Rhizosphere microbiomes of cereal crops as extraterrestrial agriculture models

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Abstract. This mini-review examines the role of rhizosphere microbiomes associated with cereal crops as functional models for extraterrestrial agriculture within closed ecological systems. The rhizosphere microbiome, conceptualized as a plant's "second genome," plays a central role in nutrient acquisition, stress resilience, and disease suppression through complex plant–microbe interactions. The review synthesizes current knowledge on microbiome assembly, emphasizing the contributions of soil-derived, seed-borne, and host genotype-dependent microbial communities. Particular attention is given to biological nitrogen fixation and other nutrient-mobilizing processes mediated by plant growth-promoting microorganisms, which are critical in environments where synthetic inputs are limited. Furthermore, the paper explores microbiome-mediated mechanisms of abiotic stress tolerance, including hormonal regulation and metabolic adaptation under extreme conditions. Advances in microbiome engineering - such as synthetic microbial consortia, host-mediated selection, and microbiome transplantation - are discussed as strategies to enhance plant productivity in controlled and resource-constrained environments, including space-based greenhouses. Finally, key translational challenges are identified, including context-dependent inoculant performance, ecological compatibility, and the gap between laboratory findings and field application. The review highlights the necessity of integrating multi-omics approaches, precision breeding, and genome editing technologies to fully exploit microbiome-assisted agriculture for sustainable extraterrestrial food production.
Keywords: cereal crops, closed ecological systems, plant - microbe interactions, nitrogen fixation, plant growth-promoting microorganisms, synthetic microbial consortia, stress tolerance, microbiome engineering.

Introduction. The rhizosphere microbiome functions as a plant's "second genome," governing nutrient acquisition, stress resilience, and disease suppression through root–microbe crosstalk (Păpuc & Bora, 2023; Xun et al., 2024; Farooq et al., 2026; Feng et al., 2026). For cereal crops, this microbial community is assembled from both the surrounding soil environment and host genetic factors, with a small but stable proportion consistently recruited by a specific plant genotype regardless of soil conditions (Xun et al., 2024; Shen et al., 2024). Seed-borne bacteria can surpass native soil microbes as the dominant source of the rhizosphere microbiome in wheat, using niche partitioning and cross-feeding interactions to structure the community. These assembly dynamics are highly relevant to closed ecological systems, where the initial microbial inoculum carried by seeds may determine the trajectory of the entire rhizosphere community (Garrido-Sanz & Keel, 2025). Engineering these microbiomes through synthetic microbial consortia (SynComs) and optimized root exudate profiles offers a pathway to sustain plant productivity in resource-limited, extraterrestrial environments (Yusuf et al., 2025).

Aim of the Study. The aim of this mini-review is to critically synthesize current scientific knowledge regarding the structure, function, and engineering of rhizosphere microbiomes in cereal crops, with a particular focus on their applicability to extraterrestrial agriculture. The study seeks to elucidate how microbial communities contribute to nutrient cycling, plant stress resilience, and overall productivity in closed ecological systems. Additionally, it aims to evaluate emerging microbiome engineering strategies and identify key limitations and research gaps that must be addressed to enable the successful implementation of microbiome-assisted crop production in space-based environments.

Nitrogen Fixation and Nutrient Acquisition. Biological nitrogen fixation by rhizosphere bacteria converts atmospheric nitrogen into plant-available forms, a function critical for cereal crops in closed ecosystems where chemical fertilizers are unsustainable (Timofeeva et al., 2023; Feng et al., 2026). Plant growth-promoting rhizobacteria (PGPR), including symbiotic rhizobia and free-living diazotrophs, colonize the rhizosphere to perform nitrogen fixation alongside phosphate solubilization and siderophore secretion (Hakim et al., 2021; Igiehon et al., 2024). The combination of these beneficial bacteria into consortia has been demonstrated to increase soil fertility and crop yields, meeting the objectives of sustainable agriculture by reducing reliance on mineral fertilizers (Timofeeva et al., 2023). In cereal crops, nitrogen-fixing bacteria and mycorrhizal fungi enhance plant growth by increasing nutrient availability and influencing hormonal signaling (Solomon et al., 2023). The assembly and functional capacity of these nutrient-acquiring communities are driven by host plant genotype, developmental stage, and soil properties (Park et al., 2023; Feng et al., 2026) (Table 1).

Table 1

Functional groups of rhizosphere microorganisms and their relevance to closed agricultural systems

Functional group	*Mechanism*	*Relevance to closed systems*
Nitrogen-fixing bacteria	Atmospheric nitrogen conversion	Eliminates need for chemical N fertilizers (Timofeeva et al., 2023)
Phosphate-solubilizing bacteria	Organic/inorganic P mobilization	Recycles phosphorus in limited substrate (Hakim et al., 2021)
Siderophore producers	Iron chelation	Enhances iron uptake in controlled media (Hakim et al., 2021)
Mycorrhizal fungi	Nutrient transport enhancement	Extends root absorption surface (Park et al., 2023).

Microbiome-Mediated Stress Tolerance. Plants actively recruit specific soil microorganisms into the rhizosphere when experiencing abiotic stresses such as drought, salinity, and extreme temperatures (Ge et al., 2023; Xun et al., 2024). PGPMs enhance plant tolerance through phytohormone production, osmotic adjustment, and antioxidant enzyme activation, with key signaling pathways involving jasmonate, ethylene, and strigolactones (Ali et al., 2024; Song et al., 2026). Stress conditions alter root exudate composition, enabling plants to attract specific microbes that aid in stress mitigation by acting as chemoattractants that selectively shape the rhizosphere microbiome (Wankhade et al., 2025). The coexistence of microbial communities forms stable systems involving nutritional competition and metabolic exchange, ultimately enhancing plant stress tolerance (Ge et al., 2023). PGPR produce stress-alleviating compounds such as 1-aminocyclopropane-1-carboxylate deaminase, which modulates ethylene levels and improves plant survival under harsh environmental conditions (Hakim et al., 2021). These stress-resilient PGPMs and their application to induce tolerance mechanisms are of growing interest for agriculture facing severe environmental challenges (Backer et al., 2018; Hakim et al., 2021).

Engineering Microbiomes for Closed Ecosystems and Space Greenhouses. The deliberate manipulation of the rhizosphere microbiome is becoming increasingly sophisticated, with approaches including host-mediated microbiome engineering, microbial inoculants, and rhizo-microbiome transplantation (Park et al., 2023; Yang et al., 2023). Synthetic microbial communities (SynComs) designed through trait-based screening and multi-omics integration have shown promising potential in enhancing plant resilience against both abiotic and biotic stresses (Yusuf et al., 2025; Iqbal, 2026). Microbial biocontrol agents contribute to plant tolerance by modulating rhizosphere microbial communities, offering a framework for precision-designed SynComs that maintain microbiome resilience under stress (Iqbal, 2026). Host plants can shape their rhizosphere microbiomes at different genomic levels to recruit specific beneficial microorganisms, suggesting that breeding "microbiome-assisted" crop varieties could improve adaptability in controlled environments (Luo et al., 2024; Xun et al., 2024). The integration of microbiome research with precision farming practices and advanced gene editing tools like CRISPR is advocated to optimize biostimulant formulations for diverse agro-ecological systems, including those relevant to space agriculture (Ali et al., 2024; Sarsaiya et al., 2025) (Table 2).

Table 2

Strategies for engineering rhizosphere microbiomes applicable to closed ecological life support systems

Engineering strategy	*Application*	*Evidence of efficacy*
Synthetic consortia (SynComs)	Tailored microbial inoculants	Enhanced resilience against drought and salinity (Yusuf et al., 2025)
Host-mediated engineering	Breeding for microbiome recruitment	Genotype-specific beneficial microbe recruitment (Yang et al., 2023)
Prebiotics from root exudates	Shaping microbial assembly	Selective recruitment of beneficial taxa (Yang et al., 2023)
Microbiome transplantation	Transferring functional communities	Improved stress tolerance and growth (Park et al., 2023)

Translational Challenges and Future Directions. A primary challenge in transferring rhizosphere microbiome technologies to closed ecosystems is the context-dependent efficacy of microbial inoculants and the persistent lab-to-field gap (Ali et al., 2024; Song et al., 2026). Inconsistent field performance, knowledge gaps in stress-related molecular signaling, and regulatory hurdles continue to limit broader adoption of microbial biostimulants (Ali et al., 2024). The complexity of microbial interactions and the variability of environmental conditions affect crop growth, making the integration of findings into practical applications difficult (Sarsaiya et al., 2025). Inoculant persistence, ecological compatibility, and microbiome-level trade-offs remain key knowledge gaps that limit field-scale effectiveness (Iqbal, 2026). Addressing these challenges requires a multidisciplinary approach combining multi-omics, synthetic communities, and genome editing to realize the potential of microbiome-assisted agriculture in extraterrestrial settings (Song et al., 2026).

The conceptual relationships among cereal crops, rhizosphere microbiomes, nutrient acquisition, stress adaptation, and microbiome engineering strategies are summarized in Figure 1.

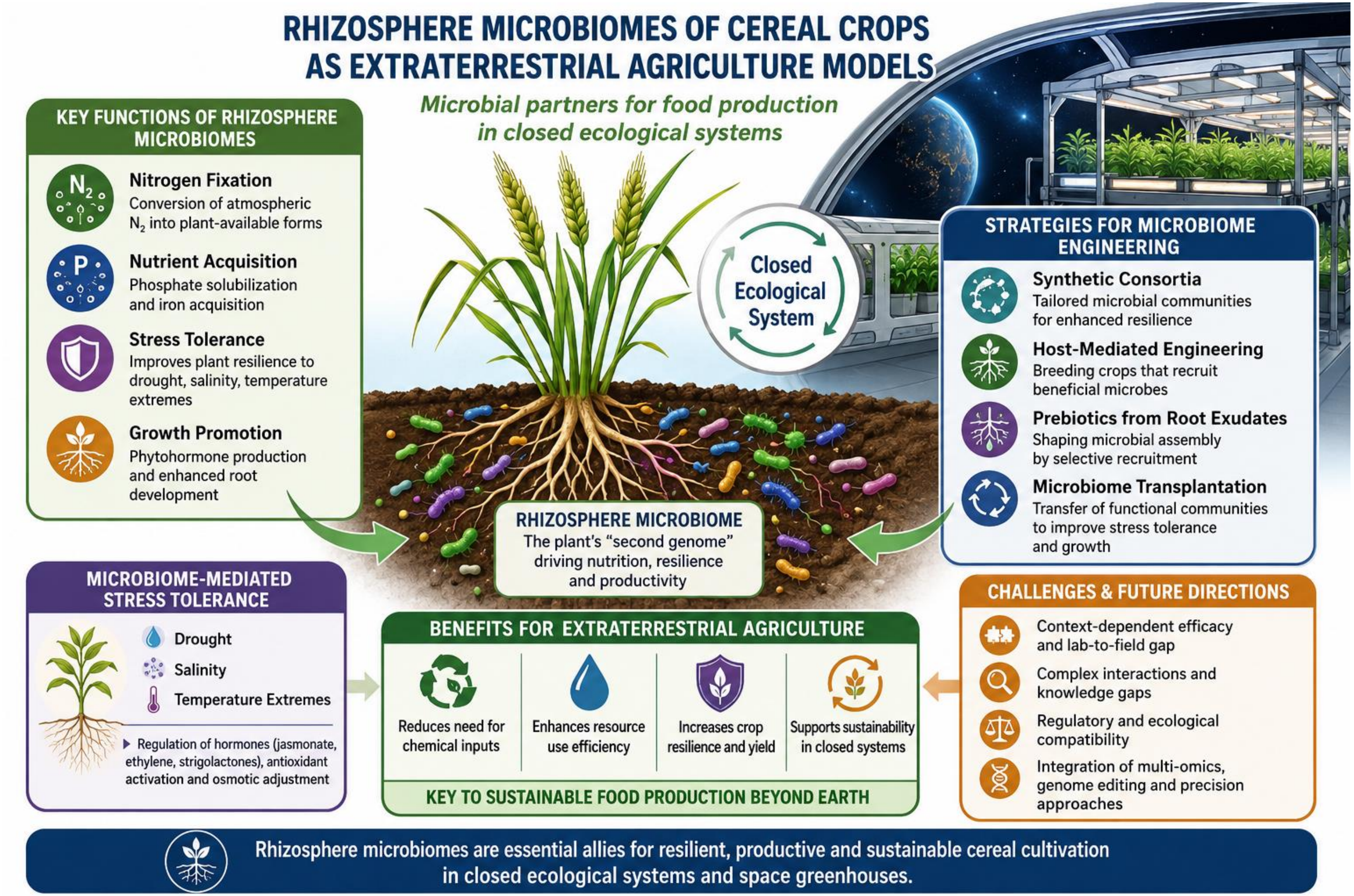

Figure 1. Conceptual framework of cereal crop–rhizosphere microbiome interactions for extraterrestrial agriculture.

Conclusions. Rhizosphere microbiomes represent a pivotal component of sustainable agriculture, particularly within the context of closed ecological and extraterrestrial systems. Their capacity to mediate nutrient acquisition, enhance stress tolerance, and stabilize plant health underscores their potential as biological substitutes for chemical inputs in resource-limited environments. Advances in microbiome engineering, including the development of synthetic microbial consortia and host-guided microbiome assembly, offer promising avenues for optimizing crop performance under controlled conditions. However, significant challenges remain, notably the variability of microbial inoculant efficacy across environmental contexts, limited understanding of complex microbial interactions, and constraints in translating laboratory findings to operational systems. Addressing these challenges will require integrative, multidisciplinary approaches combining molecular biology, systems ecology, and advanced breeding technologies. Ultimately, harnessing rhizosphere microbiomes may be essential for enabling resilient and productive agricultural systems beyond Earth.

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