayati Y (2020) Potential of aqueous ozone for the in vitro sterilization procedure of Solanaceae. *Asian J Pharm Clin Res* 13. <https://doi.org/10.22159/ajpcr.2020.v13i10.38945>
12. Zhao Q, Dong J, Li S, et al. (2024) Effects of micro/nano-ozone bubble nutrient solutions on growth promotion and rhizosphere microbial community diversity in soilless cultivated lettuces. *Front Plant Sci* 15: 1393905. <https://doi.org/10.3389/fpls.2024.1393905>
13. Qiao C, Cheng H, Zhang Z (2025) Root-zone oxygen supply mitigates waterlogging stress in tomato by enhancing root growth, photosynthetic performance, and antioxidant capacity. *Plant Physiol Bioch* 222: 109744. <https://doi.org/10.1016/j.plaphy.2025.109744>
14. Shankar N, Srivastava H (1997) Nitrate reductase activity and uptake of nitrate and oxygen as affected by nitrate supply to detached maize organs. *Biol Plantarum* 39: 583–589. <https://doi.org/10.1023/A:1000982832369>
15. Morard P, Silvestre J (1996) Plant injury due to oxygen deficiency in the root environment of soilless culture. *Plant Soil* 184: 243–254. <https://doi.org/10.1007/BF00010453>
16. Massa GD, Wheeler RM, Morrow RC, et al. (2017) Plant Habitat: A New Facility for Large-scale Physiological Studies on the International Space Station. *68th International Astronautical Congress*.
17. Agbna Ghd, Zaidi SJ (2025) Hydrogel Performance in Boosting Plant Resilience to Water Stress—A Review. *Gels* 11: 276. <https://www.mdpi.com/2310-2861/11/4/276>
18. Stutte G, Monje O (2005) Microgravity Effects on Plant Boundary Layers, *NASA Technical Reports Server (NTRS)*, Document ID: 20050217285. <https://ntrs.nasa.gov/citations/20050217285>
19. Nangle SN, Wolfson MY, Hartsough L, et al. (2020) The Case for Biotech on Mars. *Nat Biotechnol* 38: 401–407. <https://doi.org/10.1038/s41587-020-0485-4>
20. Robson D, Capelletti C (2022) Biomedical payloads: A maturing application for CubeSats. *Acta Astronaut* 191: 394–403. <https://doi.org/10.1016/j.actaastro.2021.11.017>
21. Sack FD (1991) Plant gravity sensing. *Intern Rev Cytol* 127: 193–252.
22. Sack FD (1997) Plastids and gravitropic sensing. *Planta* 203: S63–S68.
23. Herranz R, Medina FJ (2014) Cell Proliferation and Plant Development under Novel Altered Gravity Environments. *Plant Biol* 16: 23–30. <https://doi.org/10.1111/plb.12103>

- 24.Hasenstein KH, van Loon JJWA (2015) Clinostats and other rotating systems—design, function, and limitations. In: Beysens DA, van Loon JJWA, *Generation and Applications of Extra-Terrestrial Environments on Earth*, Eds. River Publishers, Aalborg, Denmark, 147–156.
- 25.Kim Y, Park S, Kim S (2026) Comparison of clinostat control strategies to achieve simulated microgravity with uniform gravity vector distribution. *Nat Microgravity* 12. <https://doi.org/10.1038/s41526-026-00570-8>
- 26.Pedersen C, Antonic A, Alqaraghuli F, et al. (2024) CubeSat Terrariums to Evaluate Biological Systems in Deep Space. *AIAA SciTech Forum* Orlando, FL. <https://doi.org/10.2514/6.2024-1552>
- 27.*PlantSat: Carga de Experimentos Biológicos en el Espacio*, Available from: <https://uchile.cl/noticias/183605/plantsat>.
- 28.Garrido C, Obreque E, Vidal-Valladares M, et al. (2024) The First Chilean Satellite Swarm: Approach and Lessons Learned. *Small Satellite Conference* Utah State University, Logan, UT.
- 29.Nicholson WL, Ricco AJ (2020) Nanosatellites for Biology in Space: In Situ Measurement of *Bacillus subtilis* Spore Germination and Growth after 6 Months in Low Earth Orbit on the O/OREOS Mission. *Life* 10. <https://doi.org/10.3390/life10010001>
- 30.Marzioli P, Gugliermetti L, Santoni F, et al. (2020) CultCube: Experiments in autonomous in-orbit cultivation on-board a 12-Units CubeSat platform. *Life Sci Space Res* 25. <https://doi.org/10.1016/j.lssr.2020.02.005>
- 31.Trouillefou CM, Law-Kam Cio YS, Jolicoeur M, et al. (2021) An autonomous plant growing miniaturized incubator for a Cubesat. *Acta Astronaut* 179: 439-449. <https://doi.org/10.1016/j.actaastro.2020.11.009>
- 32.Janairo AG, Concepcion R, Guillermo M, et al. (2025) A Cloud Computing Framework for Space Farming Data Analysis Using a 2U CubeSat. *AgriEngineering* 7: 149. <https://doi.org/10.3390/agriengineering7050149>
- 33.Massaro TS, Liddell LC, Santa Maria SR, et al. (2022) BioSentinel: A Biological CubeSat for Deep Space Exploration. *Astrobiology* 23: 631–636. <https://journals.sagepub.com/doi/10.1089/ast.2019.2068>
- 34.Montaldi ER (1985) Conferencia del académico de número Ing. Agr. Edgardo R. Montaldi sobre Morfogenesis Experimental en el Gramón (*Cynodon dactylon*), *Anales de la Academia Nacional de la Agronomía y Veterinaria*, Tomo XL, Buenos Aires, Argentina.
- 35.Yuri Gravity (2026) Factsheet-RPM-Clinostat. Available from: <https://wordpress.yurigravity.com/wp-content/uploads/2023/09/Factsheet-RPM-Clinostat.pdf>.
- 36.Pochai M, Sirijaturaporn P, Jongjittanon N, et al. (2018) An Aeroponic Technology for Microgravity Plant Experiments on Earth, *15th ECTI-CON, Chiang Rai, Thailand*, <https://doi.org/10.1109/ECTICon.2018.8619918>



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