Role of cultivated plants in bioregenerative life support systems

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Abstract. Bioregenerative life support systems (BLSS) represent a critical technological pathway toward sustaining long-duration human space exploration by enabling the closure of material loops for air, water, food, and waste. This mini-review synthesizes current knowledge on the role of cultivated plants within BLSS architectures, emphasizing their multifunctional contribution as primary producers of edible biomass, oxygen generators, and agents of water purification. Key candidate species—including staple crops such as wheat, rice, potato, and soybean, as well as fast-growing plants like *Wolffia globosa* and microalgae—are evaluated in terms of productivity, nutritional value, and adaptability to space conditions. The review further examines nutrient recycling strategies, particularly nitrogen and phosphorus recovery from waste streams, and highlights the operational principles of major BLSS programs such as NASA's CELSS and ESA's MELiSSA. Special attention is given to the challenges of species selection under extraterrestrial constraints, including microgravity, radiation, and limited resources, as well as to emerging solutions involving extremotolerant microorganisms and in situ resource utilization (ISRU). Despite significant advances, current BLSS designs remain limited by incomplete nutrient closure and insufficient dietary completeness. Future progress will depend on the integration of biological and physicochemical subsystems, the optimization of crop systems for both yield and nutrition, and the validation of fully closed-loop systems at operational scale.

Keywords: space agriculture, cultivated plants, nutrient recycling, MELiSSA, CELSS, microgravity, ISRU, space missions.

Introduction. Bioregenerative life support systems (BLSS) aim to close material loops, regenerating air, water, food, and waste, using biological components, with higher plants serving as primary producers of edible biomass, oxygen, and purified water (Fu et al., 2016; Romano & Aronne, 2021; Revellame et al., 2023). Current physicochemical life support on the ISS recycles only a fraction of water and oxygen and cannot produce food, making regular resupply mandatory and rendering it unsuitable for deep-space missions (Verbeelen et al., 2021; Revellame et al., 2023). For long-duration missions to the Moon and Mars, integrating biological elements into these mostly abiotic systems is considered essential to achieve self-sustainability (Fu et al., 2016; De Micco et al., 2023; Ellena et al., 2025).

Aim of the Study. The aim of this mini-review is to critically evaluate the role of cultivated plants within bioregenerative life support systems designed for long-duration space missions. Specifically, the study seeks to (i) identify and assess candidate plant species suitable for space-based agriculture, (ii) analyze current approaches to water and nutrient recycling within BLSS frameworks, (iii) review major international BLSS programs and their technological advancements, and (iv) highlight the principal biological, environmental, and engineering challenges associated with achieving fully closed, self-sustaining life support systems beyond Earth. By synthesizing recent literature, this work aims to provide a comprehensive overview of the current state of the field and identify key directions for future research and system optimization.

Candidate Species for Space Farming. Staple crops such as wheat, potato, rice, and soybean must be included to provide the carbohydrates, proteins, and fats of the basic diet (De Micco et al., 2023; Petre & Pandey, 2026), while several vegetables and fruits with longer growth cycles (~100 days), including tomato, peppers, beans, and berries, can supplement nutritional diversity (De Micco et al., 2023). Soybean is one of four candidate species studied for soilless cultivation within ESA's MELiSSA program, selected for the high nutritional value of its seeds (Micco et al., 2012; Paradiso et al., 2013). Lettuce cultivars have been evaluated for BLSS integration, with baby Romaine demonstrating superior light-use efficiency under suboptimal light and red oak leaf contributing high polyphenol and carotenoid content (Rouphael et al., 2019). The dwarf tomato *Solanum lycopersicum* 'Microtom' has been assessed for radiation tolerance, with seed irradiation at 25 Gy Ca ions producing more compact plants with enhanced photochemical efficiency and berries richer in carotenoids, ascorbic acid, and anthocyanins (Arena et al., 2019).

Microalgae offer advantages over higher plants in edible biomass productivity, cultivation length, and growth requirements, and can grow on human-derived wastewaters and Martian regolith simulant (Revellame et al., 2023). The duckweed *Wolffia globosa*, the smallest existing higher plant, has been proposed as an ideal BLSS candidate due to its rapid growth, high nutritional density, and minimal resource requirements (Romano & Aronne, 2021). Growth of *W. globosa* under simulated microgravity and partial gravity reduced relative growth rates but still maintained a substantial RGR of 0.33 day^{-1}, supporting its adaptability to lunar and Martian gravity (Romano et al., 2024). Genetically transformed plum (*Prunus domestica*) overexpressing the FT1 gene exhibits dwarf growth, early flowering, and continuous fruit production, overcoming the architectural and phenological constraints that previously precluded tree fruits from BLSS designs (Graham et al., 2015). Aquatic bryophytes (mosses) such as *Taxiphyllum barbieri* and *Leptodictyum riparium* have been investigated as novel BLSS components, with *T. barbieri* showing the highest photosynthetic efficiency and *L. riparium* effectively removing nitrogen compounds and heavy metals from water (Amitrano et al., 2025) (Table 1).

Table 1

Candidate plant species evaluated for bioregenerative life support systems, their functional roles, and principal advantages

Species	*Role in BLSS*	*Key advantage*
Wheat, potato, rice, soybean	Staple calorie/protein production	Provide basic dietary macronutrients (De Micco et al., 2023)
Lettuce (baby Romaine, red oak leaf)	Fresh supplemental food	High light-use efficiency; rich in polyphenols (Rouphael et al., 2019)
Tomato 'Microtom'	Fresh fruit with nutraceutical value	Radiation-tolerant; compact growth; enriched berries (Arena et al., 2019)
Wolffia globosa (duckweed)	Fast-turnover edible biomass	Smallest higher plant; high RGR under altered gravity (Romano & Aronne, 2021; Romano et al., 2024)
Plum (FT1-transgenic)	Tree fruit for menu diversity	Dwarf habit; continuous fruiting (Graham et al., 2015).

Water and Nutrient Recycling. Within BLSS architectures, the photoautotrophic compartment recycles carbon dioxide, wastewater, and other wastes to produce edible biomass, oxygen, and clean water through plant transpiration (Paradiso et al., 2013; Romano & Aronne, 2021; De Micco et al., 2022). Nutrient recovery from waste streams is a prerequisite for self-sufficient BLSS operation, since shipping fertilizers from Earth would be prohibitively costly. The MELiSSA loop explicitly connects compartments so that each delivers processed waste-derived nutrients to downstream plant cultivation chambers (Verbeelen et al., 2021; Frossard et al., 2023). Substantial research has addressed nitrogen and phosphorus recovery from human urine, but recovering nutrients from other liquid and solid organic waste remains largely unexplored (Frossard et al., 2023). Efficient removal of sodium and chloride from urine and other organic waste is essential to prevent these elements from spreading through the MELiSSA loop and damaging plant cultures (Frossard et al., 2023).

A full nitrogen balance at habitat level must reconcile the need for sufficient atmospheric N_2 to maintain cabin pressure with the need for enough mineral nitrogen to sustain plant biomass production (Frossard et al., 2023). Compartment III of the MELiSSA loop is specifically responsible for nitrogen recovery from waste streams, converting urea and organic nitrogen into forms usable by the downstream photoautotrophic compartment (Verbeelen et al., 2021). In the Lunar Palace 1 experiment, 20.5% nitrogen recovery from urine and 41% solid waste degradation were achieved during a 105-day closed integrative BLSS trial with 21 plant species (Fu et al., 2016). A stoichiometric model of a conceptually fully closed MELiSSA-inspired BLSS demonstrated that balancing compartment dimensions can achieve zero loss for 12 of 14 compounds at steady state, with only minor oxygen and CO_2 losses (Vermeulen et al., 2023). One novel approach recycles urine on a bacterial filter to produce nitrogen fertilizer for vegetable cultivation (Häder, 2020), while mosses such as *L. riparium* can complement these processes by removing total ammonia nitrogen and heavy metals from water (Amitrano et al., 2025).

Major BLSS Programs: NASA CELSS and ESA MELiSSA. NASA has investigated bioregenerative life support systems for 60 years, with plants and other photosynthetic organisms central to the concept for their ability to produce food and oxygen, remove CO_2, and help recycle wastewater (Johnson et al., 2021). Controlled Ecological Life Support Systems (CELSS) or BLSS are based on Earth biosphere principles and aim to combine food crops and decomposers for continuous supply of water and oxygen without resupply (Rouphael et al., 2019). NASA's Biomass Production Chamber represents one of the early ground-based systems for studying closed biological life support (Häder, 2020). Estimates for full bioregenerative support range from 40 to 50 m² or more of crop growing area per person under high light intensities (> 500 µmol m^{-2} s^{-1}) (De Micco et al., 2023; Johnson et al., 2021), but early missions will not have these volumes available, prompting NASA to pursue supplemental fresh food production in chambers under 5 m² as a stepping stone toward larger systems (Johnson et al., 2021). The Eu:CROPIS mission, launched within a DLR satellite program, included tomato plants alongside *Euglena* as an oxygen producer, representing an integrated spaceflight test of biological life support (Häder, 2020).

ESA's MELiSSA program, launched in 1989, is designed as a five-compartment bioengineered system able to produce fresh food and oxygen and to recycle water for long-term space exploration (Verbeelen et al., 2021; Amitrano et al., 2025). The MELiSSA loop aims to reduce initial payload and Earth dependency by producing food, oxygen, and recycling water and carbon dioxide through interconnected compartments housing microorganisms and higher plants (Romano & Aronne, 2021; Ellena et al., 2025). Soybean was selected as one of four candidate crops for hydroponic cultivation within MELiSSA, with a two-step selection procedure developed to identify the most suitable European cultivars through theoretical scoring and controlled-environment trials (Micco et al., 2012; Paradiso et al., 2013). The MELiSSA concept has been used as the reference system for stoichiometric modeling of a fully closed BLSS, providing the first continuous provision of 100% of food and oxygen needs for a crew of six (Vermeulen et al., 2023). NASA's CUBES program parallels MELiSSA in developing technologies for future mission support through biological engineering in space (Ellena et al., 2025). The conceptual organization of major BLSS programs, their biological components, and resource recycling strategies is summarized in Figure 1, while the main characteristics and reference mission scenarios of these systems are compared in Table 2.

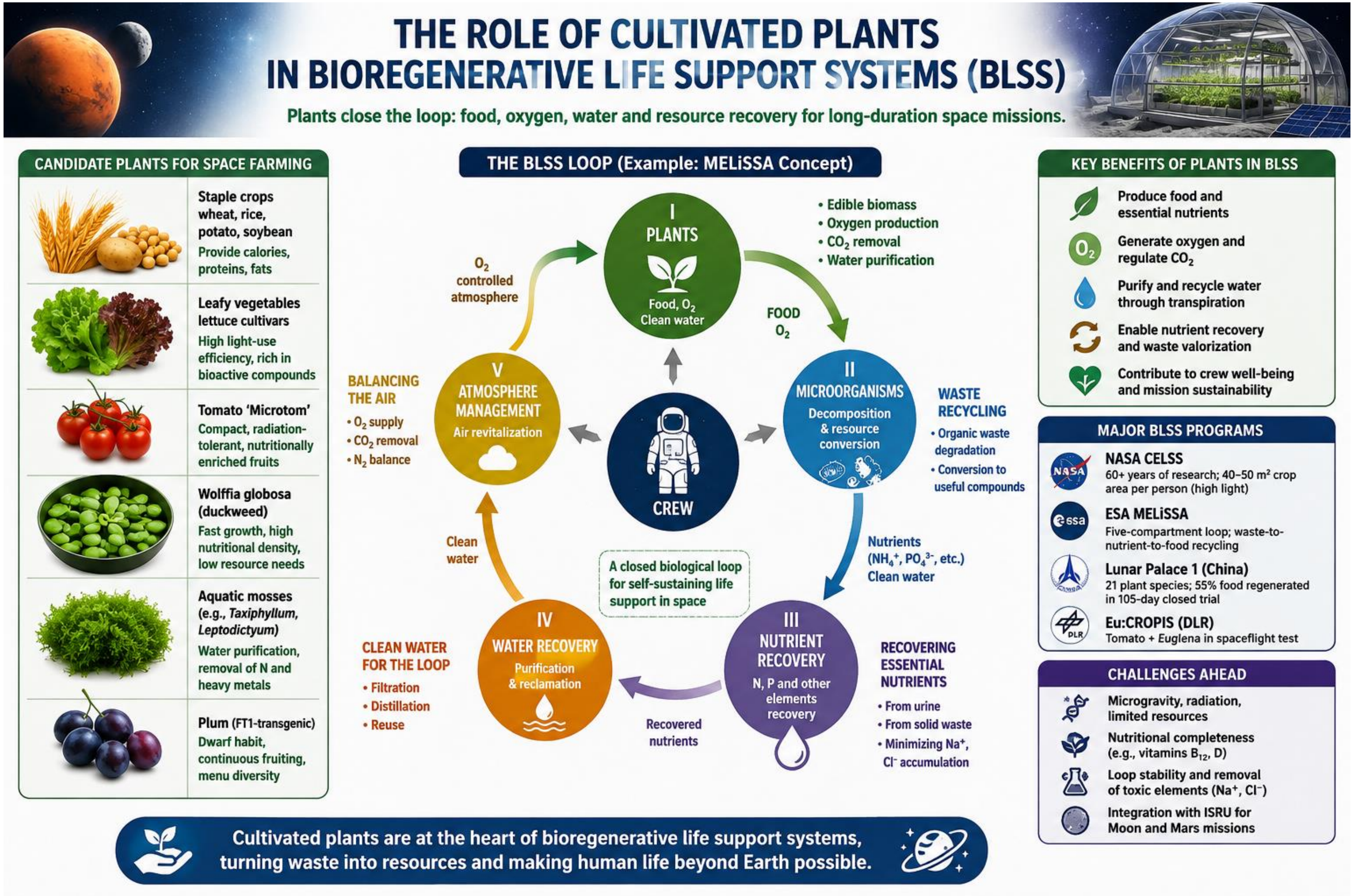

Figure 1. Conceptual framework of cultivated plants within bioregenerative life support systems.

Table 2

Major bioregenerative life support system programs, their agencies, defining features, and reference mission scenarios

Program	*Agency*	*Key features*	*Reference mission*
CELSS / Biomass production chamber	NASA	Ground-based closed biological systems; 40-50 m² crop area per person	ISS supplemental food; planetary surface (Häder, 2020; Johnson et al., 2021)
Veggie / Advanced plant habitat	NASA	Small-scale (< 5 m²) fresh food on ISS	ISS; lunar surface stepping stone (Johnson et al., 2021)
MELiSSA	ESA	Five-compartment loop; waste-to-nutrient-to-food recycling	Long-duration Moon/Mars missions (Romano & Aronne, 2021; Verbeelen et al., 2021)
Lunar palace 1	China	21 plant species; 55% food regenerated in 105-day trial	Lunar base simulation (Fu et al., 2016)
Eu:CROPIS	DLR	Tomato + *Euglena* on satellite	Mars/low-gravity simulation (Häder, 2020).

Species Selection for Lunar and Martian Bases. Species selection for planetary outposts must account for nutritional value, resource requirements (water, nutrients, light), edible-to-waste biomass ratio, storage requirements, and waste treatment needs. Space farming places more demands on plants than conventional agriculture due to cosmic radiation, absence of gravity, and the need to sustain astronaut life while maximizing resource utilization (Romano & Aronne, 2021). For long-duration missions, seed-to-seed cycles become a necessity to achieve independence from Earth supplies, but these reproductive phases are delicate, with simulated microgravity experiments showing possible aberrations in pollen tube development. Acclimation and adaptation to space environmental factors will be crucial criteria for both species and cultivar selection (De Micco et al., 2023).

Current crop lists used by ESA (MELiSSA), NASA (BVAD), and the Chinese Space Agency remain focused primarily on energy requirements and technical aspects of cultivation, while complete nutritional adequacy has not been the main selection criterion. Analyses of proposed crop sets from Eden ISS, Lunar Palace, and Mars 500 did not explicitly account for nutritional requirements, and even the more diverse Advanced Life Support System menu failed to fully meet vitamin B_{12} and vitamin D requirements. Plant-based BLSS diets may lack key micronutrients including cobalamin, riboflavin, and calciferol, prompting the search for nutrient-producing extremotolerant microbes to supplement crop-based diets (Ellena et al., 2025). In situ resource utilization (ISRU) approaches, including the use of Martian regolith as a growth substrate and microbial amendments for lunar and Martian soils, are being explored to reduce dependence on Earth-supplied materials (De Micco et al., 2023; Revellame et al., 2023; Esposito et al., 2026). The most realistic path toward sustainable settlements lies in coupled ISRU-BLSS architectures where external resource acquisition and internal regenerative loops are coordinated across shared material and energy flows (Esposito et al., 2026). Integrated Earth-based test facilities that include all BLSS modules, reactors, bioreactors, higher plant chambers, separators, and purification processes, at representative crew size and duration are urgently needed to demonstrate loop closure before deployment (De Micco et al., 2023).

Conclusions. Cultivated plants are indispensable components of bioregenerative life support systems, providing not only food but also essential ecosystem services such as oxygen production, carbon dioxide removal, and water purification. The diversity of candidate species—from staple crops to microalgae and novel organisms such as duckweed and aquatic bryophytes—demonstrates the breadth of biological solutions available for space agriculture. However, the successful implementation of BLSS remains constrained by several unresolved challenges, including incomplete nutrient recycling, accumulation of toxic compounds, and the difficulty of maintaining balanced biogeochemical cycles under closed conditions.

Current BLSS programs, particularly NASA's CELSS and ESA's MELiSSA, have made substantial progress in demonstrating the feasibility of integrating biological components into life support architectures. Nevertheless, these systems are not yet capable of achieving full autonomy, especially with respect to micronutrient provision and long-term stability. The limitations of plant-based diets in supplying essential vitamins highlight the need for complementary biological systems, including microbial consortia.

Future developments in BLSS will require a systems-level approach that integrates plant biology, microbial ecology, engineering, and space environmental sciences. The coupling of BLSS with in situ resource utilization strategies represents a promising pathway toward sustainable extraterrestrial habitats. Ultimately, the transition from experimental systems to operational, fully closed-loop life support systems will depend on large-scale validation under realistic mission conditions, as well as on the optimization of species selection and resource-use efficiency.

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