

ARTIFICIAL BIOLOGICAL SYSTEMS FOR TERRESTRIAL AND SPACE AGRICULTURE: PLANT–MICROBIAL COMPLEXES AND ADAPTATION MECHANISMS

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The article analyzes the current development of artificial biological systems (ABS) for controlled agriculture on Earth and in spaceflight conditions. Particular attention is given to plant–microbial complexes (PMCs), hydroponic and substrate-based growing systems, and plant adaptation mechanisms under altered gravity. Results of laboratory, orbital, and microgravity cultivation experiments are summarized. Microgravity-induced changes in chloroplast ultrastructure, photosynthetic metabolism, cytoskeletal organization, and hormonal regulation are reviewed. Application of biofertilizers and microbial inoculants significantly enhances plant performance in controlled environments. Key technological needs for long-term bioregenerative life support systems are identified.

Keywords: *controlled environment cultivation, hydroponic nutrient delivery, bioregenerative life support, chloroplast ultrastructure, photosynthetic metabolism, gravity-related responses, rhizosphere interactions, biofertilizer application.*

INTRODUCTION

Artificial biological systems have been developed as part of the agricultural industry to provide food for a growing global population [1; 2]. These systems offer distinct advantages over traditional farming: 1) they reduce dependence on adverse weather, weeds, and pests; 2) enable full utilization of fertilizers; 3) allow year-round cultivation (including fall and winter); 4) free up large tracts of land; and 5) help address agricultural, environmental, and demographic challenges. Indeed, soilless and hydroponic cultivation has become increasingly feasible and efficient [3; 4].

This study aims to identify current advances in controlled-environment agriculture, characterize the role of plant–microbe interac-

tions, analyze plant responses to altered gravity, and define technological priorities for bioregenerative life support systems.

ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

Cultivation of plants in an artificial environment with hydroponic nutrient delivery is recognized as more effective than soil-based growing under equivalent climatic conditions. Science-based agricultural technologies further enhance product quality [1; 2; 5–7]. Recent reviews document how modern hydroponic systems with optimized nutrient films, automation, and monitoring can significantly boost yield, resource-use efficiency, and sustainability [8; 9].

However, using artificial conditions for plant cultivation is challenging due to the requirements for large volumes of nutrient solutions, continuous monitoring of composition, aeration, and prevention of microbial contamination. Consequently, there is renewed interest in developing new, easily renewable substrates with defined chemical composition, capable of supporting multiple high-yield cycles, and eliminating plant pests and pathogens [9; 10]. More recently, attention has turned to integrating plant-microbe systems and substrate innovations for closed-loop cultivation, particularly in controlled environments [11].

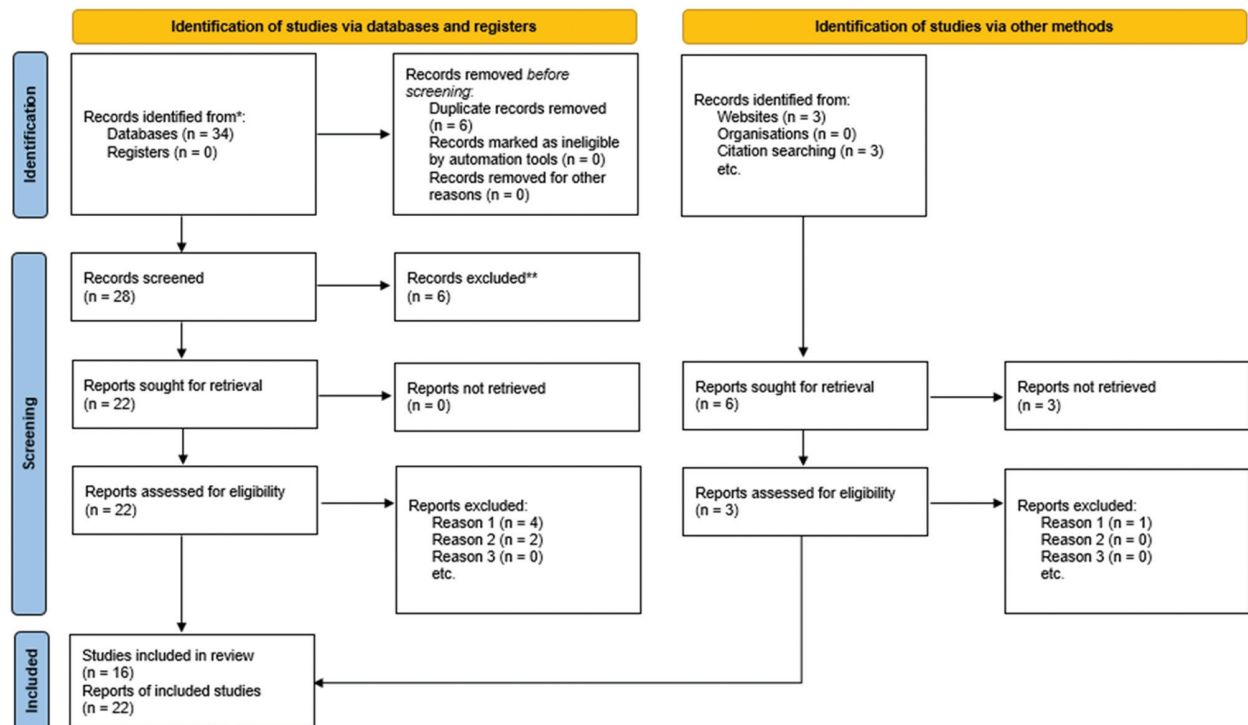
Particular interest among researchers is drawn to experiments on developing advanced life-support systems for space crews in microgravity, such as greenhouse modules on the research docking module of the International Space Station (ISS). At present, only technologies for cultivating certain crops on artificial non-renewable substrates (to supply vitamins for crew members) have been developed. Extending the service life of greenhouse chambers (i.e., growing plants without replacing the substrate) will require productive plant-microbial complexes in microgravity conditions, capable of performing the three core

processes that sustain life on Earth — photosynthesis, nitrogen fixation, and mineralization. Research in plant biology for space remains a critical area, addressing both the fundamental problem of gravity sensing and adaptation at the cellular/molecular level, and the applied challenge of creating controlled biological life support systems for human spaceflight [12;13].

MATERIALS AND METHODS

The methodology of this study was based on a systematic literature review conducted in accordance with the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. A structured search strategy was applied to identify relevant publications through scientific databases and additional sources. Records obtained from databases and other methods were screened for relevance, duplicates were removed, and eligibility was assessed using predefined inclusion and exclusion criteria. The study selection process is summarized using a PRISMA flow diagram (Fig. 1), which transparently presents the stages of identification, screening, eligibility assessment, and inclusion. As a result of this procedure, 38 peer-reviewed sources

PRISMA 2020 flow diagram for new systematic reviews which included searches of databases, registers and other sources



*Consider, if feasible to do so, reporting the number of records identified from each database or register searched (rather than the total number across all databases/registers).
**If automation tools were used, indicate how many records were excluded by a human and how many were excluded by automation tools.

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Fig. 1. PRISMA 2020 flow diagram of the literature selection process

were selected and included in the final analysis, forming the evidence base for the synthesis and interpretation of results.

RESULTS AND DISCUSSION

In the early 1970s, the Institute of Microbiology and Virology of the Academy of Sciences of the Ukrainian SSR developed a theoretical basis for space biological experiments with organisms in an active physiological state during flight. Since then, it has been important to study the vital activity of organisms during prolonged spaceflight and to elucidate adaptation mechanisms to spaceflight conditions [14; 15]. Today, Ukraine is one of the principal centres for comprehensive cell biology studies in space conditions, with Ukrainian scientists contributing important findings on the gravity sensitivity of plant cells and general patterns of biological effects of microgravity, a constant factor in spaceflight [16; 17].

It is well known that microgravity alters plant growth, its morphology, physiology, and biochemistry [18; 19]. Modern research in space biology now focuses on cellular mechanisms of plant adaptation to microgravity. Plant cells of different functional specializations respond to changes in the gravitational vector [16; 17]. Under microgravity, in the columella cells of the root cap, amyloplasts may be distributed throughout the cell volume rather than sedimenting, thereby preventing mechanical pressure on the plasma membrane, suppressing cytoplasmic Ca^{2+} elevation, calmodulin activation, and the formation of auxin pumps in the distal statocyte. The result is disruption of plant growth polarisation, in line with the hormonal inhibitory theory of plant gravitropism [21; 22]. Cytoskeletal elements in plant statocytes play a major role in the transmittal of gravitropic stimuli [16], and responses in other axial organs proceed according to a common scheme [19; 22].

Biospace cultivation experiments have been followed by intensive methodological and technical improvements. Special cultivators have been developed (e.g., IFS, "Growth", "Svitoblok 1", "Biocontainer") along with corresponding analyzers for the experimental setup. Within NASA programs (1995–1997), experiments "Orangery", "Orangery 2", and "Orangery 3" grew three generations of rape-seed, demonstrating seed viability in space and resistance of morphological, anatomical, and biochemical characteristics to spaceflight factors [18; 19; 22]. Meta-analyses of plant transcriptomes in space confirm the consistent response mentioned previously [20].

In the Svitlo greenhouse, experiments under ground and flight conditions demonstrated high biomass growth and favourable taste in leafy

vegetables such as Chinese cabbage, using salt-saturated Balkan zeolite as a substrate. However, productivity was reduced eight-fold during spaceflight, highlighting key research tasks such as: 1) comparing productivity on different substrates, 2) determining maximum biomass achievable without replacement of substrates, 3) extending vessel service life, and 4) optimizing substrate volume per plant. Cereals, particularly wheat (USU Apogee), were included to provide dietary carbohydrates and proteins [22]. Microgravity effects on wheat included slight reductions in leaf nitrogen, 40% decrease in non-protein nitrogen, and an 18–25% decrease in photosynthesis [19].

Spaceflight studies aboard Biosatellite II, Cosmos, and Salyut/Space Shuttle platforms revealed microgravity-induced changes in ultrastructure, including photosynthetic tissues [19; 20; 23]. Some of the species-specific effects observed include CO_2 assimilation decrease in cowpea, but the reverse was true for oat seedlings, and epiphytic orchids maintained near-ground RuBisCO activity [25]. Advanced greenhouses such as Lada mitigate growth inhibition via capillary-porous substrate moisture control, optimized lighting ($\sim 300 \mu\text{mol m}^{-2} \text{s}^{-1}$), and automated monitoring ($<100 \text{ W}$).

Microgravity cultivators for *Arabidopsis thaliana* enable full ontogeny cycles in space, facilitating studies of rhizosphere and endophytic bacterial communities for Plant Microbial Community (PMC) development. Cultivation without substrate replacement requires long-lived PMCs. Experiments with *Brassica rapa* in microgravity chambers showed chloroplast ultrastructural changes: increased cell size, chloroplast number, stromal thylakoid elongation, partial vesiculation, destacking of grana, and plastoglobule accumulation. PMCs coordinate growth, reproduction, and environmental stress response [11; 23].

Chloroplastogenesis studies reveal proplastid-etioplast transformation as the foundation for photosynthetic energy systems. Distal chloroplast localization maximizes photosynthetic surface, and spatial heterogeneity of pigment-protein complexes ensures flexible energy flow [24]. Mitochondrial ultrastructure reflects photosynthetic load. Photomembrane architecture, lipid/protein ratios, PS1/PS2 distribution, and carotenoid content contribute to photomembrane formation and repair.

Experiments with barley (*Hordeum vulgare*) and *B. rapa* under clinostat conditions using vermicompost-based Vermistim demonstrated adaptive modifications in chloroplast ultrastructure, mesophyll heterogeneity, starch and plastoglobule accumulation, and thylakoid rearrangements [25]. Integration of microbial inoculants mitigated stress

effects, enhanced chloroplast biogenesis, and stabilized photomembrane architecture, providing a strategy for long-lived PMCs in terrestrial and space systems [11; 23].

CONCLUSIONS

1. Microgravity and clinorotation significantly influence chloroplast ultrastructure, mesophyll organization, and photosynthetic metabolism.

2. Application of biofertilizers enhances plant adaptation under altered gravity.

3. Formation of productive PMCs is essential for sustainable cultivation in artificial systems and bioregenerative life support technologies in spaceflight.

These results deepen understanding of plant structural and functional plasticity under environmental stress and inform optimization of controlled agroecosystems for terrestrial and extraterrestrial food production.

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ШТУЧНІ БІОЛОГІЧНІ СИСТЕМИ ДЛЯ НАЗЕМНОГО Й КОСМІЧНОГО ЗЕМЛЕРОБСТВА: РОСЛИННО-МІКРОБНІ КОМПЛЕКСИ ТА МЕХАНІЗМИ АДАПТАЦІЇ

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У статті проаналізовано сучасний стан розвитку штучних біологічних систем (ШБС) для контрольованого землеробства на Землі та в умовах космічних польотів. Розглянуто потенціал рослинно-мікробних комплексів (РМК) у гідропонних і субстратних системах, а також механізми адаптації рослин до мікрогравітації та модифікованих фізичних умов. Узагальнено результати експериментів, виконаних у наземних лабораторіях, на орбітальних комплексах і в мікрогравітаційних культивуваційних модулях. Показано, що мікрогравітація суттєво впливає на ультраструктуру хлоропластів, фотосинтетичний апарат, цитоскелет і гормональну регуляцію рослин. Доведено, що включення біодобрив і мікробних інокулянтів підвищує адаптивні можливості культур у контрольованих середовищах. Визначено ключові напрями оптимізації технологій для сталого вирощування рослин у системах біорегенеративного забезпечення життєдіяльності.

Ключові слова: вирощування в контрольованому середовищі, гідропонне живлення, біорегенеративні системи життєзабезпечення, ультраструктура хлоропластів, фотосинтетичний метаболізм, реакції на гравітаційні чинники, ризосферні взаємодії, застосування біодобрив.

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