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CROP CULTIVATION UNDER SIMULATED CONTROLLED CONDITIONS: RESEARCH PRIORITIES AND SYSTEM INTEGRATION CHALLENGES (ANALYTICAL REVIEW)

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The article presents a systematic review of scientific studies devoted to the cultivation of agricultural crops under simulated conditions with fully controlled environmental parameters, with particular emphasis on closed-type bioregenerative agricultural systems (CELSS/BLSS). It is shown that under artificially reproduced environments characterized by isolation from external factors, limited resources, the use of artificial lighting, altered gravity, and elevated radiation background, plants perform not only a productive function but also a system-forming role, participating in the regulation of gas exchange, water regimes, and biogeochemical cycles within closed agroecosystems.

The evolution of scientific approaches to plant cultivation under simulated conditions is analyzed, ranging from the confirmation of the fundamental possibility of plant growth and completion of the full ontogenetic cycle to the development of complex integrated systems focused on long-term stability and controllability. Particular attention is paid to the problem of so-called "system integration contradictions," in which locally optimal solutions for individual crops or technological components (such as light spectral composition, substrate type, or nutrient solutions) fail to ensure the stable functioning of the modeled agricultural system as a whole.

The synthesis of literature sources indicates that fragmented studies of individual growth factors are insufficient for understanding the functioning of agroecosystems under closed conditions. The necessity of a systemic interdisciplinary approach is substantiated, integrating agronomy, plant physiology, microbiology, and engineering solutions for environmental control. The prospects of applying controlled, moderately intensive simulated stresses (eustress) are highlighted as a tool for enhancing plant adaptive potential and improving the stability of agricultural systems under artificially reproduced cultivation conditions.

Key words: *simulated cultivation conditions; controlled environment; closed agroecosystems; CELSS; BLSS; plant adaptation; abiotic stresses; eustress; system integration; bioregenerative agricultural systems.*

Тао Вей, Бакуменко О.М., Власенко В.А. Вирощування сільськогосподарських культур за модельованих контрольованих умов: дослідницькі пріоритети та виклики системної інтеграції (огляд літератури)

У статті здійснено системний огляд наукових досліджень, присвячених вирощуванню сільськогосподарських культур у модельованих умовах із повністю контрольованими *параметрами середовища, з особливим акцентом на біорегенеративні аграрні системи закритого типу (CELSS/BLSS). Показано, що за умов штучно відтвореного середовища, ізоляції від зовнішніх факторів, обмеженості ресурсів, використання штучного освітлення, зміненої гравітації та підвищеного радіаційного фону рослини виконують не лише продукційну, а й системоутворюючу функцію, беручи участь у регуляції газообміну, водного режиму та біогеохімічних циклів у замкнених агроекосистемах.*

Проаналізовано еволюцію наукових підходів до культивування рослин у модельованих умовах – від підтвердження принципової можливості росту й завершення повного онтогенезу до формування комплексних інтегрованих систем, орієнтованих на довготривалу стабільність та керованість. Особливу увагу приділено проблемі так званих «суперечностей системної інтеграції», коли локально оптимальні рішення для окремих культур або технологічних елементів (спектральний склад освітлення, тип субстрату, поживні розчини) не забезпечують стабільного функціонування всієї модельованої аграрної системи.

Узагальнення літературних джерел свідчить, що фрагментарні дослідження окремих факторів росту є недостатніми для розуміння функціонування агроекосистем у замкнених умовах. Обґрунтовано необхідність системного міждисциплінарного підходу, який поєднує агрономію, фізіологію рослин, мікробіологію та інженерні рішення керування середовищем. Окремо підкреслено перспективність використання контрольованих модельованих стресів помірної інтенсивності (еустресу) як інструменту підвищення адаптивного потенціалу рослин і стабільності аграрних систем у штучно відтворених умовах вирощування.

Ключові слова: *модельовані умови вирощування; контрольоване середовище; замкнені агроекосистеми; CELSS; BLSS; адаптація рослин; абіотичні стреси; еустрес; системна інтеграція; біорегенеративні аграрні системи.*

Relevance of the Research Topic. In the context of the development of simulated systems for agricultural crop cultivation, increasing importance is attached to studying the functioning of plant agroecosystems under fully controlled and artificially reproduced environmental parameters. Such simulated conditions are applied in specialized ground-based facilities, phytotrons, bioregenerative life support systems, as well as in extraterrestrial plant production projects, particularly in the development of lunar research bases.

Simulated cultivation conditions are characterized by strict regulation of growth factors, limited exchange of matter with the external environment, a high degree of isolation, and the necessity to maintain system stability under the influence of a complex of abiotic stresses. Under these conditions, agricultural crops perform not only a productive function but also a system-forming role, participating in gas exchange, water cycling, and biogeochemical nutrient cycles. This determines the relevance of synthesizing scientific approaches to crop cultivation in simulated environments, with particular emphasis on lunar agriculture within controlled ecological life support systems (CELSS/BLSS).

Problem Statement. Despite a substantial body of experimental and theoretical research devoted to plant cultivation under simulated conditions, the current scientific output is characterized by fragmentation and a focus on individual growth factors or isolated technological solutions. In many publications, plants are considered primarily as objects of productivity, whereas in simulated agroecosystems – especially under conditions of complete isolation – they represent key functional components of closed ecological systems.

Locally optimal solutions that are effective for individual crops or specific technological elements (such as artificial lighting, substrates, or nutrient delivery systems) do not always ensure the stable functioning of the system as a whole. Under simulated conditions, this leads to the emergence of system integration contradictions, manifested in imbalances of gas exchange, disruption of nutrient cycling, and reduced system resilience to internal disturbances. These issues are particularly critical for simulated lunar plant production systems, where compensation for negative effects through natural environmental buffering is not possible.

Research Methodology (Review Methodology). The study was conducted in the form of a review article using methods of systemic, comparative, and critical analysis of scientific sources. The review synthesizes results of studies focused on agricultural crop cultivation under simulated conditions, including ground-based experimental complexes, bioregenerative life support systems, and experiments simulating lunar environmental conditions.

Publications addressing the effects of combined abiotic factors – limited space, resource constraints, artificial lighting, altered gravity, and radiation exposure – on plant growth, development, and functional roles within closed simulated agroecosystems were analyzed. The evaluation of the reviewed materials was carried out from the perspective of system integration of crops into simulated cultivation environments and their contribution to the stability and efficiency of controlled ecological systems.

Results of the Research (Analysis of Literature Sources). Human exploration of the Moon is transitioning from short-term visits to long-term stays and settlement. However, the primordial lunar environment is extremely hostile: its surface is near-vacuum, diurnal temperature variations exceed 300°C, the lack of a magnetic field exposes it to intense cosmic radiation and solar energetic particles, and gravity is only one-sixth that of Earth. Under these conditions, plants cannot grow naturally, and essential resources for human survival – oxygen, water, and food – cannot be directly obtained.

Constructing a CELSS, also known as a Bioregenerative Life Support System (BLSS), capable of achieving closed-loop material cycling, has become imperative. CELSS integrates higher plants, microorganisms, algae, and physicochemical processing units to partially simulate the functions of Earth's ecosystems, aiming for a high degree of closure in food production, air revitalization, water purification, and waste recycling. Lunar Base Agriculture typically refers to the crop cultivation unit within the CELSS. The internal environment of such closed systems is characterized by multi-factor coupling and significant chain reactions, making its impact on crop growth, yield, and ecosystem stability highly complex [1, 3].

With the rapid advancement of global lunar exploration programs and lunar research station construction plans, lunar base agricultural research has become an urgent task. This paper posits that current research faces three major challenges: First, over the past two decades since the 21st century began, CELSS research has generally slowed, and plant cultivation experiments have gradually deviated from systems logic, exhibiting a trend towards independent and fragmented research themes. Second, agricultural and biological researchers have not sufficiently engaged with the latest advancements in aerospace technology and lunar exploration, failing to integrate new technologies and perspectives into their work. Third, the focus on isolated plant cultivation experiments and interpretation of results has overlooked the issue of"system integration contradictions."

Based on this background, this article aims to: (1) systematically outline the development trajectory of lunar agriculture and CELSS technology, clarifying research themes and achievements at various stages; (2) elaborate in detail on the relationship between key CELSS technologies and crop cultivation research, as well as the new challenges faced at the current stage; (3) argue for the necessity, scientific rationale, and future directions of a paradigm shift in lunar base agricultural research. Through systematic review and discussion, this article aims to provide value orientation and theoretical support for subsequent applied research in lunar agriculture.

Driven by the demands of manned spaceflight missions and the refinement of CELSS technology, the development of lunar base agricultural research can be divided into three stages.

Concept Proposal and Early Exploration (1970s–1980s)

n 1975, early orbital plant cultivation experiments aboard the Salyut-4 space station revealed disoriented root and shoot growth under microgravity compared with Earth-based patterns. In 1979, the Salyut-6 station achieved complete life-cycle cultivation of Arabidopsis thaliana from seed to seed, confirming the reproductive capability of plants in microgravity. Together, these pioneering experiments provided the first experimental evidence supporting the feasibility of extraterrestrial agricultural cultivation.

In June 1987, NASA hosted the specialized workshop"Lunar Base Agriculture: Soils for Plant Growth"in Houston. The resulting monograph, Lunar Base Agriculture: Soils for Plant Growth, became a milestone in the field, offering the first comprehensive discussion of lunar environmental constraints on agricultural systems and potential engineering solutions [1].

In 1989, NASA released the "90-Day Study on Human Exploration of the Moon and Mars", proposing a return to the Moon and the establishment of a permanent base in the early 21st century, listing the"regenerative life support system"involving plants and microorganisms as the top priority among seven key technologies. Although this blueprint was later shelved, the technical concepts and mission architecture it proposed provided important theoretical and practical references for subsequent exploration plans, including the current Artemis program.

CELSS Theoretical Framework and Deepening Cultivation Experiments (1990s). The theoretical framework of CELSS was gradually refined, with its core objective being the highly closed recycling of resources like water, air, and food within the system. Large-scale ground-based integrated tests were conducted by multiple countries, such as the US's"Biosphere 2"and Japan's Closed Ecology Experiment Facilities (CEEF). The research focus expanded from single-species plant cultivation to the synergistic regulation of multiple biological units, including"human-plant-microorganism."

NASA's Johnson Space Center"Lunar Base Controlled Ecological Life Support System"(LCELSS) project evaluated the growth performance of wheat, potatoes, and other crops in lunar soil simulants. Results showed that with nutrient supplementation and precise photoperiod control, crops could complete their life cycle, but their biomass, yield, and photosynthetic efficiency were generally lower than Earth control conditions, revealing the physicochemical limitations of simulated lunar regolith [2, 4, 5].

Among the crops selected by NASA for LCELSS were four with underground edible parts: potatoes, sweet potatoes, beets, and peanuts [3]. These crops were grown in open and closed cycles, solid media, and liquid hydroponic systems. Experiments indicated that fluorescent lamps, fluorescent plus incandescent lamps, and high-pressure sodium plus metal halide lamps were all effective light sources. Under continuous light and day/night temperatures of 16–28/22°C, potatoes and sweet potatoes achieved the highest yields, respectively [6, 7, 8].

System Optimization and Long-Term Simulation Testing (2000s–2010s)

The construction of the International Space Station (ISS) provided a long-term and stable platform for space plant cultivation. A series of specialized facilities, including the Plant Growth Unit (PGU) and the European Modular Cultivation System (EMCS), successfully enabled the completion of full plant life cycles of Arabidopsis thaliana, dwarf wheat, Brassica species, and other crops under microgravity conditions. These platforms also allowed for in-depth investigation of the effects of the space environment on plant cell structure, gene expression, hormonal regulation, and associated microbial communities [9, 10]. The results of these studies substantially advanced the understanding of plant biological behavior and adaptive responses in space.

During this phase, ground-based CELSS simulation tests focused on obtaining key design parameters and operational experience for future extraterrestrial life support systems, verifying their long-term stable operation capabilities in extreme environments such as space stations, the Moon, and Mars.

The European Space Agency's (ESA) MELiSSA (Micro-Ecological Life Support System Alternative) initiative, launched in the late 1980s, aimed to develop a closed-loop bio-regenerative life support system based on lake ecosystem principles. This system utilizes five functionally complementary compartments to convert astronaut metabolic waste into oxygen, water, and food, achieving resource recycling [11, 12].

China's"Lunar Palace 1"ground-based simulation system conducted experiments such as"2-person 30-day"and"4-person 180-day,"establishing an artificial closed ecosystem with a"Human-Plant-Animal-Microorganism"four-biological chain. Its complexity and stability surpassed previous US systems, achieving 100% regeneration of oxygen and water, and partial regeneration of food [8].

Concurrently, research on cultivating model plants in simulated lunar regolith increased. In 2005 the National Academy of Sciences of Ukraine, based on experimental results, theoretically demonstrated the feasibility of cultivating healthy, low-cost pioneer plants at a lunar base [5]. The study used Turchynka anorthosite as a lunar regolith simulant to explore marigold cultivation in regolith with low bio-availability, proposing that pioneer plants must possess characteristics such as survivability in low-bioavailability regolith, acceptable yield under constrained conditions, strong disease resistance, and low requirements for factors like light and low gravity.

Breakthroughs were also made in in-situ lunar plant experiments. In 2019, China's Chang'e-4 mission achieved cotton seed germination on the far side of the Moon, marking humanity's first biological growth experiment on the lunar surface. Although the seedling died due to the low temperatures of the lunar night, its brief survival demonstrated the possibility of short-term plant survival under lunar radiation, microgravity, and temperature fluctuations [14].

System Integration and Multidisciplinary Convergence (2020s–Present)

With the advancement of new-generation lunar exploration programs like NASA's Artemis program and China's crewed lunar exploration missions, lunar base agriculture has entered a new phase oriented towards system integration and practical application. Research focuses on CELSS closed-loop reliability, multi-technology integration, and efficient in-situ resource utilization.

Liangchang Zhang (2022) validated the feasibility of reusing treated sanitary wastewater and urine as a hydroponic medium for plants, providing insights for the design and operation of hydroponic and water recycling systems in CELSS [6]. Chenjunnan Zhou (2024) conducted research on solid waste generation and compost recycling in CELSS, aiming to screen waste types, quantities, and treatment methods generated during aerospace missions, analyze oxygen demand patterns of different organic wastes, and summarize optimal critical oxygen levels for the aerobic composting process [7].

Yemets and S. Plokhovska from the Institute of Food Biotechnology and Genomics of the National Academy of Sciences of Ukraine found that the number of autophagosomes in plant root cells significantly increased under simulated microgravity, gradually recovering later, indicating plant adaptation [15, 16]. Exogenous application of nitric oxide (NO) donors enhanced plant tolerance to microgravity and promoted root growth.

Melatonin treatment improved plant antioxidant capacity and synergized with NOto enhance plant survival under microgravity, revealing a new mechanism of the NO-autophagy pathway in plant space adaptation [17].

In 2024, a team from the Chinese Academy of Sciences reported a significant discovery: lunar regolith minerals store substantial amounts of hydrogen due to long-term solar wind irradiation. Computational simulations showed that nanoscale channels exist within lunar ilmenite, capable of adsorbing and storing hydrogen atoms from the solar wind, with each ilmenite molecule able to adsorb up to four hydrogen atoms. The team proposed a feasible strategy for in-situ lunar water extraction and utilization: heating the regolith to approximately 1000°C to melt it, triggering redox reactions between solar-wind-implanted hydrogen and iron oxides to produce water, elemental iron, and ceramic glass, yielding about 51–76 kg of water per ton of regolith. This technology could significantly alter the development conditions for lunar base agriculture [18].

Furthermore, this period continued the conceptualization of the"Extraterrestrial Distributed Ecological Cultivation Network"(EDEN), envisioning the use of distributed greenhouse modules across different lunar longitudes to achieve continuous crop production by leveraging natural lunar diurnal rhythms, representing a new paradigm in lunar agricultural system design. Thus, the research perspective has expanded from lunar base agriculture within CELSS towards maximizing the use of in-situ resources and constructing semi-natural ecosystems.

Key CELSS Technologies and Their Impact on Lunar Base Crop Cultivation

As a complex systems engineering endeavor, the technological evolution of CELSS directly determines the feasibility and efficiency of lunar base agriculture. Scholars worldwide have discussed the fundamental theories and technical support paths for crop cultivation in CELSS environments for decades. Taking the CELSS Experimental Facility (CEF) as an example, its design includes 10 subsystems, with the core control system covering temperature, humidity, ventilation, air partial and total pressure, ethylene concentration, plant lighting, nutrient delivery, and airborne microbial monitoring [19]. These subsystems embody the advancements in CELSS technology and are common functional modules in ground-based space simulation experiments globally. The maturity and application of related technologies enable the potential for scaling up and sustaining lunar base agriculture.

The following briefly introduces four key technologies:

Artificial Lighting Technology

To date, artificial light remains the sole or primary source of illumination for crops inside CELSS. Light-emitting diodes (LEDs) have become the mainstream light source for space agriculture due to their small size, high efficiency, long lifespan, and precise spectral tunability [20]. By adjusting the ratio, intensity, and photoperiod of red (600–700 nm), blue (400–500 nm), and far-red (700–800 nm) light, optimization can be achieved for different crop species and growth stages, significantly improving photosynthetic efficiency, regulating morphogenesis, and enhancing secondary metabolite content (e.g., vitamins, antioxidants) [21]. For instance, lettuce grows best under red-blue light combinations, while adding far-red light promotes stem elongation, beneficial for light resource acquisition in dense cultivation. Shen Yunze (2014) improved wheat energy use efficiency by adjusting the photoperiod, applying four photoperiod treatments (12 h, 16 h, 20 h, 24 h) each before and after flowering, using red-blue LEDs (90% red + 10% blue) [8].

Environmental Temperature Control Technology

The extreme temperatures on the lunar surface pose lethal threats to living organisms. The CELSS temperature control system must maintain a relatively stable and suitable temperature range for crop growth (typically 18–25°C). Firstly, the greenhouse structure requires high-performance insulation materials to minimize heat exchange with the external environment. Secondly, phase change materials (PCMs) can be utilized to absorb or release heat, dampening internal temperature fluctuations. Finally, active temperature control systems (e.g., heat pumps, fluid circulation systems) are responsible for precise regulation of the internal cabin temperature, removing waste heat generated by plant transpiration and equipment operation [19]. The energy consumption of temperature control systems is extremely high, and their reliability and efficiency directly impact the viability of the entire CELSS.

Microgravity Countermeasure Technology

Lunar low gravity affects multiple plant physiological processes, notably altering root gravitropic growth direction, leading to disorganized root architecture, which in turn impacts water and nutrient uptake efficiency [10]. Additionally, in low gravity, soil capillary action is enhanced while gravitational drainage is weakened, potentially causing uneven water-air distribution in the root zone and leading to root hypoxia. To address these challenges, researchers have developed various techniques: soilless cultivation methods such as hydroponics and aeroponics have become mainstream, directly providing water, nutrients, and oxygen to roots via nutrient solution circulation or mist spraying, effectively circumventing microgravity-related issues.

Radiation Protection Technology

The lack of atmospheric and magnetic field protection on the lunar surface results in cosmic radiation intensities hundreds of times greater than on Earth's surface. High-energy particle radiation can directly cause DNA damage, organelle disruption, leading to gene mutations, abnormal growth and development, or even death [22]. Radiation protection in CELSS primarily relies on physical shielding. The greenhouse structure (especially the habitation module) typically needs to be covered with a sufficient thickness of shielding material, such as lunar regolith, water walls, or special composites, to attenuate radiation doses to safe levels. Additionally, biological protection strategies are also emphasized, including breeding radiation-resistant crop varieties through genetic engineering or traditional methods, and leveraging plant antioxidant mechanisms to repair radiation damage [23].

Challenges and Logical Shifts in Lunar Base Agricultural Research

From its conceptual proposal to its peak research period, CELSS took only slightly over a decade. Searches in academic databases reveal that the foundational theories, basic models, simulation experiments, and applied technologies of CELSS were largely established during this period. However, in the two decades following 2000, CELSS research entered a relatively flat development phase, with the quantity and pace of publications slowing down periodically.

The main reasons are as follows:

Firstly, as the principles were validated, the research focus shifted towards more engineering-oriented challenges such as subsystem optimization, long-term stable operation, and system integration. CELSS projects require substantial investment, long cycles, and breakthrough results are not easily achieved; reduced global lunar exploration activities during this period also limited CELSS research funding.

Secondly, space mission priorities shifted. The International Space Station entered routine operation, with its life support systems emphasizing physicochemical regeneration technologies, thereby limiting opportunities for CELSS experiments.

Thirdly, the influence of research incentive mechanisms. The global prevalence of evaluating research output based on publication count and citation metrics tends to favor"consolidative"research that is fast-producing and low-risk. Large-scale, high-risk systems engineering research like CELSS, requiring long-term investment, is relatively less attractive under such evaluation systems.

Furthermore, due to the complexity, interdisciplinary nature, and constrained experimental conditions of lunar base agricultural research, this period produced many studies deviating from the core of CELSS, diminishing the value of their outcomes. The author summarizes three common issues:

<u>Neglecting the Integration of Existing and Potential Technologies</u>

Barriers between disciplines exist in lunar agricultural research, creating a concerning research inertia: scholars often delve deeply into detail optimization within their own specialized fields but overlook the potential breakthroughs from cross-disciplinary technology integration, leading to relatively conservative design approaches for lunar agricultural systems. For example, some studies focus on breeding stress-resistant varieties, improving the microbial environment of lunar regolith, or addressing diurnal temperature stress, yet fail to reference the latest advancements in aerospace engineering, space physics, lunar geology, and other fields (such as the aforementioned technical conditions). Instead, they base their hypotheses, deductions, and arguments on assumed primitive lunar environmental parameters. This not only increases the research burden but also falls into repetitive, non-essential misconceptions, lacking practical application value.

For instance, Chinese scholars proposed establishing airtight confined spaces within polar lava tubes as the basic concept for a lunar farm, equipped with agricultural, living, environmental control, and water-fertilizer recycling systems, managed via sensors and automated control systems [14]. Additionally, as mentioned earlier, the Chinese Academy of Sciences team proposed producing 51–76 kg of water per ton of regolith through high-temperature processing [18], not only addressing the water source issue but also establishing a complete resource recycling system. Such advancements provide new perspectives for agricultural and biological scholars intending to conduct lunar base agricultural research.

<u>Overlooking the Role of Crops as"System Components"within CELSS</u>

Resource recycling is the core of CELSS, aiming to convert all"waste"within the system into"resources."On a lunar base, the crop system not only supplies food but also serves as an indispensable functional"component"within the CELSS, playing multiple key roles in the closed ecological cycle. In recent years, due to a lack of support from relevant disciplinary theories and experiments, scholars in agronomy have gradually deviated from the fundamental logic of CELSS, moving away from viewing crop value from a"component"perspective.

For example, in the MELiSSA program, astronauts act as consumers, microorganisms serve as decomposers and transformers, and plants and cyanobacteria act as producers, together forming a complete closed cycle: In Compartment I, anaerobic thermophilic bacteria break down waste like feces and urine into CO_2, volatile fatty acids (VFAs), and ammonium salts, a process that avoids carbon loss and safety risks by suppressing methane production; in Compartment II, the photoheterotrophic bacterium Rhodospirillum rubrum further processes VFAs, generating biomass and additional ammonium; Compartment III is the core stage for nitrogen recovery, where ammonium is sequentially oxidized to nitrite and nitrate, meeting the nitrogen demands of plants and cyanobacteria while preventing toxic ammonia accumulation; Compartment IV uses nitrate as fertilizer, producing oxygen and food through photosynthesis by plants and cyanobacteria; finally, astronauts in Compartment V consume these products and generate waste again, re-entering Compartment I, thus completing the MELiSSA cycle [11, 12].

In reality, the closed ecosystem of a lunar base is even more complex than the MELiSSA program, and the component role played by crops as a single unit (or module) within the system is more diverse and intricate. Therefore, research should return to this fundamental positioning.

Neglecting the"System Integration Contradiction"Problem

Although numerous crop cultivation experiments based on CELSS environments have been conducted, new conclusive findings are limited, and even"system integration contradictions"arise. This contradiction refers to the phenomenon where conclusions or technical solutions deemed"optimal"for a single plant species or a single growth factor, when integrated into the operation of the entire highly coupled, resource-closed complex system, may see their positive effects weakened, negated, or even transformed into"sub-optimal"or"inferior"solutions that negatively impact system stability and efficiency. This issue is often overlooked by agricultural and biological scholars.

For example, a specific dwarf wheat variety might be considered the"optimal"choice due to its highest one-time harvest grain yield per unit area. However, this high-yield wheat might release large amounts of oxygen concentrated during its reproductive stage while consuming significant CO_2 during the seedling stage, causing drastic fluctuations in O_2 and CO_2 concentrations within the system. This poses a significant risk to crew members and other crops requiring stable gas environments.

Clearly, integration contradictions manifest in CELSS as resource competition and trade-offs, metabolic flow mismatches, conflicts between system stability and redundancy, etc., which are often ignored by many scholars.

Future Research Directions for Agricultural Systems in CELSS Environments. In summary, lunar base agricultural research urgently needs to break down disciplinary barriers and establish cross-domain knowledge-sharing mechanisms. Researchers should actively follow and integrate technological breakthroughs from adjacent fields such as materials science, energy engineering, and in-situ resource utilization, viewing lunar agriculture as a complex engineering endeavor involving multiple coupled systems, rather than a simple extension of traditional agronomy, biology, or physical sciences [24, 25, 26, 27, 28, 29].

Over the past five years, with the advancement of major projects like the US Artemis program and China's crewed lunar landing plans, the demand for long-term life support for extraterrestrial bases has become unprecedentedly urgent. The new wave of space exploration targeting lunar research stations regards CELSS as a key technology, reigniting research fervor. The author believes future research needs to focus on the following directions:

Focus on the Long-Term Stability and Resilience of Crop Components within CELSS

As components (or units) of CELSS, maintaining their long-term stable operation is the ultimate challenge. Long-term ground-based experiments like"Lunar Palace 365"have demonstrated system feasibility under ideal conditions, but in the real lunar environment, systems will face more uncertain disturbances.

Biotic Community Stability: The long-term dynamic balance of interrelationships among plants, microorganisms, and potentially animals (e.g., insects or fish as protein sources).

Nutrient Cycling Efficiency: Whether, under long-term operation, nutrient elements experience difficult-to-recover"leakage"or"immobilization,"leading to declining system fertility.

System Resilience: The capacity and mechanisms for the system to self-recover to a stable state after significant disturbances (e.g., cascading effects triggered by internal environmental stresses). The introduction of more theories and methods is required.

In-Depth Analysis from Phenotype to Mechanism and Intelligent Design

To fundamentally enhance crop adaptation to combined stresses within CELSS environments, a comprehensive understanding of the underlying molecular, physiological, and genetic mechanisms is essential. The integration of high-throughput phenomics, transcriptomics, proteomics, metabolomics, and other multi-omics approaches enables the systematic reconstruction of regulatory networks governing plant responses – from stress perception and signal transduction to the formation of adaptive traits – under complex, combined stress conditions [25, 30].

For example, Italy's *Lunar Rice* project applies assisted evolution strategies to accelerate the breeding of rice varieties adapted to space-related constraints. Such studies not only contribute to the development of specialized crop varieties but, when combined with large-scale datasets and artificial intelligence or machine learning algorithms, also enable the construction of predictive models for plant growth and stress responses. These models provide the basis for intelligent optimization and precise control of environmental parameters within CELSS, thereby improving system efficiency and stability.

Emphasis on the Application of Eustress

Traditional research on crop production under controlled environments has primarily focused on minimizing stress-induced damage. However, concepts such as *stress acclimation* and *cross-adaptation* in ecology and agronomy suggest that moderate, well-controlled stress – referred to as *eustress* – can stimulate adaptive responses in plants. Such eustress factors may include targeted light spectrum modulation, moderate water deficit, short-term temperature fluctuations, or controlled nutrient limitation.

These mild stressors can "train" plants by activating endogenous defense and stress-response pathways, thereby enhancing tolerance to subsequent, more severe stresses and, in some cases, improving crop quality and nutritional value [30]. For instance, precise regulation of UV-B or blue light exposure has been shown to induce the synthesis of anthocyanins, flavonoids, and other antioxidant compounds in crops such as lettuce and tomato, enhancing both plant stress resistance (including radiation tolerance) and the health-promoting properties of the harvested products. Future research should therefore focus on systematically identifying optimal types, intensities, durations, and application stages of eustress suitable for crops cultivated in space-related environments.

Conclusions and Prospects for Further Research. The analysis of literature sources indicates that research on agricultural crop cultivation under simulated conditions, particularly within controlled ecological life support systems (CELSS/BLSS), has evolved over recent decades from demonstrating the fundamental feasibility of plant growth to the development of complex, system-oriented approaches. The current stage of this field is characterized by increasing attention to the integration of biological components into closed ecosystems and a reassessment of the role of agricultural crops not only as sources of food but also as functional elements that ensure the stability of matter and energy exchange within the system.

The synthesis of scientific evidence shows that fragmented approaches focused on optimizing individual growth factors or crop productivity are insufficient to ensure the long-term and reliable functioning of simulated agroecosystems. Of particular importance is the issue of system integration, in which locally efficient technological or biological solutions may lead to imbalances in gas exchange, disruption of biogeochemical cycles, and a reduction in overall system resilience under isolated conditions.

Future research in this area should prioritize interdisciplinary approaches that integrate advances in agronomy, plant physiology, microbiology, systems ecology, and engineering sciences. Key directions include the selection and breeding of crop species with high tolerance to the combined stress factors of simulated environments, the development of intelligent control systems based on real-time physiological feedback, and the exploration of controlled stress (eustress) applications to enhance plant adaptive potential.

Further progress in research on crop cultivation under simulated conditions, particularly for lunar agricultural applications, should be grounded in a system-level perspective that views agroecosystems as dynamic, multi-component entities. Such an approach will provide the scientific basis for improving the stability, efficiency, and bioregenerative capacity of CELSS and will support the practical implementation of sustainable agricultural production for long-term human presence beyond Earth.

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