

SELECTION OF HIGHLY ADAPTABLE CROPS FOR CONTROLLED ECOLOGICAL LIFE SUPPORT SYSTEMS UNDER SIMULATED ENVIRONMENTAL CONDITIONSWei TAO^{1,2}, PhD, ORCID: 0009-0001-4843-9018Olha BAKUMENKO¹, Candidate of Agricultural Sciences, Associate Professor, Senior Researcher, Laboratory of Mechanical and Chemical Impact in Agrotechnologies, ORCID: 0000-0003-1625-7401Oksana DATSKO¹, PhD in Agronomy, Senior lecturer, Senior researcher, Senior Researcher, Laboratory of Mechanical and Chemical Impact in Agrotechnologies, ORCID: 0000-0001-9610-3087¹Sumy National Agrarian University, 160 H. Kondratieva St., Sumy, 40021, Ukraine²Shangdong Agriculture and Engineering University, Jinan, Shandong, *People's Republic of China*
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The development of plant cultivation technologies in controlled environments requires the identification of species capable of efficient functioning in closed or semi-closed ecological systems with limited resources. One of the promising directions in this field is the use of Controlled Ecological Life Support Systems (CELSS), where plants perform key functions in maintaining gas balance, participating in water and biogeochemical cycles, and producing fresh food biomass. The aim of this study was to substantiate approaches for selecting plant species with high adaptive potential for cultivation under controlled environmental conditions and to develop an experimental platform for investigating their growth and functional characteristics. Based on an analysis of international research and existing crop selection criteria for bioregenerative systems, a set of principles for selecting promising crops was formulated, considering ecological adaptability, morphological traits, nutritional value, and technological suitability for cultivation in regulated environments. As candidate species, *Mesembryanthemum crystallinum* L., *Anredera cordifolia* (Ten.) Steenis, and *Anoectochilus roxburghii* (Wall.) Lindl. were proposed due to their compact morphology, high nutritional and bioactive compound content, and potential suitability for cultivation in limited space conditions. To evaluate their adaptive potential, an experimental facility, the Micro-Lunar Greenhouse System (MLGS), was designed to simulate key parameters of a controlled environment, including temperature, humidity, atmospheric gas composition, light conditions, and nutrient solution characteristics. A standardized cultivation experiment scheme and a system for evaluating morphological, physiological, biochemical, and resource efficiency indicators were proposed. The obtained results provide a methodological basis for further studies on plant adaptation in controlled ecological systems and may contribute to the development of cultivation technologies for closed growing environments.

Keywords: Controlled Ecological Life Support Systems, CELSS, controlled environment agriculture, crop selection, plant adaptation, closed ecological systems, Micro-Lunar Greenhouse System, simulated environment

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Introduction

Deep space exploration missions, including the construction of lunar bases and future Mars expeditions, increasingly focus on long-term human presence beyond Earth. Under such conditions, life support technologies capable of sustaining astronauts in extraterrestrial environments become one of the key limiting factors for mission implementation. Controlled Ecological Life Support Systems (CELSS) represent an integrated technological approach that enables the regeneration and recycling of essential life-support resources such as oxygen, water and food within a closed ecological loop. These systems rely on artificial ecosystems integrating plants, microorganisms, animals and humans to maintain material circulation and ecological balance. Due to their low resource consumption, high sustainability and high degree of closure, CELSS technologies are considered fundamental for long-duration extraterrestrial habitation missions (Wheeler R.M., 2017; Bakumenko O. et al., 2026).

Within CELSS, crop cultivation plays a central biological role. Plants not only provide fresh food and diversified nutritional sources for astronauts, but also perform critical ecological functions such as carbon dioxide fixation, oxygen release, water purification and

waste recycling. Therefore, the selection of crop species and the optimization of cultivation technologies directly influence the efficiency of material circulation, the nutritional stability of astronaut diets and the long-term operational reliability of CELSS systems.

Over the past several decades, major spacefaring nations including China, the United States, European countries and Japan have conducted extensive research on CELSS-based crop cultivation. Various experimental platforms and technical models have been developed to investigate the feasibility of growing crops such as wheat, lettuce and tomato under simulated or real space conditions. These studies have demonstrated the possibility of partial regeneration of oxygen, water and food in closed ecological systems (Dong C. et al., 2015; Abe K., et al., 2005; Nitta K., et al., 2001). Nevertheless, the currently tested crops still exhibit several limitations. Many species lack a balanced nutritional profile and do not provide important nutrients such as ω -3 polyunsaturated fatty acids, vitamin B12, iron and zinc. In addition, some crops have relatively large plant architectures, making them unsuitable for limited spacecraft or habitat space. Other crops demonstrate insufficient ecological adaptability, including high

water consumption or relatively low photosynthetic efficiency, which restricts the improvement of system closure and overall resource efficiency.

Research progress of CELSS crop cultivation in different countries. Different countries have developed distinctive CELSS crop cultivation models according to their space exploration strategies and technological priorities. These models differ in terms of experimental platform design, crop selection principles and system functional orientation. Their research results provide important theoretical and methodological foundations for crop selection, experimental device construction and cultivation experiment design.

China has focused on long-term extraterrestrial habitation scenarios and developed two representative research platforms: the Lunar Palace-1 ground simulation system and plant cultivation experiments conducted aboard the Tiangong Space Station. The Lunar Palace-1 facility has a total volume of approximately 160 m³ and contains two plant cultivation cabins with a total planting area of 69 m², together with a comprehensive cabin and a waste treatment unit. The system combines substrate cultivation with hydroponic technologies and forms a four-component material circulation loop involving plants, animals, microorganisms and humans. During 105-day and 365-day closed ecological experiments, dozens of crop species were cultivated, achieving 100% oxygen regeneration, more than 95% water regeneration and approximately 55–80% food regeneration, while the overall system closure approached 98% (Dong C. et al., 2015). The key advantage of the Chinese model lies in its highly integrated material cycling system, where crop selection prioritizes ecosystem functionality, long-term environmental adaptability and nutritional diversity.

The United States has primarily oriented its CELSS research toward near-Earth orbit missions and shorter lunar exploration scenarios. Its approach emphasizes fresh food production for astronauts through systems designed for immediate harvest and consumption. Several experimental platforms have been developed, including Veggie, the Advanced Plant Habitat (APH) and the CHAPEA simulation environment. The Veggie system employs a “seed pillow” planting method combined with red-blue LED lighting, enabling the first successful harvest of lettuce in space in 2015 and marking a milestone in astronaut consumption of fresh vegetables during orbital missions. The APH facility provides precise control of temperature, humidity and atmospheric composition. In 2022, pepper plants cultivated in this system produced 15–20 fruits per plant during a 110-day growth cycle, representing a significant advancement in space crop diversity (Morrow R.C. et al., 2017). The American model emphasizes compact plant architecture, rapid growth cycles, high nutritional density and good taste acceptance. Dwarf cultivars such as Outredgeous lettuce and Red Robin tomato have demonstrated strong adaptability to space cultivation conditions. Selection criteria developed in these programs, including

microgravity tolerance, nutritional efficiency and system integration capability, provide important methodological references for crop screening in CELSS research (Morrow R.C. et al., 2016).

In Europe, the European Space Agency (ESA) has developed the MELiSSA (Micro-Ecological Life Support System Alternative) program, which represents one of the most advanced bioregenerative life support concepts. MELiSSA is characterized by a five-stage ecological loop integrating microorganisms and plants to mimic natural terrestrial biogeochemical cycles. Through this system, organic waste can be decomposed and transformed into usable nutrients, supporting the life requirements of a four-person crew for up to two years without external supply (Dong C. et al., 2015). Crops such as wheat, potato, lettuce and spirulina have been incorporated into the system due to their compatibility with microbial metabolic cycles and their contribution to efficient resource recycling (Lasseur C., et al., 1996). Furthermore, European research programs have explored the cultivation of medicinal plants under controlled environments to address health challenges associated with long-term space missions. These studies provide important inspiration for selecting crops that combine both nutritional and medicinal value.

Japan has also developed advanced closed ecological systems, particularly the Closed Ecology Experiment Facilities (CEEF) designed for future lunar base and asteroid exploration missions. The CEEF facility simulates closed environmental conditions with volumes ranging from 50 to 100 m³ and supports small crews of two astronauts. By combining physical-chemical technologies with biological processes, the system can maintain CO₂ concentrations at approximately 0.1–0.2% while regulating water and oxygen cycles. Core crops in the Japanese system include rice, wheat and lettuce, selected for their rapid growth and high vitamin content. Experimental results have shown that rice cultivated in the simulation chamber can shorten its growth cycle by 10–15 days while achieving yields of approximately 0.8–1.0 kg·m⁻². In addition, an efficient gas circulation system increases CO₂ absorption efficiency by about 30% compared with conventional cultivation systems, while water recycling rates exceed 93% (Nitta K., et al., 2001). The compact design and precise environmental regulation of the Japanese system provide valuable guidance for developing miniaturized experimental platforms for CELSS crop research.

Limitations of existing CELSS crop experiments. Despite significant progress in CELSS research worldwide, several limitations remain in current crop cultivation systems. Many of the species previously tested cannot fully meet the requirements of long-term extraterrestrial habitation due to limitations related to nutrition, spatial efficiency, cultivation management and ecological cycle integration.

First, the nutritional structure of currently tested crops is often incomplete. Many cultivated species lack important micronutrients such as vitamin B12, vitamin

D, iron and zinc. In addition, essential fatty acids such as ω -3 polyunsaturated fatty acids are insufficiently represented in many crops, which may negatively affect cardiovascular health and intestinal stability. Staple crops such as wheat and rice also contain relatively low levels of lysine and threonine, limiting their protein nutritional value (Morrow R.C., et al., 2017).

Second, space utilization efficiency remains a major challenge. Crops such as wheat and maize may reach heights of 1–1.5 m, occupying considerable vertical space that could otherwise be used for multilayer cultivation systems. Some species also exhibit low leaf area index and limited light-use efficiency, resulting in suboptimal productivity per unit cultivation volume and inefficient resource utilization (Morrow R.C. et al., 2016; Morrow R.C., et al., 2017).

Third, cultivation and management complexity may increase operational demands on astronauts. Certain tuber crops such as potato require specialized substrates and harvesting procedures, which increase labor requirements in space environments. Some food crops also have relatively long growth cycles exceeding 100 days, which limits the ability to maintain continuous food supply and rapid crop turnover in closed systems (Dong C. et al., 2015).

Furthermore, insufficient ecological adaptability remains a challenge for many crops. Variations in water use efficiency can impose additional pressure on water recycling systems, while crops with low photosynthetic capacity contribute less effectively to CO₂ fixation and oxygen regeneration, reducing the overall efficiency of the CELSS material cycle.

Crop selection criteria and candidate species.

Given these limitations, the selection of new crop species that combine high nutritional value with strong environmental adaptability is essential for improving the performance of CELSS crop cultivation systems. In addition, the development of standardized experimental platforms and cultivation protocols is necessary to ensure the reliability and reproducibility of future experiments.

The present study represents a preliminary stage within a broader research program focused on supplementary crops for CELSS systems. The research integrates three key components: scientific crop selection, the design and construction of a specialized experimental device, and the development of a standardized cultivation experiment framework. By combining these elements, the study aims to provide methodological and technological support for future CELSS crop cultivation experiments and to establish a reliable basis for collecting accurate experimental data.

Based on more than forty years of international CELSS research and considering the 35 fundamental crop selection criteria proposed by NASA (Salisbury F.B., Clark M.A., 1996; Hoff J.E., Howe J.M., 1981; Zabel P., 2021), four key principles were formulated for selecting candidate crops suitable for CELSS environments.

The environmental and system function adaptation principle emphasizes the ability of crops to tolerate specific CELSS environmental conditions such as microgravity, elevated CO₂ concentrations (0.1–0.2%) and high humidity in closed systems. Crops should demonstrate high photosynthetic efficiency and strong CO₂ fixation capacity, while non-edible biomass should be easily recyclable through microbial decomposition or other ecological processes (Hoff J.E., Howe J.M., 1981).

The growth characteristic adaptation principle focuses on plant morphology and growth dynamics. Ideal CELSS crops should possess compact or dwarf plant architecture suitable for multilayer vertical cultivation systems, thereby improving spatial efficiency. In addition, crops should have growth cycles compatible with staged semi-continuous production systems, with leafy vegetables completing their cycle within approximately 40 days and medicinal-nutritional crops capable of long-term harvesting (Zabel P., 2021).

The nutritional supply adaptation principle requires crops to provide high nutritional density and compensate for deficiencies in existing CELSS crop systems. In particular, candidate crops should supply essential micronutrients, bioactive compounds and beneficial metabolites while also contributing to dietary diversity and astronaut health maintenance (Rose C.W., 1989).

Finally, the cultivation and management simplicity principle highlights the importance of crops that are compatible with hydroponic or substrate-based cultivation systems and can be managed through automated technologies. High microbial safety, stable genetic traits and the ability to support multiple generations of cultivation are also essential to ensure long-term system stability (Salisbury F.B., Clark M.A., 1996; Dong C. et al., 2015).

Based on these criteria and considering experimental feasibility, growth characteristics and nutritional potential, three candidate species were selected for further investigation: *Mesembryanthemum crystallinum* L., *Anredera cordifolia* (Ten.) Steenis and *Anoectochilus roxburghii* (Wall.) Lindl. These crops demonstrate promising environmental adaptability within CELSS conditions and possess complementary nutritional and functional properties. Their morphological characteristics, growth cycles, nutritional advantages and potential roles in CELSS crop systems are summarized in Table 1.

As shown in Table 1, the selected species differ in growth habit, cultivation cycle and functional value, which determines their complementary role in CELSS crop systems. *Mesembryanthemum crystallinum* L. exhibits a creeping dwarf growth habit (15–25 cm), which significantly improves vertical space utilization compared with traditional crops such as wheat and maize. Its tolerance to elevated CO₂ concentrations and saline environments may reduce the energy requirements associated with environmental regulation in CELSS systems.

Table 1. Characteristics and CELSS Adaptation Points of Three Test Crops

Crop	Plant Type Characteristics	Growth Cycle	Nutritional Advantages	CELSS Adaptation Key Points	Cultivation Features
 <i>Mesembryanthemum crystallinum</i> L. (Lee J.W. et al., 2016; Cha M.K., et al., 2014; Xia J., et al., 2021)	Dwarf and compact plant type, 15~25 cm, creeping growth	30~40 days	Rich in minerals such as sodium, potassium and calcium, high vitamin C content	Tolerant to 400 mM NaCl and high CO ₂ , transpiration can regulate cabin humidity, stable photosynthetic efficiency	All three crops can be cultivated by hydroponics, which is compatible with CELSS cultivation methods; cultivation method is simple.
 <i>Anredera cordifolia</i> (Ten.) Steenis (Bari I.N., et al., 2019; Silalahi M., 2024)	Dwarf and compact plant type, twining vine, plant height 20~30 cm and crown width 30~40 cm after artificial pruning	Propagated by bulbils/stem cuttings, harvestable in 30~40 days, one planting for multiple continuous harvests	Dry weight protein content 20~25% (higher than lettuce and spinach), high easily absorbable calcium, containing mucopolysaccharides and carotene	Tolerant to low light and high temperature, adapted to high CO ₂ closed environment; stable photosynthetic oxygen production, strong disease resistance, easy plant type regulation	
 <i>Anoectochilus roxburghii</i> (Wall.) Lindl (Chen M.X., et al., 2021; Dong Q., et al., 2022; Li H., et al., 2025)	Dwarf and compact plant type, plant height 10~15 cm, crown width 8~12 cm	6~8 months, one planting for continuous harvest for 2~3 years	Rich in bioactive components such as polysaccharides, flavonoids and alkaloids, medicine-food homologous	Shade-tolerant (50~150 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), tolerant to high humidity and high CO ₂ , aerial roots suitable for soilless cultivation, can alleviate the health problems of astronauts in closed environment	

Anredera cordifolia (Ten.) Steenis possesses a relatively high protein content of 20–25% in dry biomass, exceeding that of many commonly cultivated leafy vegetables such as lettuce or spinach. In addition, its capacity for repeated harvest from a single planting cycle supports continuous food supply. *Anoectochilus roxburghii* (Wall.) Lindl, a medicinal-nutritional plant rich in polysaccharides, flavonoids and other bioactive compounds, may help mitigate physiological stress associated with long-term closed environments experienced by astronauts.

Together, these three crops combine compact plant architecture with nutritional and functional diversity. When integrated with staple crops such as wheat and tomato, they may contribute to a CELSS crop cultivation system characterized by “basic nutrition + functional supplementation”, improving both the

Materials and Methods

The research was conducted as a phased 6–10 month ground simulation experiment aimed at assessing

efficiency and resilience of extraterrestrial agricultural systems.

Despite extensive studies on crop cultivation in CELSS systems, most research has focused on staple food crops such as wheat, lettuce and tomato. However, the selection of supplementary crops capable of improving nutritional diversity, ecological stability and functional value of the system remains insufficiently explored. In particular, the integration of crops providing functional bioactive compounds and high nutritional density has received limited attention in CELSS crop design. The aim of this study was to develop a methodological framework for the selection and experimental evaluation of supplementary crops suitable for Controlled Ecological Life Support Systems and to design a ground-based experimental platform for testing crop adaptability under simulated CELSS environmental conditions.

the adaptability of selected crops to a simulated Controlled Ecological Life Support System (CELSS). The experimental design was based on the principles of

single-factor comparison, parallel replication and quantitative evaluation. The study included three main stages: pretreatment of plant material, cultivation under controlled environmental conditions, and determination of growth, physiological and ecological indicators.

The objects of the study were *Mesembryanthemum crystallinum* L., dwarf strain of *Anredera cordifolia* (Ten.) Steenis, and *Anoectochilus roxburghii* (Wall.) Lindl. These species were selected as candidate crops for CELSS cultivation on the basis of their compact growth habit, nutritional value, ecological adaptability and compatibility with controlled-environment cultivation systems. For all crops, seeds or planting material with uniform size, full development and no visible symptoms of diseases or pest damage were selected to minimize experimental error.

The pretreatment of plant material was carried out according to the biological characteristics of each species. Seeds of *Mesembryanthemum crystallinum* L. were soaked in 75% ethanol for 15 s, disinfected in 0.1% potassium permanganate solution for 10 min, rinsed with sterile water 3–5 times, soaked in clean water for 2 h at room temperature, germinated in a moist chamber at 20°C, and transferred to hydroponic seedling cultivation after radicle emergence. For *Anredera cordifolia* (Ten.) Steenis, full bulbils or vigorous stem cuttings with two nodes were selected, air-dried at the incision site, disinfected in 0.1% carbendazim solution for 10 min, treated with rooting agent at the basal part, and fixed directly in hydroponic planting sponge. *Anoectochilus roxburghii* (Wall.) Lindl was subjected to aseptic pretreatment by immersion in 75% ethanol for 30 s, followed by disinfection in 2% sodium hypochlorite solution for 10 min, rinsing with sterile water 5–6 times, germination on sterile medium, seedling acclimatization for 15 days, and subsequent transfer to the hydroponic system.

A single-factor comparative experiment was established in which the cultivation environment was the only variable. The experimental group was cultivated under simulated CELSS conditions in a self-constructed Micro-Lunar Greenhouse System (MLGS), whereas the control group was cultivated under conventional laboratory conditions. All other parameters, including planting density, nutrient solution composition, cultivation method and management schedule, were maintained at comparable levels in both treatments. Each treatment included three biological replications, with 20 uniformly developed plants in each replication.

To simulate the core environmental parameters of CELSS, a Micro-Lunar Greenhouse System (MLGS) was designed and constructed. The device was developed as a compact, modular and relatively low-cost platform for precise environmental regulation, real-time monitoring and automated data collection (Abinaya M. et al., 2015; Morrow R.C. et al., 2016; Tang Y. et al., 2018; Miyajima H., 2020). The system consisted of a closed cultivation chamber with an internal volume of about 1.52 m³, built on a stainless-steel frame. The

chamber walls were made of double-layer acrylic panels with insulating materials to ensure both light transmission and thermal stability. Sampling ports, operation doors and observation windows were integrated into the structure for routine experimental procedures. The environmental regulation range and control accuracy of the MLGS device are presented in Table 2.

Compared with large-scale CELSS simulation facilities, the proposed MLGS system was designed specifically for single-factor crop cultivation experiments. In contrast to platforms limited mainly to light regulation, the MLGS allowed integrated control of atmospheric, light and nutrient conditions, including temperature, relative humidity, CO₂ and O₂ concentration, air flow, light intensity and spectral composition, nutrient solution properties and circulation of simulated waste liquid. The parameter settings were selected in accordance with the environmental requirements reported for CELSS crop cultivation (Hoff J.E., Howe J.M., 1981; Morrow R.C. et al., 2016; Fu Y., 2016). The device included four main modules: an environmental generation module, a perception and monitoring module, an intelligent control and data management module, and a crop cultivation module.

As presented in Table 2, the MLGS provides controlled regulation of atmospheric, light, substrate and circulating substance parameters required for simulated CELSS experiments. In the experimental treatment, the MLGS device was used for automatic and precise regulation of temperature, humidity, gas composition, light conditions, irrigation and nutrient supply. Since the selected crops differed substantially in their ecological and physiological requirements, differentiated cultivation regimes were established for each species. For *Mesembryanthemum crystallinum* L., the cultivation regime emphasized moderate temperature, relatively low humidity, elevated CO₂ concentration, hydroponic cultivation and modified Hoagland nutrient solution. For *Anredera cordifolia* (Ten.) Steenis, the cultivation conditions included higher temperature and humidity, moderate ventilation, long photoperiod and a high-nitrogen nutrient solution. For *Anoectochilus roxburghii* (Wall.) Lindl, the cultivation regime was adapted to shade-tolerant and humidity-demanding growth, with low light intensity, short photoperiod and diluted modified MS nutrient medium. The optimized cultivation parameters for the tested crops under MLGS conditions are summarized in Table 3.

According to the cultivation regimes summarized in Table 3, each crop required a differentiated combination of temperature, humidity, CO₂ concentration, light intensity and nutrient solution parameters. The control treatment was carried out in a conventional laboratory cultivation system using the same hydroponic method, planting density, cultivation tanks and general nutrient solution approach as in the experimental group. Environmental control in the control group was performed manually.

Table 2. Environmental Parameter Regulation Range and Accuracy of MLGS Device

Parameter Category	Indicator	Adjustable Range	Regulation Accuracy
Atmospheric environment (Dougher T.A. et al., 1997; Abinaya M. et al., 2015)	Temperature/°C	5~40	±1
	Relative humidity/%	35~90	±2
	CO ₂ concentration/μmol·mol ⁻¹	25~5000	±0.2
	O ₂ concentration/%	5~25	±5
	Air flow speed/(m/s)	0.1~1.0	±0.1
Light environment (Gómez C. et al., 2013; Berkovich Y.A., et al., 2019)	Light intensity/(μmol/(m ² ·s))	0~3000	-
	Photoperiod/h	0~24	-
	Spectral wavelength/nm	400~750	-
Cultivation substrate (Morrow R.C. et al., 2016; Tang Y. et al., 2008)	Root zone temperature/°C	5~40	±1
	pH	4.8~8.0	±0.2
	Electrical conductivity/(dS/m)	0.5~5.0	±0.5
	Dissolved oxygen concentration/(μmol/mol)	5~20	±2%
Circulating substances (Morrow R.C. et al., 2016; Fu Y. et al., 2016)	Simulated astronaut organic waste liquid	Waste liquid formula: urea 1.5 g/L, creatinine 0.15 g/L, uric acid 0.05 g/L, sodium chloride 5 g/L, potassium chloride 1 g/L, potassium dihydrogen phosphate 0.5 g/L, pH 7.0~7.5. Start adding 1 time a week according to 10% of the nutrient solution volume on the 15th day after crop planting	Same as the adjustable range

Table 3. Cultivation parameters of selected crops under MLGS conditions

Parameter category	Indicator	<i>Mesembryanthemum crystallinum</i> L.	<i>Anredera cordifolia</i> (Ten.) Steenis	<i>Anoectochilus roxburghii</i> (Wall.) Lindl
Atmospheric environment	Temperature (day/night), °C	20–25 / 15–18	25–30 / 20–22	23–25 / 18–20
	Relative humidity, %	40–60	60–80	70–85
	CO ₂ concentration, μmol mol ⁻¹	800–1200	1000–1500	600–800
	Air flow speed, m s ⁻¹	0.3–0.5	0.2–0.3	0.1–0.2
Light environment	Light quality	Red:Blue (3:1) + white	White + 10–15% red	Red:Blue (7:3) + weak white
	Light intensity, μmol m ⁻² s ⁻¹	150–180	200–300	50–150
	Photoperiod, h day ⁻¹	12–14	14–16	10–12
Cultivation management	Cultivation method	Hydroponics	Hydroponics	Hydroponics
	Nutrient solution pH	6.0–7.0	6.0–6.5	5.5–6.0
	Electrical conductivity (EC), μS cm ⁻¹	800–1500	1000–1400	500–800
	Planting density, plants m ⁻²	25	25	50
	Irrigation regime	10 min every 2 h circulation	15 min every 3 h circulation	3–4 spray cycles per day (5–10 min)
	Nutrient solution formula	Modified Hoagland solution	High nitrogen formula (N:P:K = 3:1:2)	Modified MS medium (¼–½ strength)

The nutrient solution EC, pH and dissolved oxygen concentration were measured once a week and adjusted as necessary; the solution was replaced weekly. The environmental parameters corresponded to standard indoor cultivation conditions (Abinaya M. et al., 2015; Gómez C. et al., 2013; Berkovich Y.A.,

et al., 2019). Light was provided by a fixed red-blue LED source (660/450 nm) at an intensity of 200 μmol m⁻² s⁻¹ with a 12 h photoperiod and light uniformity of at least 80%. The atmospheric conditions were maintained at 25 ± 2°C, 70 ± 5% relative humidity, and ambient CO₂ concentration of about 400 ppm. General

management practices in both treatments included weekly cleaning of cultivation systems, removal of senescent plant organs, regular sanitation of the cultivation environment and continuous recording of plant growth, cultivation operations and environmental deviations.

The assessment of crop performance included three groups of indicators: growth phenotype, physiological and biochemical characteristics, and environmental adaptation with material cycle efficiency. Growth phenotype indicators included plant height, crown width or creeping area, functional leaf area, fresh and dry biomass, root-shoot ratio, biomass accumulation rate, growth duration, harvest index, root length, root surface area, root volume, root tip number, and plant uniformity. These indicators were used to characterize the growth and morphological adaptability of the crops under different cultivation conditions.

Physiological and biochemical indicators included SPAD value, net photosynthetic rate (P_n), stomatal conductance (G_s), transpiration rate (Tr), intercellular CO_2 concentration (C_i), antioxidant enzyme activity, malondialdehyde content, vitamin C, soluble sugar, and crop-specific nutritional components. For *Mesembryanthemum crystallinum* L., the contents of sodium, potassium and calcium were determined; for *Anredera cordifolia* (Ten.) Steenis, soluble protein and fatty acid composition were analyzed; and for *Anoectochilus roxburghii* (Wall.) Lindl., polysaccharides, flavonoids and alkaloids were quantified. Microbial safety was evaluated at harvest stage using high-throughput sequencing to assess the microbial diversity on the crop surface and the proportion of beneficial and potentially pathogenic microorganisms.

The environmental adaptation and material cycle assessment focused on the core CELSS functions, namely efficient resource utilization and system closure. The degradation rate of crop residues and simulated waste liquid, nitrogen and phosphorus cycle efficiency, viable microbial count in the nutrient solution, water use efficiency, salt use efficiency, CO_2 fixation efficiency, nutrient solution stability and system safety indicators were determined. Additional analyses included the composition of plant volatiles and root exudates, heavy metal accumulation and the ability of crops to tolerate and utilize simulated human and plant-derived wastes.

Statistical analysis of experimental data was performed using SPSS 26.0. One-way analysis of variance (ANOVA) was used to determine the significance of differences between treatments. Differences were considered significant at $P < 0.05$ and highly significant at $P < 0.01$. In the subsequent stage of the research, the analytic hierarchy process (AHP) combined with the entropy weight method will be used to determine the relative weight of each indicator and to construct an objective evaluation system for screening CELSS supplementary crops

Results and Discussion

The main objective of CELSS crop cultivation research is to ensure the in-situ production of food in extraterrestrial environments while maintaining environmental adaptability, balanced nutritional supply and efficient material circulation. Most existing studies have focused on the cultivation verification of traditional food and vegetable crops. However, the selection and experimental justification of supplementary crops remain critical for overcoming the functional limitations of current CELSS crop systems and improving the overall adaptability and stability of the system (Carillo P., 2020; Miyajima H., 2020).

Based on the analysis of the limitations of existing CELSS crops, the present study summarized standardized crop selection principles and indicators and proposed three candidate supplementary crops: *Mesembryanthemum crystallinum* L., *Anredera cordifolia* (Ten.) Steenis and *Anoectochilus roxburghii* (Wall.) Lindl. These crops were selected considering their compact morphology, high nutritional value, functional bioactive compounds and potential adaptability to controlled ecological environments.

The three species represent different functional roles within a potential CELSS crop system. *Mesembryanthemum crystallinum* is characterized by high salt tolerance, efficient CO_2 assimilation and compact plant architecture, which may improve space utilization efficiency in closed cultivation systems. *Anredera cordifolia* demonstrates relatively high protein content and rapid vegetative growth, contributing to the diversification of protein sources within CELSS crop production systems. *Anoectochilus roxburghii* is a medicinal-nutritional plant rich in bioactive compounds such as polysaccharides and flavonoids, which may contribute to maintaining astronaut physiological health under long-term closed environmental conditions.

The three species represent different functional roles within a potential CELSS crop system. *Mesembryanthemum crystallinum* is characterized by high salt tolerance and efficient CO_2 assimilation, *Anredera cordifolia* provides a high-protein biomass source, while *Anoectochilus roxburghii* contains medicinal bioactive compounds that may support astronaut health. The conceptual integration of supplementary crops within the CELSS framework, including their interaction with atmospheric regulation and nutrient cycling modules, is illustrated in Figure 1.

Figure 1 presents a conceptual model of the integration of supplementary crops into the CELSS system. In contrast to traditional crop configurations focused mainly on staple food production, the proposed structure incorporates functionally differentiated plant groups that contribute to system stability and nutritional diversity. Basic crops such as wheat and tomato provide primary biomass production, while supplementary crops perform specialized roles: *Mesembryanthemum crystallinum* contributes to

mineral and physiological regulation, *Anredera cordifolia* serves as a protein-rich biomass source, and

Anoectochilus roxburghii provides bioactive compounds with potential health-supporting functions.

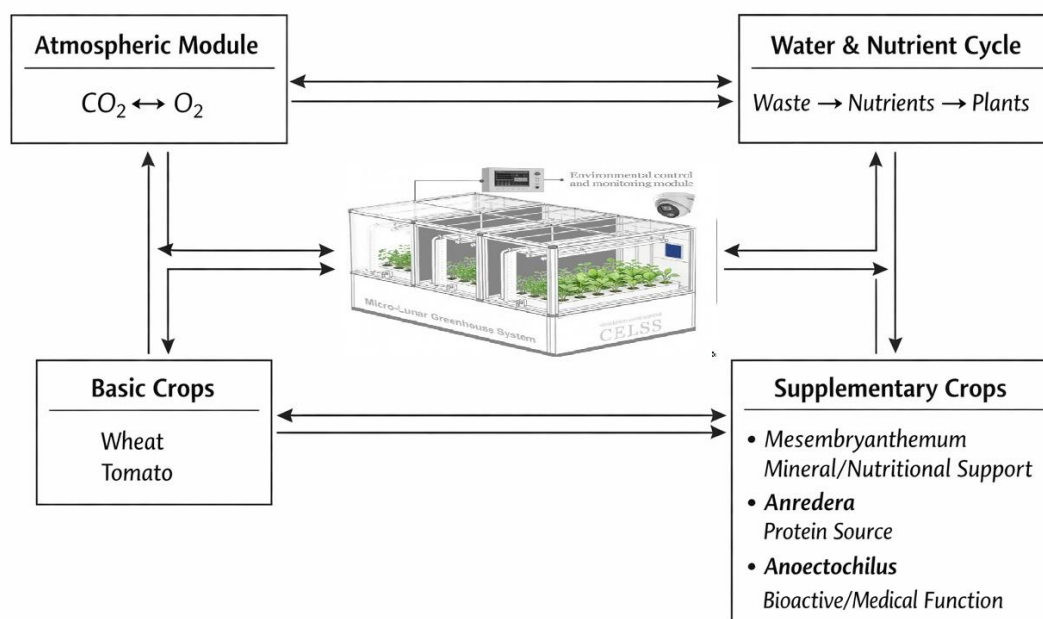


Figure 1. Conceptual integration of supplementary crops within a Controlled Ecological Life Support System (CELSS)

The integration of these crops within atmospheric and nutrient cycling modules enhances overall system efficiency, resilience and functional completeness. This approach represents a shift from conventional CELSS crop systems toward a functionally diversified and resilience-oriented design.

These characteristics indicate that the selected crops can complement traditional CELSS crops such as wheat, lettuce and tomato by providing additional nutritional components, improving ecological system stability and increasing functional diversity within extraterrestrial agricultural systems (Miyajima H., 2020; Gale J. et al., 1989).

Environmental adaptability and cultivation potential of selected crops. The environmental adaptability of the selected crops was evaluated based on their physiological requirements, morphological characteristics and compatibility with controlled-environment cultivation systems. All three crops possess relatively compact growth habits and moderate biomass accumulation rates, making them suitable for multilayer cultivation systems commonly proposed for extraterrestrial agriculture.

In particular, *Mesembryanthemum crystallinum* demonstrates strong tolerance to saline and high CO₂ environments, which may reduce the operational burden of atmospheric and nutrient solution regulation within CELSS. *Anredera cordifolia* shows vigorous vegetative growth and continuous harvest potential, which supports stable food supply in long-duration missions. *Anoectochilus roxburghii*, although requiring relatively specific environmental conditions,

has high medicinal value and could provide additional health benefits in long-term space habitation scenarios.

The cultivation parameters determined in the present study indicate that the selected crops can be successfully integrated into controlled hydroponic systems and managed under regulated environmental conditions provided by the MLGS experimental platform.

Evaluation of the MLGS experimental platform. The Micro-Lunar Greenhouse System (MLGS) developed in this study provides a compact and flexible experimental platform capable of simulating key CELSS environmental parameters. Compared with large-scale CELSS simulation facilities, the MLGS system offers advantages in terms of modular structure, cost efficiency and experimental controllability.

The device enables precise regulation and monitoring of environmental factors such as temperature, humidity, atmospheric composition, light conditions and nutrient solution parameters. This integrated environmental control allows for the simulation of key CELSS conditions, including elevated CO₂ concentrations and closed ecological environments. The modular design also enables independent cultivation zones for different crop species, which facilitates comparative experiments and parameter optimization.

The use of such compact experimental systems is particularly important for the development of standardized ground simulation experiments in controlled-environment agriculture and space crop research.

Scientific significance of the proposed crop selection strategy. The crop selection strategy proposed in this study integrates multiple criteria including environmental adaptability, nutritional value, functional bioactive components and cultivation feasibility. Compared with traditional crop selection approaches focusing mainly on yield and basic nutrition, the proposed approach emphasizes multifunctional crop roles within a closed ecological system.

The three selected crops represent complementary functional groups: nutritional supplementation crops (*Mesembryanthemum crystallinum*), high-protein biomass crops (*Anredera cordifolia*) and medicinal-functional crops (*Anoectochilus roxburghii*). The integration of these species with traditional staple crops could contribute to the development of a more balanced and resilient CELSS crop cultivation system.

Furthermore, the standardized experimental framework developed in this study provides a methodological basis for future research aimed at evaluating the adaptability and productivity of candidate crops under simulated extraterrestrial conditions.

Scientific and practical implications. The results of this study contribute both theoretical and practical insights to CELSS crop research. From a

Conclusions

The present study proposed a systematic framework for the selection and experimental evaluation of supplementary crops for Controlled Ecological Life Support Systems (CELSS). Based on an analysis of the limitations of currently used CELSS crops, a set of standardized selection criteria integrating environmental adaptability, nutritional value, cultivation feasibility and system compatibility was formulated.

Using these criteria, three candidate crops – *Mesembryanthemum crystallinum* L., *Anredera cordifolia* (Ten.) Steenis and *Anoectochilus roxburghii* (Wall.) Lindl – were identified as promising supplementary species for CELSS crop systems. The selected crops represent complementary functional groups within a potential extraterrestrial agricultural system, including nutritional supplementation, high-protein biomass production and medicinal-functional regulation.

A compact ground simulation platform, the Micro-Lunar Greenhouse System (MLGS), was designed and constructed to reproduce the key

theoretical perspective, the study expands the range of candidate crops considered for extraterrestrial agriculture and proposes a systematic framework for evaluating supplementary crops in closed ecological systems.

From a practical perspective, the MLGS experimental platform and the standardized cultivation protocol developed in this research provide a scalable and reproducible approach for conducting ground-based CELSS crop experiments. Such systems may support further investigations into crop adaptability under simulated space environmental conditions and facilitate the preparation of future on-orbit plant cultivation experiments.

Overall, the integration of innovative crop selection strategies with modular experimental systems represents an important step toward the development of sustainable agricultural systems for long-duration space exploration missions.

The present study represents a conceptual and methodological stage of a broader research project. The formal cultivation experiments and quantitative data analysis are planned for subsequent research phases. Therefore, the conclusions of this study primarily relate to the methodological framework and experimental system design rather than to final crop performance evaluation.

environmental parameters of CELSS. The modular structure of the device enables precise environmental regulation, real-time monitoring and standardized experimental operation, providing a reliable platform for controlled crop cultivation experiments.

In addition, a standardized cultivation experiment scheme was developed, including pretreatment procedures for plant material, environmental control parameters, cultivation management protocols and a multi-dimensional system of evaluation indicators. The proposed experimental framework ensures the scientific validity, repeatability and comparability of subsequent experiments.

The results of this study provide a methodological and technological foundation for further experimental verification of crop adaptability under simulated CELSS conditions. The proposed crop selection strategy and experimental system may contribute to the development of diversified crop cultivation systems capable of supporting sustainable food production for long-duration extraterrestrial missions.

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ВІДБІР ВИСОКОАДАПТИВНИХ РОСЛИННИХ КУЛЬТУР ДЛЯ КЕРОВАНИХ ЕКОЛОГІЧНИХ СИСТЕМ ЖИТТЄЗАБЕЗПЕЧЕННЯ В УМОВАХ МОДЕЛЬОВАНОГО СЕРЕДОВИЩА

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Розвиток технологій вирощування рослин у контрольованих середовищах потребує пошуку видів, здатних ефективно функціонувати в замкнених або напівзамкнених екологічних системах із обмеженими ресурсами. Одним із перспективних напрямів таких досліджень є використання керованих екологічних систем життєзабезпечення (Controlled Ecological Life Support Systems, CELSS), у яких рослини забезпечують регенерацію газового середовища, беруть участь у водному та біогеохімічних циклах і формують харчову продукцію. Метою роботи є обґрунтування підходів до відбору рослинних культур із високим адаптаційним потенціалом для вирощування в контрольованих умовах та розроблення експериментальної платформи для дослідження їх росту і функціонування. На основі аналізу наукових джерел сформульовано принципи відбору перспективних культур з урахуванням екологічної адаптивності, морфологічних характеристик, поживної цінності та технологічної придатності до вирощування у регульованому середовищі. Як кандидатні види запропоновано *Mesembryanthemum crystallinum* L., *Anredera cordifolia* (Ten.) Steenis та *Anoectochilus roxburghii* (Wall.) Lindl., які характеризуються компактною морфологією, високим вмістом поживних і біологічно активних речовин та потенційною придатністю до вирощування в умовах обмеженого простору. Для дослідження їх адаптаційного потенціалу розроблено експериментальну установку Micro-Lunar Greenhouse System (MLGS), що забезпечує моделювання основних параметрів контрольованого середовища, зокрема температури, вологості, газового складу атмосфери, освітлення та параметрів живильного розчину. Запропоновано стандартизовану схему культивативного експерименту та систему оцінювання морфологічних, фізіолого-біохімічних і ресурсоефективних показників рослин. Отримані результати формують методологічну основу для подальших досліджень адаптації рослин у контрольованих екологічних системах та можуть бути використані під час розроблення технологій вирощування культур у замкнених середовищах.

Ключові слова: керовані екологічні системи життєзабезпечення, CELSS, контрольоване середовище вирощування, відбір рослинних культур, адаптація рослин, замкнені екологічні системи, Micro-Lunar Greenhouse System, модельоване середовище

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