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ASTRO-AGRICULTURE: A CONCEPTUAL FRAMEWORK FOR AUTONOMOUS PLANT GROWTH SYSTEMS IN SPACE HABITATS

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ABSTRACT

Long-duration human space missions require life support systems that can sustain life and limit dependence on supplies and store consumables from Earth. Plants can be a complete solution by providing fresh food, recycling CO2, generating O2, and improving crew health and well-being. NASA's Veggie and Advanced Plant Habitat and other analogs, such as EDEN-ISS, have shown space farming is possible; however, the capacity of the current systems was restricted because there was narrow spectral lighting used, difficulty of reaching roots due to microgravity, and inability to monitor them effectively. This paper provides a conceptual framework for an automated Astro-Agriculture system that will overcome the challenges of current systems. The automated system has three unique features to be developed: broad-spectrum tunable lighting to promote optimal photosynthesis and crop quality; a hydroponic /aeroponic, gravity-agnostic, scalable nutrient delivery system that will provide roots access to reliable hydration in microgravity, and hyperspectral and depth imaging for continuous, non-disruptive monitoring of plant physiology, growth characteristics, and biomass. The complete system is designed to connect environmental sensors to imaging and provide automated control of lighting, nutrient delivery systems, and the environment to minimize crew engagement. The system is sought as a compact modular unit for implementation in in-space human spaceflight missions in controlled-environment agriculture and vertical farming.

KEYWORDS: Space agriculture, Microgravity crops, plant growth systems, and Life support.

INTRODUCTION

The viability of human life beyond Earth is key to the success of future missions in outer space. Conventional life-support systems, based largely on consumables that are stored for the duration of the trip, are inadequate for Moon, Mars, and deep space outposts because of the prohibitive cost of launching supplies, the limits on resupply of consumables for long-term missions, and the unavoidable physiological and psychological stressors imposed on astronauts living under isolated and confined conditions. Thus, space agencies around the world have acknowledged the potential for bioregenerative life support systems, in which plants and microorganisms convert carbon dioxide to oxygen, filter water, and grow fresh food for astronauts. Growing crops as part of bioregenerative life support has many advantages, including the ability to give astronauts emerging nutritional supplements to their diet, to enhance crew morale, and provide a direct link to the atmospheric and waste management loops.

Early demonstrations on the International Space Station, for example, NASA's Veggie and the Advanced Plant Habitat, have confirmed that crops will complete their life cycles in microgravity with both plant growth systems, which have included lettuce, mustard greens, and dwarf wheat. These early demonstrations demonstrated that astronauts could grow edible plants in microgravity using controlled LED lighting, hydroponic growth substrates, and atmospheric controls. Likewise, analogs in local Earth environments, including the EDEN-ISS Antarctic greenhouse and the prototypes of the Mars-Like Growth Habitats, highlight that food plants can be produced with high yields and closed environmental controls under extremes of climate. However, regardless of these successful descriptions, there are still significant gaps to be filled before space agriculture is regarded as a reliable and scalable operation that can be routinely integrated into a space mission's objectives.

One of the most significant impediments is nutrient and water delivery in microgravity. In typical terrestrial hydroponic systems, gravity pulls fluids around the grow medium to the roots; however, in orbit, fluids will not even hydrate any given area of the substrate concerning the roots, which can lead to gas bubble formation, suffocate roots, and other unwanted changes. Although the use of wicking mats for moisture delivery and porous substrates has made progress towards this challenge, there is still a need for a well-considered, gravity-independent delivery of nutrients. The second challenge is lighting. Most existing space programs utilize narrow-band red and blue LEDs, which do use far less energy but fail to closely imitate the solar spectrum entirely. There is now increasing evidence that a broad spectrum of wavelengths, including green, far-red, and UV, can make important contributions to photosynthesis, morphology, or the quality of crop nutritional content. Third, all existing systems have a limited ability to monitor crops. They typically only have RGB cameras and environmental sensors, which can only provide basic data, but not what are familiar we feel are minute physiological stages like early nutrient deficiencies, early water stress, or onset of a pathogen infection. Any advanced method like hyperspectral or depth imaging, which we are all familiar with using in controlled-environment agriculture in most terrestrial applications, has not likewise been incorporated into space systems. These limitations highlight the need for a new generation of automated, intelligent agricultural modules that can provide sustenance to astronauts on long missions with minimal crew time and maximum reliability. The Astro Agriculture system proposed in this study aims to address these limitations with three innovations:

1. Broad-spectrum tunable lighting allows finely tuned control of photosynthetically active and regulatory wavelengths.
2. Gravity-agnostic hydroponic/aeroponic nutrient delivery systems are designed to preclude bubble formation and ensure uniform hydration of root zones.
3. Integrated hyperspectral and depth imaging for real-time monitoring of plant health, growth dynamics, biomass estimation, and AI-based environmental control.

In addition to generating food, a module of this kind would also provide a direct contribution to closed-loop life support by regulating atmospheric gases: plants will absorb the CO_2 produced by astronauts and release the O_2 needed for respiration. This coupling of breath and nourishment will transform the plant growth chamber from a food generator into a multi-functional subsystem for spacecraft. The significance of this research is particularly evident in the Indian context because with the forthcoming human spaceflight, developing indigenous space-farming technology will facilitate strategic autonomy and limit reliance on foreign systems. Moreover, spin-off benefits for terrestrial applications will certainly be realized from this research, including vertical farming, smart agriculture, and climate-resilient crop production.

This paper proposes a conceptual design and research framework for an automated Astro-Agriculture system. The goals are to review the current state of space agriculture technologies, highlight gaps and challenges in existing approaches, propose a system architecture that integrates lighting, nutrient delivery, and monitoring subsystems, and provide a roadmap for experimental validation and implementation into future missions. The goal is not only to enhance the field of space life support, but also, and perhaps more importantly, to contribute to achieving India's long-term vision of sustainable human space exploration.

LITERATURE SURVEY

Spaceflight agricultural systems development has long been considered a major barrier to bioregenerative life support for decades. Long-duration missions not only require used food supplies but also the capability of producing new crops in space. Plants provide not only nutrition, but mental well-being as well, and can close the environmental control loop through the recycling of carbon dioxide and oxygen production. Space agriculture is a key component of sustainable habitation outside Earth.

2.1 Space-Based Plant Growth Experiments - NASA began developing plant growth experiments in space with the Veggie system aboard the ISS. Veggie successfully produced lettuce and other leafy greens in a microgravity environment utilizing red and blue LEDs and wick mats to supply nutrients (Massa et al.). These studies confirmed microbiological safety and nutritional value of lettuce grown aboard ISS, establishing confidence in human consumption during missions (Khodadad et al., 2020). NASA also developed the APH as a more capable growth chamber with multispectral LEDs, sophisticated environmental controls, and over 180 sensors for continuous monitoring of humidity, CO_2, and airflow (Massa et al., 2016). APH has been used for more complex studies, including long-duration growth cycles and multigenerational studies, although APH's size and requirements for energy make it impractical for compact resource-constrained missions. Similar developments include China’s experiments on the Tiangong space station, growing rice and Arabidopsis in orbit. While these studies proved technical feasibility, they reported similar barriers to autonomous yield and reproducibility.

2.2 Analog Greenhouses and Earth-Based Testbeds - Analog missions on Earth have provided relevant information about growing in an extraterrestrial environment. For example, the EDEN-ISS Antarctic greenhouse project was able to reproduce extreme conditions, e.g., isolation, limited supply, and extremely harsh environments like Mars. (Zabel et al., 2022).

EDEN-ISS achieved impressive outputs with hydroponics and LED lighting, which allowed for the demonstration of continuous monitoring of crops, operational remote-control systems, and exploration of fully autonomous crop production systems. However, the significant complexity and large-scale applications make it impractical for a targeted spacecraft or small orbital module. The MLGH effort, conducted by the University of Arizona and NASA, studied inflatable greenhouse designs using hydroponics to test the integration of life support as a focus. Although this study presents an exciting opportunity for improved understanding, the current prototypes involved, and the limited automation or imaging systems mean this work is also at a prototype state. The MELiSSA program, spearheaded by the ESA, takes a more holistic closed-loop, high-level model recycling waste streams via algae, bacteria, and higher plants. MELiSSA is certainly conceptually powerful, and makes no mistake, very much represents an experimental program as full-scale has yet to be deployed.

2.3 Advances in Plant Monitoring and Imaging - The recent advances in plant phenotyping technologies are dramatically changing the way crop health is monitored. Hyperspectral imaging indicates physiological changes, for example, nutrient deficiencies and water stress that can occur long before they are visible to the human eye (Mahlein, 2016), and depth imaging with 3D reconstruction can provide biomass estimation and allow for determining architecture (Banerjee et al., 2020). While some terrestrial controlled environment agriculture has started extending the use of such tools, no major space-based agricultural trial has integrated hyperspectral or 3D depth imaging into its monitoring capabilities. So far, most regimes on the ISS have basic RGB imaging with manual observations, and similar monitoring frameworks with terrestrial imagery also require manual observations. In an analogous manner, while most space plant growth facilities utilize narrowband red/blue LED lighting for plant growth, recent evidence suggests that full-spectrum lighting, including UV and far-red wavelengths, can drastically affect plant morphology, photosynthetic efficiency, and nutritional content (Li et al., 2020). As of now, the use of light from adjustable UV–VIS–NIR lighting systems has been given extraordinarily little attention in the futures of space agriculture systems. But it does address an unexplored area where adjusting these variables could explore new opportunities for optimizing crops.

2.4 Challenges in Microgravity Crop Cultivation - One of the most challenging and persistent problems is the delivery of water and nutrients to plant roots in microgravity. Conventional soil and hydroponics rely on gravity to drive water flow, and this all breaks down in orbit. Experience utilizing porous substrates, capillary wicks, and forced-flow hydroponics has achieved some success, but ways to deliver consistent and continually available hydration and manage the formation of air bubbles remain open engineering problems (Jones & Or, 1999). This is in addition to balancing the atmospheric environment with pilot missions where CO_2 enrichment is needed for photosynthesis, along with O_2 consumption from astronauts, which requires tightly controlled and extremely energy-efficient methods.

2.5 Research Gap and Novelty - When studied together, all these studies demonstrate that plants can indeed grow in space, but current systems suffer from several limitations:

1. Restricted spectral lighting and uncertainty about wavelength impacts.
2. Little use of advanced imaging for early detection of plant stress and biomass estimates.
3. Limited autonomy and use of crew time.
4. Most systems are designed for NASA/ESA initiatives, with little consideration for scalability for future Indian space missions.

The proposed Astro-Agriculture system aims to close these gaps by offering a system that combines UV–VIS–NIR adjustable illumination, gravity-agnostic nutrient delivery, and hyperspectral plus depth imaging, all integrated into a compact, autonomous system designed for future ISRO missions. This offers not only a significant scientific advancement, with are understanding of plant responses to microgravity, but the opportunity for India to develop its own, indigenously developed, scalable mission to undertake appropriate aspects of space farming.

Conceptual Framework

To establish a conceptual framework for the proposed Astro-Agriculture system, we consolidated experiences from previous research on space plant production and controlled environment agriculture while considering the remaining barriers to successful designs. The Astro-Agriculture system is intended to be a compact, modular growth chamber that includes the major subsystems of light, nutrient delivery, imaging and monitoring data, and system control. Each subsystem has been designed to achieve results in microgravity and spacecraft environments to decrease astronaut workload and maximize crop reliability, growth yield, and bioregenerative life support contribution by growing food crops in space.

3.1 System Overview - For a general scheme, we imagine creating a fully contained growth chamber that can grow small- to medium-sized crops in controlled conditions. The growth chamber will host environmental sensors, imaging modules to assess plant growth and environmental conditions, and a control unit to maintain plant growth parameters without requiring continuous human assistance. Most existing growth systems or technologies are designed to measure or optimize environmental parameters for a limited scope of growth, for example, in isolation from other important parameters. The Astro-Agriculture system will take a more holistic approach to growing crops in space by co-locating advanced light management systems, gravity-independent nutrient delivery systems, and remote non-destructive imaging and monitoring capabilities.

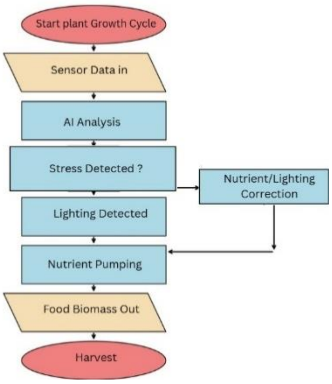

Figure 1: Workflow of the automated Astro-Agriculture system showing sensor-driven monitoring, AI-based analysis, stress detection, corrective control, and final biomass harvest.

3.2 Lighting Module - Light is the most energy-intensive and the most physiologically important input for space agriculture. Most of the existing light-providing facilities use narrow-band red and blue LEDs. These LEDs are energy efficient, but they will never reproduce the complexity of sunlight on Earth. Instead, the proposed system provides irradiance via a tunable broad-spectrum LED system that spans the UV–VIS–NIR (300–800 nm) wavelengths. The broad spectral range of the proposed system allows researchers to customize the spectral profile that delivers irradiance to fulfill developmental and physiological needs. For example, the proposed system can deliver greener and/or far-red wavelengths, which may improve canopy penetration and photosynthetic efficiency. The proposed system can deliver ultraviolet light, which could stimulate the generation of protective compounds and secondary metabolites that may have effects on nutritional quality. The added benefit of programmable lighting to simulate diurnal cycles influences circadian rhythms for plants, which is essential for the regulation of growth and metabolism.

3.3 Nutrient Delivery Module - Providing sufficient water and nutrients to plants in microgravity is not a new problem in space life sciences. Traditional hydroponic methods rely strongly on gravity for inflating water/hydrogen and evenly distributing fluids to the root zone, neither of which is present in orbit. Nutrients are provided from a pressurized reservoir that is designed to inhibit bubble formation, which is a typical failure mechanism of ISS-based experiments. Passive wicking components supply moisture, dissolved nutrients, a uniform distribution over a wide area, and an optionally provided misting system can add supplemental oxygenation to the plant roots interface. The use of a combination of gravity-driven momentum and control pressure provides an integrated solution to curtail the incidences of root desiccation or waterlogging, the two primary hazards of microgravity cultivation.

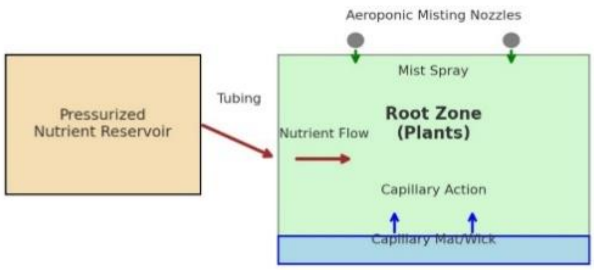

Figure 2: Conceptual design of the nutrient delivery system, combining capillary mat wicking for hydration in microgravity.

3.4 Monitoring and Imaging Module - A key benefit of the system will be the incorporation of many enhanced imaging and monitoring capabilities to replace the manual RGB cameras and crew observations. A hyperspectral imaging unit can provide reflectance values in hundreds of very narrow bandwidths, allowing for the incorporation of spectral reflectance analysis to enable early stress, nutrient deficiency detection, or water status in plants without overt visual symptoms. Depth-sensing cameras can provide quantitative three-dimensional reconstruction of a plant canopy to help with accurate biomass estimation and tracking of growth. Real-time measurements of environmental nutrients were also captured regarding temporal developmental goals. This approach improves resilience, allows for timely intervention by limiting astronaut labour in day-to-day crop monitoring.

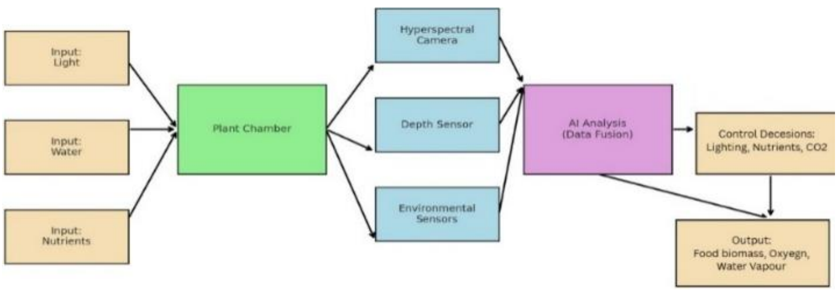

Figure 3 - Monitoring and imaging pipeline integrating hyperspectral and depth sensing for AI-driven control decisions in plant growth.

3.5 Control and Automation Module - At the heart of the system is an autonomous control unit that receives sensor feedback and can control aspects of the environment. For example, it can change the color, intensity, and photoperiod of light, depending on crop needs and growth stage. Alternatively, it can selectively dispense abstract solution nutrient quantities, as well as the amount of water to deliver, based on direct root-zone effect data from sensors, as well as imaging input. The parameters of the environment, such as humidity and temperature, are individually assessed to support the needs of the plants and volume of work to be completed by the crew in a schedule that connects the growth chamber to the spacecraft's life-support loop. The user interface to the control unit also provides visual feedback, with a summary in the form of data and alerts on a tablet or control screen. Most of the operations stay fully automated, with applied control adjustments reflecting real-time conditions and previously engaged environmental modifications that require no human feedback. Plus, there is the added capability of using AI-informed predictive models to allow for predictive change in decisions when unexpected conditions arise in the greenhouse, such as equipment malfunction or a sudden threat from plant disease that requires human intervention.

3.6 Candidate Crops and Selection Criteria - In addition to the primary design of the system, the system design also had to consider the selection of suitable crops for space farming. The ideal conditions for crops can be variable and may have effects on their success as edible crops. In the design of the cultivation system, consideration of crops was about rapid growth life cycle, compact morphology, and other factors for the desired nutritional value. The primary example of a crop candidate deserving consideration for space farming is leafy greens, which, for space farming, will be outfitted foods on the ship from harvest to consumption. Lettuce and spinach offer truly short growth durations of 30-40 days and nutritional success in multiple growth experiments on previous ISS missions. Root vegetables were considered, such as radishes, to also complement leafy greens in dietary variety, with radishes also completing their growth within the same general duration of 30-40 days. Root crops such as radishes add diet diversity and can be completely grown in a similar timeframe. Longer cycle crops, such as dwarf wheat and micro-tomatoes, can result in staple nutrition and mental relaxation benefits for astronauts but require greater energy use and space. A summary comparison of these candidate crops is outlined in Table 1, which includes the length of time to harvest, nutritional input, and suitability for space use.

Table 1: Candidate crops for space agriculture, summarizing their growth duration, nutritional contributions, and overall suitability for controlled environments.

Crop	Nutritional Value	Suitability for Space
Lettuce	Rich in vitamins A and K	Already tested in ISS Veggie, fast growth cycle
Radish	High in vitamin C, antioxidants	Compact root crop, proven in prior tests
Wheat	Carbohydrates: a staple calorie source	Longer cycle, requires more space and resources
Soybean	Protein, oil, essential amino acids	Useful for protein intake; moderate growth needs
Potato	Carbohydrates, potassium	Bulky tubers, challenging in microgravity soils
Tomato (cherry)	Vitamins C, lycopene	Fruit crops with higher light and water demands

3.7 Closed-Loop Life Support - The Astro-Agriculture system provides more than just food production when used as a BLSS. Plants will remove carbon dioxide from the air contributed by the astronauts' respiration and produce oxygen to maintain the cabin atmosphere through photosynthesis. Nutrient inputs can be provided from some of the processed wastewater, and water vapor released from plant transpiration can be reused for water reclamation purposes. This means that not only can the impact of current astronauts' diet be improved, but the BLSS also adopts the most circular and effective use of resources in a spacecraft environment. If further human exploration spaceflight should occur outside low Earth orbit, units can be designed in a modular way to combine several units for a larger volume of food production to support a larger size project, such as a lunar base or Martian habitation.

3.8 Experimental Roadmap - Though conceptual, the proposed system includes a phased experimental roadmap to perform verification. Initial ground-based testing could be conducted with random positioning machines or clinostats to test fluid delivery systems that achieve microgravity. Terrestrial analogs such as Antarctic stations or parabolic flight experiments would allow for validating performance, in microgravity, on extreme reaches of the Earth, or for truly short periods. A small-scale prototype could then be deployed in the International Space Station or a CubeLab platform as an in-orbit test. Ultimately, scaled deployment is envisioned for future Indian crewed missions, with the system functioning to both provide a food source and as a bioregenerative life support module.

4. RESULTS AND DISCUSSION

We have designed the Astro-Agriculture growth system to be a modular, stand-alone unit for incorporating plant growth into future Indian missions. Although the system has not yet been experimentally implemented, potential outcomes can be derived from existing literature on plant growth operations on the International Space Station, the EDEN-ISS Antarctic greenhouse, and controlled-environment agriculture research on the ground.

4.1 Expected Outcomes of the System - Lighting performance. The proposed UV–VIS–NIR tunable light (300–800 nm) provides a wider spectral range than the narrow red–blue spectra provided by the lights used in typical space plant growth experiments. While plants have evolved in an environment dominated by solar energy, literature indicates that green and far-red light is useful for improving both canopy penetration and overall plant carbon gain through photosynthesis. Supplementing with UV-A also promotes antioxidant and flavonoid content (Dumont et al. 2019, Wang et al. 2022). Hence, we expect the Astro-Agriculture growth system to achieve greater biomass and potentially better nutritional density than that observed in ISS experiments.

Nutrient and water management.- Traditional hydroponic and substrate-based systems struggle under microgravity because of altered fluid dynamics, generating uneven hydration and, at times, hypoxia. Our designed system includes a capillary wick and acquires an aeroponic mist in conjunction with capillary action; these complementary strategies provide redundancy and oxygenation in the root zone. Having both approaches provides the potential to avoid crop failures because of drought or waterlogging.

Monitoring and control. - The combination of hyperspectral imaging, depth sensing, and environmental monitoring is a major advancement towards non-intrusive, autonomous plant diagnostics. Past research with ground-based systems found that hyperspectral signatures can identify nutrient deficiencies and drought stress through spectral readings prior to visual symptoms by several days. When paired with an AI-based analytical system, the plant monitoring system can even initiate an appropriate remedial action without the need for astronaut intervention.

Closed-Loop Integration.- The implicit plan for this system within a BLSS is that the integration of these systems will lead to measurable resource reuse:

- CO_2 is removed from the astronauts' environment and assimilated by plants.

- O_2 is generated to support crew members' respiration.
- Food biomass exceeding contained rations.
- Condensed and recovered H2O vapor used as potable water.

4.2 Comparison with Current Systems - Relative to the plant growth systems that are actively implemented or explored for space and analogue environments, the new Astro-Agriculture framework has several clear benefits. NASA's Veggie module put heavy reliance on crew labour and offered narrow red–blue lighting, which significantly limited crop diversity and yield. While the Advanced Plant Habitat provided improvements in environmental condition control, APH only provided limited levels of spectral monitoring and tuning, required significant maintenance, and did not support a fully evolved "smart" plant growing system. The EDEN-ISS Antarctic greenhouse proved autonomous and productive when in a terrestrial analogue, and had "smart" capabilities, but it qualified as a hydroponic system that relies on gravitational pull to circulate its nutrients, and could not, however, be used as it was constructed in a microgravity environment. As such, the new Astro-Agriculture framework better integrates the following:

1. Full spectral flexibility within the UV–VIS–NIR range enables maximization of photosynthesis and crop quality.
2. Nutrient delivery that works in microgravity, using an innovative co-combine’s use of capillary wicking and aeroponic misters
3. Advanced monitoring and decision support, based on both hyperspectral and depth imaging capabilities, that provides AI-driven analytics to support predictive crop management with limited to no crew oversight.

Table 2: Comparative analysis of existing space plant growth systems and the proposed Astro-Agriculture framework.

System	Nutrient Delivery	Monitoring	Limitations
Veggie (ISS)	Capillary wicks	Minimal imaging	Limited crop diversity; manual harvesting
APH (ISS)	Porous substrate, water injection	Real sensors, some imaging	Complex maintenance; limited spectrum tuning
EDEN-ISS	Hydroponics	Full sensor suite, remote control	Gravity-dependent nutrient systems; space-tested
Proposed System	Capillary wick	Hyperspectral + depth + AI data fusion	High-power demand; still at the conceptual stage

A summary of these comparisons is in Table 2, indicating general advantages and disadvantages with respect to lighting, nutrients, monitoring, crew workload, and limitations across systems. By integrating broad-spectrum lighting, robust nutrient strategies with capillary wicking mechanisms, and intelligent monitoring, we propose the Astro-Agriculture framework to be a holistic, resilient framework and promising system for microgravity farming.

4.3 Considerations for Long-Duration Flights - There are many benefits to this system for long-duration missions, such as follow-up missions and future missions, that have restricted options for re-supply of cargo. These benefits include:

1. Less dependence on stored oxygen and dehydrated foods.
2. Greater astronaut health from fresh vegetables and psychological comfort.
3. Closure of the life support system through greywater recycling and plant-based oxygen regeneration.

These benefits support ISRO's overall goal of developing indigenously produced BLSS technologies.

4.4 Challenges and Limitations - While these benefits are projected, there are a range of limitations to consider:

1. Energy demand: full-spectrum LEDs may require higher power loads than the red-blue systems, requiring light with established optimal spectra to mitigate expenses related to energy costs based on crop productivity.
2. Increased hardware complexity: adding two nutrient delivery systems, and imaging through RGB to multi-spectral increases overall mass, and the complexity to maintain a system that will be flown requires reduced requirements for space.
3. Dataset limitations associated with artificial intelligence: the general models and datasets used with hyperspectral stress-detection models for plants are primarily based on terrestrial environments and need antiquating tightly planned approaches to dataset generation and modelling, to help adapt to the physiological parameters of plants grown in microgravity.
4. Trade-offs are associated with crop choice: leafy greens have a rapid cycle time to biomass, but caloric biomass, such as wheat, potatoes, or legumes, needs to be incorporated to provide long-duration flight missions with food options to optimize the nutrition involved in long-duration exposure of humans to microgravity.

4.5 Future Research Directions - Moving forward, pivotal next steps are to validate nutrient dynamics in simulated microgravity solutions, i.e., clinostats, automated random positioning machines, establish aeroponic redundancies with parabolic flight experimentation, and deploy prototypes into analog environments, e.g., Antarctica and desert/sand stations. Combining the integration of space crop production technology with waste processing systems could allow closure of the water-nutrient cycle completely. Further, ISRO could work in collaboration with agricultural research institutes to develop datasets for building AI specific to space crops. The Astro-Agriculture system proposed in this research proposes a versatile space crop production system as it incorporates each of the three significant breakthroughs: spectral flexibility, consistent flow to roots, and an artificial intelligence monitoring system. Anticipated output suggests yields, nutritional quality, and autonomy would be improved from current production systems, and therefore, it seems a suitable candidate for future modules for the ISRO life support system. However, there are still technical and operational challenges to address, but this framework has proposed significant steps to provide a sustainable human existence in orbit and on planetary surfaces.

5. CONCLUSION

Sustaining human presence beyond Earth requires life support systems that are not only dependable but also regenerative. Plants provide a unique bioregenerative solution by coupling food production with oxygen regeneration and carbon dioxide recycling. However, current space agriculture platforms remain constrained by limited spectral lighting, inconsistent root hydration under microgravity, and insufficient monitoring capacity. This paper has presented a conceptual framework for an Astro-Agriculture growth system that integrates three novel features, tunable UV–VIS–NIR lighting to optimize photosynthesis and crop quality secondly a dual-mode nutrient delivery system combining capillary wicking and aeroponic misting to ensure robust root hydration; and lastly a comprehensive monitoring pipeline using hyperspectral imaging, depth sensing, and environmental feedback, fused through AI-based control. Together, these elements establish an autonomous, compact, and modular chamber capable of minimizing crew workload while enhancing resilience. The anticipated outcomes of this system, higher biomass yields, improved nutritional value, early stress detection, and reliable integration into closed-loop life support architectures, positioning it as a significant step toward sustainable space habitation. While engineering challenges remain, particularly in power efficiency, hardware miniaturization, and AI validation under microgravity, the concept lays a sturdy foundation for India's vision of bioregenerative support systems for future important dream missions.

Beyond spaceflight, the proposed technologies also hold terrestrial potential in controlled-environment agriculture and vertical farming, where resource efficiency and automation are increasingly critical. By bridging space and Earth applications, Astro-Agriculture represents not only a pathway to self-sufficiency in orbit but also a contribution to food security and sustainable agriculture on our own planet.

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