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Sustainable Lunar Agriculture in Experiential Learning: Integrating Innovative Technologies for Space Farming

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Abstract

NASA's Artemis mission focuses on "Go, Land, Live, and Explore" the Moon, with sustaining life as a key challenge for future lunar settlements. Smart agriculture, which employs advanced automation to enhance crop productivity while reducing labor, is central to overcoming this challenge. This project explores the use of FarmBot, an open-source robotic farming system, and aeroponics, a soil-less cultivation method using Tower Garden technology. Integrating these technologies presents a scalable and innovative approach to space agriculture, with potential applications both on Earth and beyond. Over the past two years, 10 diverse STEM undergraduates (first-year to senior) and three exchange summer interns have engaged in hands-on research on sustainable lunar agriculture. They cultivated crops such as spinach, lettuce, Swiss chard, arugula, and basil in simulated lunar environments using FarmBot and Tower Garden systems. Learning objectives included (a) programming autonomous farming systems, (b) exploring lunar regolith simulants such as Lunar Highland Simulant 1 (LHS-1) and Mexico Lunar Mare 1 (MLM-1), (c) mastering aeroponics, and (d) developing skills in data collection, analysis, and research design.

Students were assessed on their ability to program FarmBot for automated watering and plant monitoring, as well as maintaining and troubleshooting the Tower Garden's aeroponic systems. They formulated hypotheses, designed experiments, and analyzed key variables such as regolith concentration and watering schedules. Growth metrics, including leaf width and plant height, were collected and analyzed. Findings were communicated through written reports and oral presentations, strengthening their scientific communication skills. This program inspires STEM students to tackle space agriculture challenges, preparing them for leadership in space exploration and technological innovation. Through hands-on experimentation and critical analysis, participants gain the expertise needed to contribute to sustaining human life on long-term lunar and Martian missions.

I. Introduction

IA. The Challenge of Sustaining Life

National Aeronautics and Space Administration's (NASA's) Artemis mission represents a transformative step in humanity's journey to explore and inhabit the Moon, setting the stage for a long-term presence that goes beyond the temporary visits of the Apollo era[1]. By emphasizing the principles of "Go, Land, Live, and Explore," the mission reflects a holistic approach to space exploration. While the "Go" and "Land" components address the logistical and technical aspects of reaching and safely arriving on the Moon, the more complex challenges of "Live" and "Explore" are rooted in creating sustainable systems for human survival and enabling scientific discovery in a harsh and unfamiliar environment [1,2].

One of the foremost obstacles to "Live" is sustaining human life on the Moon, where the environment is starkly different from Earth. Unlike Earth, the Moon has no breathable atmosphere, limited water availability (mostly in the form of ice at the poles), and no natural soil capable of supporting agriculture [3]. Moreover, extreme temperature variations ranging from blistering heat during the lunar day to freezing cold at night add another layer of difficulty. Reduced gravity, about one-sixth of Earth's, also impacts biological processes, including plant growth. These constraints make traditional farming methods relying on soil, sunlight, and abundant water resources unfeasible [4,5].

IB. Smart Agriculture in Lunar and Earth Environments

Smart agriculture offers a transformative solution to the challenges of sustaining life on the Moon by leveraging advanced technologies to grow food in controlled, resource-efficient, and automated systems. These systems operate within enclosed, climate-controlled habitats, such as modular greenhouses or inflatable biomes, which protect plants from extreme lunar temperature fluctuations and harmful solar radiation. Thermal insulation and radiation shielding ensure crops thrive in these harsh conditions, while LED lighting mimics sunlight to enable photosynthesis. These LEDs can be fine-tuned to emit specific wavelengths optimized for plant growth, ensuring efficient energy use [6,7].

Traditional soil-based farming is replaced with soilless cultivation techniques like hydroponics and aeroponics, which allow plants to grow in nutrient-enriched water or mist, ideal for the Moon's lack of arable soil and limited resources. Aeroponic systems, in particular, conserve up to 90% more water than traditional farming methods, making them essential for the Moon's water-scarce environment [3,8]. Automation and robotics further reduce the physical labor required for farming, with robotic arms and platforms like FarmBot planting seeds, monitoring plant health, and harvesting crops autonomously [9]. Integrated sensors and cameras provide real-time data on plant growth and environmental conditions, enabling precise adjustments to optimize productivity. Smart agriculture also minimizes resource waste by recycling water and nutrients in a closed-loop system, where transpired water is captured and reused, and organic waste is converted into nutrients for future crops. This integration extends to life-support systems, with plants contributing to oxygen production and carbon dioxide recycling, enhancing overall resource efficiency [10]. Central to these systems are advanced data analytics and AI tools that analyze sensor data to optimize growing conditions and predict potential issues, such as disease or nutrient deficiencies, before they arise. Machine learning models refine agricultural processes over time, tailoring them to the Moon's unique challenges. Together, these innovations make smart agriculture a cornerstone of sustainable lunar habitation, transforming how food production is conceived and executed in space [11].

The integration of smart agriculture into the Artemis mission is not just about sustaining the astronauts but also about enabling the long-term exploration and settlement of the Moon. A reliable and self-sustaining food production system reduces dependence on resupply missions from Earth, which are costly and logistically complex. This independence is critical for supporting extended missions and larger lunar populations in the future[10,11]. Moreover, the knowledge and technologies developed for lunar agriculture have implications that extend beyond the Moon: a) **Mars Colonization**: The lessons learned on the Moon will serve as a foundation for agricultural systems on Mars, where conditions are similarly extreme but with additional challenges, such as longer supply lines and different atmospheric compositions. B) **Earth Applications**: Smart agriculture technologies developed for space can be adapted to address food security challenges on Earth, particularly in regions with extreme climates or limited resources. Innovations like hydroponics, aeroponics, and automated farming can help combat food scarcity and make agriculture more sustainable globally [12].

NASA's Artemis mission is not just about returning to the Moon. It is about building a future where humans can thrive off-Earth. "Live" and "Explore" are more than aspirations; they are imperatives for advancing humanity's presence in space. Smart agriculture is central to this vision, offering innovative solutions to the challenges of sustaining life on the Moon. By leveraging automation, resource efficiency, and cutting-edge technology, smart agriculture ensures that astronauts will have the nourishment needed to survive and thrive, laying the groundwork for the next chapter of human exploration and settlement in space [1,2,6,7].

IC. STEM Education, Inclusive Experiential Learning in Sustainable Lunar Agriculture

STEM education serves as a foundational pillar for developing the technologies and expertise required to implement sustainable agriculture both on Earth and in extraterrestrial environments, such as the Moon. It equips students with the skills to design and innovate solutions for the unique challenges posed by the lunar environment, including the absence of arable soil, extreme temperature fluctuations, limited water availability, reduced gravity, and the need for closed-loop resource management. These challenges demand interdisciplinary thinking and hands-on engagement with cutting-edge technologies, making STEM education indispensable to advancing sustainable agriculture in space [13].

Key innovations, such as soilless cultivation methods (e.g., hydroponics and aeroponics), automated farming systems, and resource-efficient designs, are ideal focal points for STEM-based learning. Students can explore controlled-environment agricultural systems, such as modular greenhouses with LED lighting and thermal insulation, to protect crops from harsh conditions. Additionally, programming and working with robotic systems like FarmBots allow learners to optimize planting, monitoring, and harvesting processes with minimal human intervention. These hands-on projects not only enhance understanding of sustainable agricultural practices but also foster problem-solving, creativity, and technical skills essential for space exploration [13,14].

Incorporating sustainable agriculture into STEM education also opens doors for inclusive and accessible experiential learning, which ensures equitable opportunities for diverse learners. Technologies like FarmBots and Tower Gardens serve as transformative tools in making agriculture education accessible to individuals with varied abilities and learning styles. FarmBots, for instance, can be customized with raised platforms for wheelchair accessibility or user-friendly software for learners with sensory or cognitive impairments. Tower Gardens, compact vertical aeroponic systems, make farming feasible in urban or limited-space environments and require minimal physical labor, inspiring participation from individuals who might face mobility challenges [15]. By integrating FarmBots and Tower Gardens into educational initiatives at the University of Maryland Eastern Shore (UMES) promote diversity in science and engineering while preparing students for the future of sustainable farming. These tools facilitate collaborative learning, as students from different backgrounds and abilities work together to design, program, and maintain sustainable systems. Such experiences foster teamwork, innovation, and a shared sense of purpose. Moreover, they link agriculture with broader life-support systems, enhancing resource efficiency and preparing students to tackle real-world challenges in food security and climate resilience [16].

Beyond their application in space, these educational initiatives at the university have significant implications for Earth. Techniques developed for sustainable lunar agriculture, such as resource-efficient soilless farming and automated systems, can be adapted to address food security and sustainability challenges on Earth, particularly in regions facing resource scarcity or extreme climates [17]. By bridging technology and traditional farming, STEM education and inclusive experiential learning empower diverse learners to create a more equitable, innovative, and sustainable agricultural future, both on Earth and beyond.

ID. Objectives

The four key learning objectives of this project are:

a) ***to learn programming and operating autonomous farming systems***: Gain hands-on experience in programming and operating FarmBot systems, learning how autonomous farming technologies can optimize planting, monitoring, and harvesting processes in sustainable agriculture.
b) ***to understand sustainable agricultural practices with lunar regolith simulants***: Investigate the feasibility of growing crops in lunar-like soils using regolith simulants such as Lunar Highland Simulant 1 (LHS-1) and Mexico Lunar Mare 1 (MLM-1), and understand the challenges and solutions for extraterrestrial farming.
c) ***to develop proficiency in aeroponics with Tower Garden technology***: Develop proficiency in aeroponic growing techniques using Tower Garden systems, focusing on the principles of soil-free cultivation, water conservation, and nutrient delivery in controlled environments.
d) ***to develop skills in data collection, analysis, and research methodology***: Develop skills in hands-on research by collecting, analyzing, and interpreting data related to plant growth, environmental conditions, and agricultural productivity. Apply research methodologies to assess and refine sustainable lunar agriculture techniques.

2.0 Approach

2A. Recruitment of Students for the Summer Exchange and Academic Year

The Maryland Space Grant Consortium (MDSGC) Summer Exchange Internship Program offers a paid internship opportunity that spans a 10-week period each summer. The program primarily targets STEM undergraduate students from participating member institutions within the MDSGC, providing them with invaluable hands-on research experiences at institutions outside their home campuses. The initiative emphasizes the importance of exposing students to research environments that expand their knowledge and skills in fields related to the National Aeronautics and Space Administration’s (NASA’s) mission and the needs of the future workforce.

To participate, students must first contact the faculty coordinator at their home institution, who plays a crucial role in identifying and matching students with appropriate projects. Faculty mentors from participating member institutions submit proposals for projects aligned with NASA's goals and relevant STEM disciplines. These proposals include key project components, such as learning outcomes, timelines, mentoring plans, and expected deliverables. The program places a strong emphasis on inclusivity, actively recruiting women and members of underrepresented minorities, thereby ensuring a diverse pool of participants. Financial support is requested for one to three students per project to cover their stipends during the internship.

Eligible students must be U.S. citizens, enrolled at participating MDSGC member institutions, and majoring in a STEM discipline relevant to the project. To qualify, students must be rising sophomores, juniors, or seniors and commit to a full 10-week internship during the summer. Following the application process, faculty research mentors interview prospective interns to determine their fit for the project. Once selected, students are paired with their research mentors for the full duration of the summer exchange program. In the most recent program cycle at UMES, three student interns participated in the sustainable lunar agriculture project. One intern, a biological engineering student from **University of Maryland College Park**, a computer science student from the University of Maryland, Baltimore County, and another student majoring in Environmental Sciences from Duke University worked alongside undergraduate students from Biology, Agriculture, and Engineering majors at the home institution. Their responsibilities included assisting with experimental setups, data collection, and analysis, contributing to the development of sustainable lunar farming systems using robotics and aeroponics. Throughout the summer, these students gained practical experience in applying their academic knowledge to real-world challenges in agricultural engineering.

In addition to the summer interns, 10 students (1 junior Biology; 1 sophomore from Environmental Sciences; 2 juniors from Agriculture; 2 freshmen from Computer Science; and 2 sophomores and 2 juniors from Engineering) participated in the project during the past academic years. These students worked together to further the goals of the project, engaging in collaborative research and gaining deeper insights into sustainable agricultural technologies.

At the conclusion of their internship, all participating students were required to submit a short report reflecting on their experiences, including their research findings and the skills they developed throughout the program. This initiative not only provided hands-on experience in cutting-edge agricultural lunar research but also fostered a collaborative, interdisciplinary environment where students from diverse backgrounds worked together toward shared research goals, preparing them for careers in STEM fields.

2B. Student Involvement in Experimental Setup, Lua Programming, Data Collection, and Analysis

As part of the experiential learning initiative in sustainable lunar agriculture, undergraduate students and summer exchange interns played an integral role in designing and conducting experiments using advanced agricultural technologies. Under the supervision of faculty, post-doctoral associates, and graduate students, they engaged in hands-on research involving the setup of FarmBot and Tower Garden systems, programming automation sequences using Lua, collecting plant growth data, and analyzing experimental results.

Students actively participated in setting up both FarmBot and Tower Garden systems for sustainable agriculture research. This involved assembling and configuring the FarmBot Express V1.1 within an indoor controlled environment and ensuring the proper installation of Tower Garden FLEX units. They prepared growth media by formulating different mixtures of lunar regolith simulants, including Lunar Highland Simulant 1 (LHS-1) and Mexico Lunar Mare 1 (MLM-1), combined with potting soil in varying concentrations. Students also germinated, transplanted, and monitored crops such as spinach, lettuce, Swiss chard, arugula, and basil in both soil-based and aeroponic systems.

Students gained hands-on experience with programming FarmBot using Lua, a lightweight scripting language that enables automation of precision agricultural tasks. With guidance from faculty and post-doctoral researchers, they wrote Lua scripts to control robotic movements, schedule automated watering, and capture images of plant growth using the FarmBot's onboard Raspberry Pi camera. They also worked on troubleshooting calibration errors, ensuring accurate positioning of the robotic arm, and refining the irrigation schedules to prevent soil erosion caused by high-water pressure.

Throughout the experimental period, students monitored key plant growth parameters, including leaf width, plant height, and overall physiological responses to different regolith simulant mixtures. Using sensors from the Grove Smart Agriculture Kit integrated with Microsoft FarmBeats, they recorded environmental variables such as soil moisture, air temperature, humidity, and light intensity. They also documented anomalies such as delayed germination and stress responses in plants grown in high-regolith concentrations.

With faculty and post-doctoral supervision, students processed collected data to assess plant performance under varying conditions. They performed statistical comparisons between control and treatment groups, evaluating the impact of regolith concentration on plant growth rates. Analytical tools were used to interpret trends, and students collaborated on refining experimental conditions for future trials. Their findings were compiled into research reports and presented at university symposiums, strengthening their scientific communication skills.

By integrating hands-on experimentation with computational programming and data-driven analysis, this initiative provided students with a multidisciplinary experience in sustainable lunar agriculture, preparing them for careers in STEM, robotics, and space exploration.

2C. Regolith Simulants Experiments in the Indoor Farmbot and Laboratory

Spinach (*Spinacia oleracea*) was cultivated in mixtures of two regolith simulants-lunar mares (MLM-1) and highlands (LSH-1) to explore plant growth under simulated lunar conditions. Lunar regolith simulants, designed to replicate the physical and chemical properties of Moon soil, are essential tools for advancing the sustainability and success of future lunar missions. A steady food production system is crucial for the viability of any lunar habitat, and these simulants allow researchers to test and optimize plant growth under conditions mimicking the Moon's harsh environment[18,19]. By using these materials, effective agricultural systems can be tailored for lunar conditions, enhancing plant productivity while addressing challenges such as limited water, low nutrients, and extreme temperatures.

The integration of advanced technologies into these studies further facilitates sustainable agricultural practices, reducing labor, optimizing resource utilization, and enabling long-term self-sufficiency. At the University of Maryland Eastern Shore, the research leverages two types of lunar regolith simulants to investigate these possibilities: the lunar highlands simulant (LHS-1), sourced from the University of Central Florida, and the lunar mare simulant (MLM-1), provided by New Mexico State University. These simulants enable us to explore innovative methods for cultivating crops in lunar-like conditions, contributing to the broader goal of sustaining human life beyond Earth (Figure 1).

Figure 1. MLM-1 mare simulant (left) and LHS-1 highlands simulant (right)

Five medium-sized rectangular containers were prepared for each simulant type, yielding a total of ten containers. The containers were filled with mixtures labeled as follows: 100% potting soil (control), 25% regolith and 75% potting soil, 50% regolith and 50% potting soil, 75% regolith and 25% potting soil, and 100% regolith. Each mixture was measured to weigh approximately 2500 grams. Two spinach seeds were planted equidistantly in each container. Horse manure, serving as fertilizer [20], was incorporated at 1% of the regolith simulant content by weight. To ensure reliability, an additional replicate control was included for the MLM-1 simulant (Figure 2).

Figure 2. Top view of regolith simulants experiment set-up with the spinach plants and rocks

The experiment was conducted in a controlled laboratory environment equipped with an indoor FarmBot Express, which was monitored and managed via the FarmBot web app. FarmBots are computer numerically controlled (CNC) robots, similar in design to 3D printers, and are powered by Raspberry Pi and Arduino-like microprocessor boards [21,19] (Figures 3 and 4).

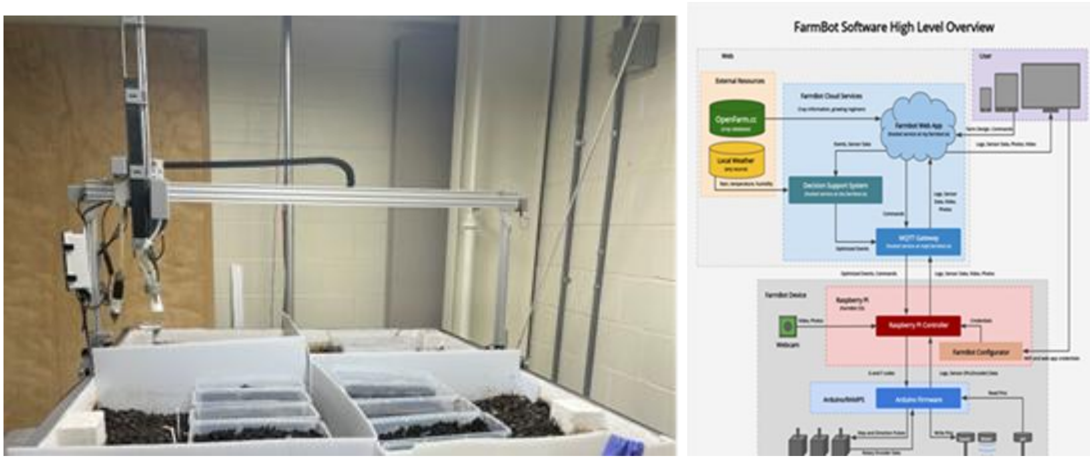

Figure 3. FarmBot Express with regolith simulants(left); Farmbot software assembly (right)

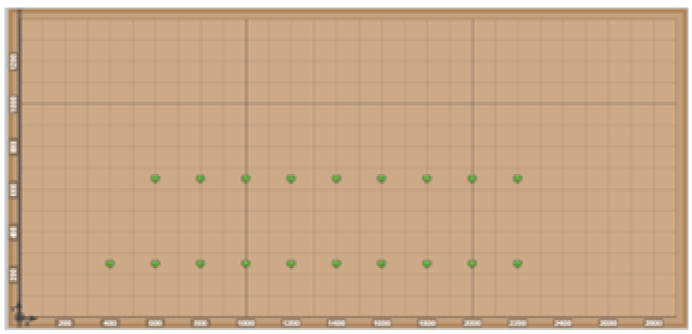

Figure 4. Spinach placement modeled in the FarmBot web app according to plot measurements

These highly versatile machines perform a wide range of tasks essential for efficient and precise crop management. Equipped with a Raspberry Pi Camera (Pi-Cam), FarmBots extend their functionality beyond basic automation. The camera supports weed detection and captures time-lapse photography, enhancing agricultural monitoring and documentation. The cloud-based accessibility feature allows users to remotely oversee and control FarmBot operations from any internet-enabled device, providing unparalleled flexibility [22]. The compact FarmBot Express V1.1 is designed to function beneath overhead grow lights, enabling precise control over photoperiods. This capability facilitates experimentation with various food and specialty crops, promoting agricultural diversification and innovation.

Autonomous watering was programmed using Lua (programming language) sequencing, delivering water for three seconds in the middle of each container on alternate days (Figure 5). Grow lights, set to a 12-hour photoperiod (6:00 am to 6:00 pm), provided consistent light exposure (Figure 6).

```lua
-- Define the pin numbers for the peripherals
local water_pin = 8
local lighting_pin = 7
local vacuum_pin = 9

-- Define the origin coordinates
local origin = {x = 0, y = 0, z = 0}

-- Define a function to take an image at the current position
local function take_image()
  move_absolute(origin.x, origin.y, origin.z)
  take_photo()
end

-- Move to each plant, take an image, and return to the origin
for _, plant in ipairs(plants) do
  move_absolute(plant.x, plant.y, plant.z)
  take_image()
end

-- Return to the origin
move_absolute(origin.x, origin.y, origin.z)
```

Figure 5. Simple Lua sequencing for FarmBot to take plant photos.

Figure 6. Indoor Farmbot with grow lights

Growth parameters, including plant height and width, were recorded weekly for spinach. Environmental conditions such as soil temperature, soil moisture, air temperature, air humidity, and light intensity were monitored weekly using sensors from the Grove Smart Agriculture Kit integrated with Microsoft FarmBeats via Data Streamer in Excel [23]. Observations of anomalies and deviations were documented throughout the study to ensure detailed data tracking and analysis.

2D. Vertical Aeroponic Growing Systems-Tower Garden FLEX

Two Tower Garden FLEX systems were assembled following the manufacturer's packaging instructions to ensure proper setup. Seeds for each plant type were sown into Rockwool cubes, as specified by the instructions on the individual seed packets. The cubes were lightly covered with vermiculite and placed in a germination tray. The tray was watered as needed to maintain approximately ¼ inch of water, ensuring consistent moisture levels for germination. The bottom reservoir of each Tower Garden was filled with approximately 20 gallons of water mixed with a nutrient solution, prepared by adding 20 mL each of mineral blends A and B per gallon of water. The built-in water pump was set to the indoor automatic setting to ensure consistent irrigation and nutrient delivery. After germinating in the tray for approximately two weeks, seedlings were transplanted into net pots on the towers (Figure 7). The tower without an extension housed 9 bibb lettuce plants (6 treatments and 3 controls) and 11 gourmet lettuce plants (6 treatments and 5 controls).

Figure 7. Tower Garden FLEX with bibb and gourmet lettuce when first transplanted (left) and after one month (right)

The tower with an extension accommodated 10 basil plants (7 treatments and 3 controls), 10 arugula plants (7 treatments and 3 controls), and 8 rainbow chard plants (5 treatments and 3 controls) (Figure 8).

Figure 8. Tower Garden Flex with basil, arugula, and rainbow chard plants

A liquid seaweed growth stimulant [24] was applied weekly to the designated treatment plants using a spray bottle. This biostimulant application aimed to investigate its effects on growth and stress resilience across the different plant types. Control plants were maintained under the same conditions but did not receive the seaweed treatment, allowing for comparative analysis of growth performance and treatment efficacy. This experimental setup ensures standardized conditions for evaluating plant growth and treatment effects while leveraging the Tower Garden FLEX systems' efficiency for sustainable aeroponic agriculture.

3.0 Results and Discussion

3.1 Farmbot Express

FarmBot technology contributes significantly to sustainability efforts by reducing the carbon footprint of vegetable production. Vegetables grown using FarmBot emit 25-30% less CO_2 compared to store-bought ones. However, the primary advantage of FarmBot lies in its precision and automation capabilities. It excels in tasks requiring accurate positioning, such as targeted planting, watering, and weeding. Despite its strengths, a notable challenge initially encountered was the issue of high-water pressure. This caused soil cratering, which disrupted soil structure and potentially hindered plant growth due to uneven water distribution. To address this issue cost-effectively, rocks were strategically placed beneath the direct water stream of the FarmBot to protect the soil (Figure 9). This simple solution successfully prevented soil erosion caused by water impact.

Figure 9. FarmBot watering plants with rock protection

The open-source nature of FarmBot is another major advantage, allowing for extensive customization and adaptation to specific research needs. However, this flexibility can present challenges for novice users, particularly in adapting to the system and troubleshooting errors. For instance, there were occasional misalignments between the FarmBot's position in the web app and its actual physical placement, likely due to connectivity issues. Additionally, the automation and movement mechanisms were somewhat inconsistent, resulting in unreliable watering from random calibration problems. While only the watering function was tested in this instance, its performance serves as a general indicator of the reliability of other FarmBot functions, as all rely on similar movement and automation processes.

Despite its potential, FarmBot’s scalability is a significant limitation. Its current design is better suited for small-scale operations, as larger agricultural applications would face greater challenges in calibration, maintenance, and troubleshooting due to increased complexity and time requirements.

3.2 Tower Garden FLEX

The Tower Garden systems, although not equipped with automated sequencing for movements, offer excellent vertical space efficiency and are ideal for growing leafy greens in compact areas, such as indoor spaces [25]. Their vertical design reduces space requirements by 90%, while the aeroponic system uses only 2% of the water required for traditional gardening. These systems are particularly beginner-friendly due to their simplicity in construction and maintenance. Tower Gardens provide a practical solution for growing healthy produce under environmental constraints and are accessible for individuals with limited mobility. Since aeroponic systems eliminate the need for soil, the risk of contamination is significantly reduced, and there is no requirement for weeding. Maintenance is minimal and time-efficient, thanks to the automated watering pump [25].

However, Tower Gardens do require a consistent power source to operate the pump that circulates water and nutrients, which can pose challenges during installation due to the dependency on a power outlet. Additionally, while versatile, these systems are not suitable for all crop types, particularly those with large root systems or requiring extensive space. In both Tower Gardens, with and without extensions, there were no significant differences observed between the control and treatment groups (Figure 10). Each plant type such as bibb lettuce, gourmet lettuce, basil, arugula, and rainbow chard grew successfully under room temperature and uniform light conditions. However, once the lettuce (bibb and gourmet) reached a substantial size, some inner leaves became paler green in color due to limited light exposure.

Figure 10. Tower Garden FLEX with bibb and gourmet lettuce when first transplanted (left) and after one month (right)

3.3 LHS-1 and MLM-1 Regolith Simulants

For LHS-1 and MLM-1, the 50% regolith and 50% potting soil mixtures exhibited the earliest germination, whereas the 100% regolith mixtures germinated a week later. Overall, the LHS-1 mixtures had a higher germination rate compared to the MLM-1 containers—90% (18 sprouts out of 20 seeds) versus 72% (13 sprouts out of 18 seeds). The most robust growth, as measured by the largest leaf widths, was observed in the 75% regolith mixtures for both types of regolith simulants (Figures 11-13).

Simulant	Condition	Height (cm)	Width (cm)
LHS-1	100% RS-1	3	1
	100% RS-2	3	0.5
	75% RS-1	5	2
	75% RS-2	4	1
	50% RS-1	4.5	0.3
	50% RS-2	5.5	1.5
	25% RS-1	3	0.3
	25% RS-2	4	0.3
	0% RS-1	4	0.3
	0% RS-2	4.5	0.3
MLM-1	100% RS-1	---	---
	100% RS-2	3.5	1
	75% RS-1	4	1
	75% RS-2	4.5	1.5
	50% RS-1	4.5	0.7
	50% RS-2	3.25	0.9
	25% RS-1	5	0.4
	25% RS-2	3	0.3
	0% RS-1	4.5	0.3

Figure 11. Height of spinach plants and width of the biggest leaves in LHS-1 and MLM-1 regolith simulant conditions after one month (note: for two plants in the same container, heights and widths were averaged together)

Figure 12. LHS-1 and MLM-1 spinach growth of various regolith simulant mixtures

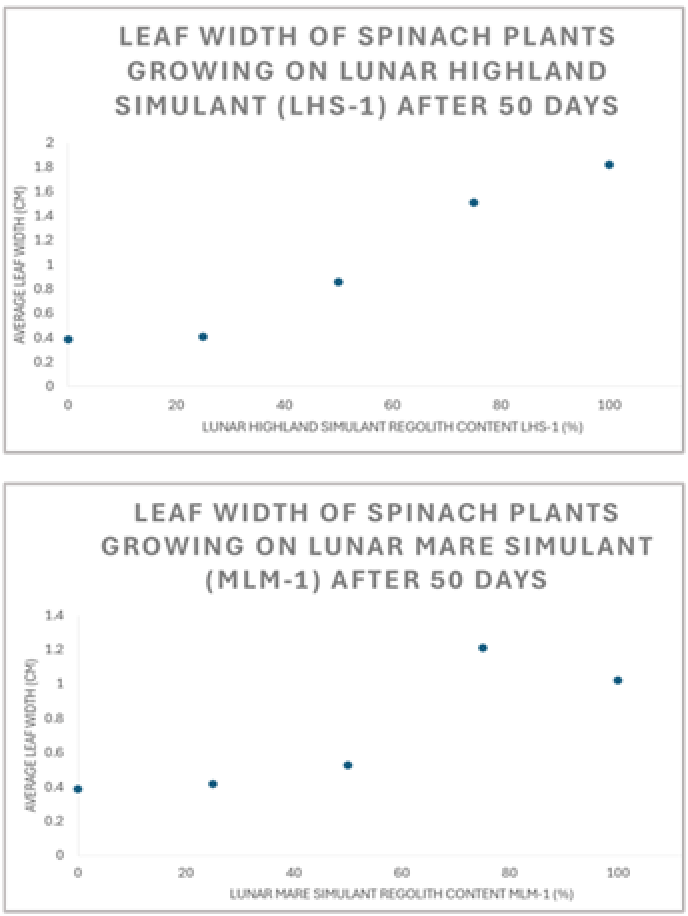

Figure 13. Spinach leaf width data for varying concentrations of LHS-1 (top) and MLM-1 (bottom) after 50 days

Spinach in the LHS-1 mixture with 75% regolith and 25% potting soil consistently showed the best growth until the final week, when plants in the LHS-1 100% regolith containers surpassed them. The superior growth observed in the LHS-1 75% and 100% regolith mixtures was attributed to the presence of consortium of crustose lichens (symbiotic organism consisting of a close association between a fungus-the mycobiont and a photosynthetic partner-the photobiont) [26], which improved water retention and provided essential nutrients such as nitrogen, phosphorus, and potassium (Figure 14).

Figure 14. A close-up of the consortium of crustose lichens

Additionally, the lichen reduced water and temperature stress, enabling better growth under otherwise challenging conditions. The high humidity and elevated temperatures in the experimental space (nearly 80°F) imposed arid conditions on the plants, despite regular watering schedules. Soil mixtures with lichens retained moisture significantly better than those without. Spinach plants in mixtures lacking lichen exhibited prolonged water stress, as evidenced by yellowing and wilting leaves. Overall, spinach growth was limited compared to standard maturation. The experimental temperature (~80°F) greatly exceeded the ideal range for spinach (50°F–60°F, with a maximum of 75°F).

These findings align with prior studies by Dutch researchers [27], where spinach performed poorly on regolith simulants. In their experiments, ten crop species including garden cress, rocket (arugula), tomato, radish, rye, quinoa, chives, pea, and leek were cultivated in lunar and Martian regolith simulants. All crops, except spinach, grew well and produced harvestable, edible parts. Spinach, however, failed to develop adequately in any soil, including Earth's organic soil, and showed signs of premature flowering.

4.0 Project Learning Outcomes

4.1 Assessments and Student Learning Outcomes in Experiential Learning in Sustainable Lunar Agriculture

Students were evaluated through a framework designed to measure their technical, analytical, and communication skills in the context of sustainable lunar agriculture. The assessments incorporated multiple dimensions to ensure a comprehensive evaluation of their learning outcomes, practical skills, and innovative thinking.

a. **Technical Skill Assessments**

Students were assessed on their ability to operate the FarmBot and Tower Garden systems effectively. This included programming the FarmBot to automate essential agricultural tasks such as watering. They learned about monitoring plant growth, and adjusting parameters based on real-time data. Troubleshooting and maintenance of the Tower Garden aeroponic systems were integral parts of the assessment, requiring students to diagnose and resolve operational challenges.

b. **Experimental Design and Research Process**

A key component of the assessment involved evaluating students' ability to design and implement experiments. This included formulating clear and testable hypotheses, selecting appropriate variables such as regolith concentration and watering schedules, and designing experiments to investigate optimal plant growth conditions. Students' understanding of research methodologies was measured through their approach to setting up controlled experiments and identifying factors influencing plant health in simulated lunar environments.

c. **Data Collection and Analysis**

Students collected quantitative and qualitative data on growth metrics such as leaf width, plant height, and physiological responses to varying regolith simulant concentrations. The consistency in their data collection was a key to evaluate their understanding of the process. Analytical skills were evaluated through students' ability to interpret the data, identify trends, and draw meaningful conclusions about the impact of experimental variables on plant growth.

d. Communication and Presentation Skills

Students were required to produce comprehensive written reports documenting their experimental processes, results, and analyses. These reports were assessed for clarity, organization, technical accuracy, and the ability to synthesize information effectively. Oral presentations were an essential part of the evaluation, focusing on students' ability to articulate their findings, explain the broader implications of their research for space farming, and propose innovative solutions for sustainable agriculture.

e. **Problem-Solving and Innovation**

Assessments emphasized the students' creativity in addressing challenges associated with space farming, including proposing enhancements to existing agricultural technologies or new methods to optimize plant growth in resource-limited environments.

f. **Teamwork and Collaboration**

Many tasks required collaborative effort, and students were evaluated on their ability to work effectively in teams. This included dividing responsibilities, sharing insights, and integrating diverse perspectives to achieve project goals.

Through these multifaceted assessments, students gained valuable experiential learning that bridged theoretical knowledge and practical application, equipping them with the skills necessary for understanding sustainable agricultural systems in both terrestrial and space exploration contexts. This approach fostered a deeper understanding of interdisciplinary problem-solving and innovation in emerging technologies.

Collaboration and Support

A cornerstone of the project is fostering a collaborative and supportive community. Students with disabilities are encouraged to work in peer groups where mutual learning and assistance are prioritized. Dedicated mentorship programs pair students with experienced faculty or advanced peers who provide guidance tailored to their needs. This structure creates a network of support that enhances both academic and personal growth.

Flexible Assessments

To ensure fair and equitable evaluation, alternative assessments are available. For example, students may present their findings through video presentations instead of written reports or participate in modified practical evaluations that align with their abilities. These options allow students to demonstrate their understanding and creativity without being constrained by traditional methods that may not suit their individual needs.

Training and Awareness

Inclusive practices are supported by training programs offered at the university for both faculty and students. These sessions cover disability awareness, inclusive teaching strategies, and how to use assistive technologies effectively. By fostering an environment of understanding and respect, the program ensures that all participants feel welcomed and valued.

At its core, the program aspires to inspire a diverse cohort of STEM students to pursue research in space agriculture. By addressing challenges like sustaining human life on long-term lunar mission, the program prepares students to tackle some of humanity's most pressing questions. Through hands-on experimentation, problem-solving, and critical analysis, participants develop skills in the emerging fields of space exploration and sustainable agricultural innovation. In doing so, the program not only advances the inclusivity of STEM education but also contributes to the broader goal of creating a more diverse and capable workforce for future technological challenges.

5.0. Conclusions

Technological applications play a crucial role in enhancing productivity, sustainability, and accessibility in both terrestrial and lunar agriculture, helping to support long-term human presence in space. The integration of innovative agricultural technologies and practices, such as autonomous farming robots like the FarmBot Express and aeroponic systems like the Tower Garden FLEX, offers distinct advantages for improving efficiency and resource management. However, each technology has its limitations in the engineering context, particularly when adapting them to space or constrained environments like lunar habitats. In the future, efforts should focus on improving the scalability of systems like the FarmBot and integrating vertical aeroponic solutions to capitalize on the strengths of both designs. Such hybrid systems could provide a more efficient and adaptable approach to agricultural automation, allowing for higher yields and greater resource efficiency in both terrestrial and extraterrestrial settings.

Further research is essential to expand the range of plants that can be cultivated in these systems, particularly through the combination of Tower Gardens and regolith simulants with FarmBot technology. Investigating the use of other types of biofertilizers and seaweed biostimulants on regolith simulants present another promising research direction, as bioactive compounds have the potential to enrich soil-like environments with nutrients, improving the viability of plant growth in lunar soil analogs. These studies are vital for understanding how different biotic and abiotic components can work together to optimize agricultural systems for space exploration.

The project intends to include the use of an Arduino clinostat, a device designed to simulate lunar microgravity conditions for growing plants, such as cress. By negating the effects of gravitational pull, this experiment can examine how plants respond to altered gravity, providing insight into how growth patterns change when gravity is removed. Understanding plant growth under simulated lunar conditions is crucial for developing agricultural practices that can be implemented on the Moon. This research is part of a broader effort to address three grand challenges in engineering [28]: (1) ***optimizing plant growth in varying soil compositions, thereby managing the nitrogen cycle and enhancing nutrient cycling***; (2) ***developing the tools necessary for scientific discovery by designing systems that simulate plant growth in harsh lunar environments***; and (3) ***creating sustainable carbon sequestration methods through the implementation of efficient, space-saving agricultural systems that reduce waste and maximize productivity in confined spaces***.

By focusing on these areas, we aim to create innovative solutions that will not only improve food production on the Moon but also provide valuable insights for advancing sustainable agriculture practices on Earth. These efforts are foundational to the success of long-term human exploration and habitation in space, contributing to the creation of self-sustaining systems that support human life beyond our planet.

6.0. Future Directions

The use of aeroponics presents a highly promising soil-less cultivation method, particularly suited for the unique challenges of growing crops on the Moon. Lunar regolith, while abundant, lacks the necessary nutrients and organic matter required for traditional soil-based agriculture, making aeroponics an ideal solution. By suspending plant roots in the air and misting them with a nutrient solution, aeroponics offers an efficient and water-conserving way to support plant growth in environments with limited resources. This method bypasses the need for soil, reducing the complexity of lunar farming while providing a controlled, efficient way to cultivate crops in the absence of terrestrial soils. In addition to aeroponics, the exploration of seaweed-based biostimulants provides an innovative way to enhance plant health and growth under lunar conditions. Seaweed (a general term for a variety of marine plants and algae that grow in oceans, seas, and other saltwater environments) is rich in bioactive compounds such as plant hormones, polysaccharides, and antioxidants, which can significantly improve plant growth by stimulating root development, enhancing nutrient uptake, and increasing stress resilience [29,30]. Seaweed-based biostimulants are especially useful in promoting plant survival and productivity in environments where nutrient availability is limited, such as on the Moon. These biostimulants help plants cope with abiotic stressors, such as temperature extremes, low water availability, and radiation exposure, which are common in space and lunar environments.

Moreover, food plants grown under varying regolith concentrations and aeroponically can be analyzed for antioxidant compounds. This research is crucial, as antioxidant-rich plants are not only vital for supporting astronaut health and immune systems but also offer insights into how these plants can adapt to the harsh conditions of space. By studying the impact of lunar regolith simulants on plant growth and antioxidant production, researchers can develop strategies to optimize plant varieties that are not only nutritious but also capable of thriving in extraterrestrial environments.

Using aeroponics, seaweed biostimulants, and antioxidant analysis will represent a comprehensive approach to sustainable lunar agriculture. These not only aim to create systems that produce nutritious crops but also pave the way for long-term human habitation on the Moon. As research continues, these innovative methods hold the potential to transform how we think about farming in space, ensuring that astronauts have access to fresh, healthy food while minimizing reliance on Earth-based resources.

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