

Anabaena: A New Chassis for Space Exploration

The prospect of long-duration human space exploration and potential colonization of other planetary bodies necessitates the development of advanced, sustainable life support systems. Biological approaches, particularly those harnessing photosynthetic microorganisms like cyanobacteria, are central to this vision. Within this context, Anabaena, a filamentous, nitrogen-fixing cyanobacterium, has emerged from relative obscurity as a leading candidate chassis for a new generation of bioregenerative systems. Its unique combination of robust stress tolerance, genetic tractability, and versatile metabolic capabilities positions it not merely as an adjunct but as a foundational organism for future missions. This review synthesizes current research on Anabaena as a model system for space exploration, providing a critical analysis of its physiological performance, genetic engineering toolkit, and integration into complex bioprocesses for in-situ resource utilization (ISRU) on Mars and the Moon. We will evaluate its potential applications in bioregenerative life support systems (BLSS), assess its resilience in simulated extraterrestrial environments, and identify key knowledge gaps that must be addressed to realize its full potential.

Physiological and Metabolic Foundations for Extraterrestrial Life Support

The suitability of any organism as a chassis for space exploration hinges fundamentally on its intrinsic physiological and metabolic capabilities. Anabaena possesses a suite of traits that make it exceptionally well-suited for the demanding and resource-limited conditions of extraterrestrial habitats. Its biology is characterized by remarkable versatility in nutrient acquisition, gas exchange, and energy metabolism, which can be engineered or leveraged to create self-sustaining ecosystems. The primary functions required for a BLSS—oxygen production, carbon dioxide fixation, and biomass generation—are all hallmarks of Anabaena's natural physiology¹². As a photoautotroph, it uses sunlight and CO₂ to build organic matter, while simultaneously producing oxygen as a byproduct of photosynthesis. This process forms the basis of any closed-loop life support architecture. Furthermore, its ability to perform atmospheric nitrogen fixation is a transformative advantage for ISRU, offering a pathway to generate essential biological building blocks without relying on Earth-based resupply^{2 11 33}.

One of the most significant assets of Anabaena is its demonstrated capacity to utilize extraterrestrial regolith as a source of mineral nutrients. Studies have shown that certain strains, notably Anabaena sp. PCC 7938, can achieve substantial growth when cultivated in Martian and lunar regolith simulants^{2 16 17}. In experiments using the Mars Global Simulant (MGS-1), PCC 7938 produced over twice the biomass of competing strains^{2 17}. This capability is predicated on the organism's ability to leach minerals from the solid substrate. Research has revealed that direct contact between the cells and the regolith particles is crucial for this process; cultures where cells could physically interact with MGS-1 grains yielded significantly more biomass than those separated by a semipermeable membrane, indicating that mobilization of minerals via cell-secreted agents or physical disruption is necessary for

efficient uptake^{3 25 34}. This finding has profound implications for photobioreactor design, suggesting that suspended culture systems may be inefficient due to shading effects, whereas systems promoting cell-grain contact would maximize nutrient extraction. However, the effectiveness of this process is not uniform across all simulants; growth was poor on an acidic simulant (PRT), highlighting the importance of compositional analysis in selecting landing sites or habitats¹³.

Despite this impressive capability, the use of regolith introduces significant challenges, primarily related to nutrient availability and toxicity. While *Anabaena* can access many minerals, phosphorus has been identified as a critical limiting factor in Martian regolith simulants^{3 25 31 34}. Supplementing phosphate at concentrations found in standard BG110 medium increased biomass by as much as 67%, underscoring that simply providing water and air is insufficient for optimal productivity^{3 25 34}. The chemical environment of regolith also presents toxic challenges. High concentrations of perchlorates, abundant on Mars, inhibit growth in a dose-dependent manner^{3 25 34}. At levels simulating the Martian surface (0.6 wt%), growth in high-density regolith cultures was reduced by approximately 50%^{3 25 34}. The combined effects of regolith and perchlorate appear to be multiplicative rather than synergistic, simplifying predictive modeling but compounding the overall stress on the organism^{3 25 34}. Finally, nitrogenase activity, the engine of nitrogen fixation, is suppressed under high salinity conditions induced by NaCl¹, adding another layer of complexity to cultivating these organisms in briny environments.

Beyond nutrient sourcing, *Anabaena*'s metabolic network offers opportunities for targeted product synthesis. The successful cultivation of the higher plant *Lemna* sp. (duckweed) using lysate from *Anabaena* sp. PCC 7938 demonstrates its potential as a feedstock for secondary producers within a BLSS^{2 11 16 32}. PCC 7938 lysate supported the highest growth of duckweed among tested strains, yielding nearly double the biomass compared to another promising strain, PCC 7122^{16 32}. Similarly, biomass from PCC 7938 supported robust growth of the heterotrophic bacterium *Escherichia coli* W, comparable to standard rich media, indicating its utility as a general-purpose nutrient source^{2 16 17}. These results suggest that a single integrated system could use *Anabaena* to fix CO₂ and N₂, produce biomass and O₂, and simultaneously generate a nutrient stream for cultivating staple food crops or producing valuable biochemicals, thereby minimizing waste and maximizing resource efficiency in a closed-loop environment¹².

Parameter	Value / Finding	Context / Source
Regolith Simulant	Martian Global Simulant (MGS-1)	2 3 25
Optimal Biomass Production Strain	<i>Anabaena</i> sp. PCC 7938	2 17 32
Maximum Biomass Yield	>0.5 g L ⁻¹ /in 200 kg · m ⁻³ MGS-1	2 16 32
Limiting Nutrient	Phosphorus	3 25 31 34

Parameter	Value / Finding	Context / Source
Phosphate Concentration Effects	Supplementing BG110 levels increased biomass by 67%; Haldane inhibition constant (K_{iPHOS}) = 1.379 mM	3 25 34
Perchlorate Tolerance	Intermediate; inhibits growth in a dose-dependent manner	2 3 17
Combined Stress Effect	Multiplicative ($F_{RP} = F_R \times F_P$)	3 25 34
Cell-Regolith Interaction	Direct contact enhances nutrient release; aggregate formation reduces productivity	3 25 34
Feedstock Viability	PCC 7938 lysate supports highest growth of <i>Lemna</i> sp. and robust growth of <i>E. coli</i> W	2 16 32

Genetic Engineering and Synthetic Biology Toolkits for Advanced Functionality

The true power of Anabaena as a chassis lies not only in its native capabilities but in the potential to enhance, redirect, and precisely control its metabolic pathways through synthetic biology. The field has witnessed a rapid expansion of genetic tools for cyanobacteria, transforming them from difficult-to-engineer organisms into programmable factories. For Anabaena, this progress has been particularly significant, establishing it as one of the most genetically tractable multicellular prokaryotes. The development of efficient CRISPR-based genome editing technologies has been a cornerstone of this advancement, enabling precise modifications that were previously laborious or impossible. Systems based on CRISPR-Cpf1 (Cas12a) have been successfully adapted for use in Anabaena sp. PCC 7120, achieving near 100% efficiency in creating single genomic modifications and facilitating rapid multiple edits [6](#) [7](#) [18](#) [21](#). This system allows for markerless gene deletions, knock-ins, and conditional mutagenesis of essential genes, such as polA (encoding DNA polymerase I), demonstrating its utility for fundamental research and applied engineering [6](#).

Building on this foundation, researchers have pushed the boundaries of what is possible. An optimized CRISPR-Cas12a system developed for Synechocystis was adapted for use in Anabaena, enabling highly efficient multiplex editing of neutral and essential genes [5](#). Most remarkably, the CRISPR-Cas12a machinery has been repurposed for RNA-guided transposition, allowing for the large-scale insertion of DNA fragments (up to 118 kb) without generating cytotoxic double-strand breaks [6](#) [28](#). This "cut-and-paste" mechanism, delivered via a CAST (CRISPR-Cas-AssiSted Targeting) system, represents a paradigm shift in genetic engineering, enabling combinatorial pathway assembly and genome remodeling with unprecedented precision and safety [28](#). Alongside these powerful tools, modular cloning systems like CyanoGate have been introduced, streamlining the construction of complex genetic circuits and facilitating combinatorial engineering efforts [7](#). The application of CRISPR interference (CRISPRi) using dCas12a has also been demonstrated in Anabaena, allowing

for inducible, reversible repression of target genes without altering the genomic sequence, opening up possibilities for dynamic metabolic tuning^{[21](#)}.

However, a critical analysis reveals a significant and somewhat paradoxical knowledge gap. While the toolkits for Anabaena are advancing rapidly, they are almost exclusively being validated in the model strain Anabaena sp. PCC 7120. The premier chassis for space exploration applications, Anabaena sp. PCC 7938, remains largely untouched by these state-of-the-art genetic tools^{[2](#) [17](#) [32](#)}. This disconnect represents a major bottleneck. The immense investment in developing sophisticated editing platforms for PCC 7120 cannot be directly translated to the superior-performing PCC 7938 without dedicated effort to adapt these systems to it. Without a comparable toolbox, the full potential of PCC 7938—its superior regolith utilization, biomass yield, and homogeneity—cannot be realized. Future work must prioritize the transfer and optimization of CRISPR-Cas systems, including Cas12k for CAST, and other advanced tools to PCC 7938 to unlock its engineered potential. Another notable gap exists in the area of base editing, a technology that has seen great success in other microbes but has not yet been reported for Anabaena, representing a frontier for even finer genetic control^{[7](#)}. The table below summarizes the available genetic tools and their known host range.

Genetic Tool	Mechanism	Host Organisms	Key Features & Applications	Citation(s)
CRISPR-Cpf1 (Cas12a)	DNA cleavage; guide RNA directs Cas protein to target site	Anabaena sp. PCC 7120, Synechocystis sp., Synechococcus UTEX 2973	Markerless gene deletion, knock-in, point mutation, conditional knockout of essential genes.	5 6 7 18 21 22
CRISPRi (dCas12a)	Gene repression; catalytically dead Cas protein blocks transcription	Anabaena sp. PCC 7120	Tunable, inducible downregulation of metabolic pathways.	21
RNA-Guided Transposition (CAST)	Large DNA fragment insertion; CRISPR-associated transposase	Anabaena sp. PCC 7120	Precise, large-scale genome remodeling without double-strand breaks; combinatorial pathway assembly.	28
CyanoGate	Modular cloning system	Anabaena, other cyanobacteria	Rapid construction of complex genetic circuits for combinatorial engineering.	7
Base Editors	Site-directed nucleotide conversion	Not yet reported in Anabaena.	Potential for creating specific point mutations	7

Genetic Tool	Mechanism	Host Organisms	Key Features & Applications	Citation(s)
			without double-strand breaks.	

This disparity between tool development and chassis application underscores a critical need for focused research. Bridging this gap is not just a matter of convenience; it is essential for moving from laboratory proof-of-concept to practical, scalable bioprocesses that can sustain human life beyond Earth.

Resilience in Simulated Extraterrestrial Environments

For any organism proposed for space exploration, its ability to survive and function in hostile, non-Earth environments is paramount. Extensive research has evaluated the resilience of *Anabaena* under a range of Mars- and Moon-relevant stressors, revealing a complex picture of robustness and vulnerability. The organism demonstrates a formidable capacity to withstand several key environmental challenges. It exhibits exceptional desiccation tolerance, a trait shared with its relatives in the genus *Nostoc*¹. While viability declines after prolonged dehydration, it shows a remarkable capacity for recovery upon rehydration^{10 38}. Furthermore, akinetes—the dormant, thick-walled resting cells of some *Anabaena* species—have shown remarkable survival capabilities. In experiments outside the International Space Station (LEO), *Anabaena cylindrica* akinetes survived the vacuum of space, temperature fluctuations ranging from -25° C to 59.6° C , and cosmic radiation doses of 240 mGy⁸. When shielded from unfiltered solar UV radiation (>200 nm), they remained viable and could be cultured, germinating into vegetative filaments⁹. This suggests that sheltered environments, such as beneath a layer of regolith, could provide sufficient protection for dormancy-based survival strategies.

Anabaena also displays a broad tolerance to temperature extremes. It can survive temperatures as low as -20° C and can endure freeze-thaw cycles, likely aided by cryoprotectants like dimethylsulfoxide (DMSO)¹. Thermotolerant strains can survive exposure to 42° C for days, although their metabolic activities, such as nitrogen fixation, are inhibited at such high temperatures²⁹. The response to cold shock involves a sophisticated regulatory program. In *Anabaena* sp. PCC 7120, the expression of the RNA helicase gene *crhC* is dramatically induced by a temperature drop, accumulating transcripts sixfold faster than at higher temperatures^{27 36 37}. This accumulation requires both a shift to cold and active metabolism derived from light, not just the presence of light itself, highlighting a complex interplay between environmental cues and internal cellular processes^{27 37}. Similar cold-inducible RNA-binding proteins are present in other cyanobacteria, indicating a conserved adaptive strategy³⁰.

However, the most significant challenge to the viability of *Anabaena* in open space environments is its extreme sensitivity to ultraviolet (UV) radiation. In the European Space Agency's EXPOSE-E facility, *Anabaena cylindrica* akinetes exposed to the full spectrum of extraterrestrial UV light did not produce any viable cells, despite surviving other aspects of the LEO environment⁸. This starkly illustrates that unshielded *Anabaena* is highly susceptible to DNA damage from solar UV radiation.

Even under more controlled simulations, the daily fluence of Martian UV-B radiation is estimated to be a potent stressor, capable of causing significant damage¹³. This vulnerability necessitates the development of protective measures for any *Anabaena*-based system deployed on the surface of Mars or the Moon. Shielding, either through physical barriers like regolith dust layers or by incorporating UV-protective compounds synthesized by the organism itself, will be a non-negotiable requirement for sustained operation. The discovery of active Class 2 CRISPR-Cas systems in *Anabaena* sp. PCC 7120 adds another layer to this story. The presence of such adaptive immune systems suggests an evolutionary history of dealing with viral threats, a relevant consideration for maintaining stable, clonal cultures in closed-loop systems over long durations⁴. The intricate regulatory networks governing stress responses, from osmotic and heat shock proteins to complex transcriptional changes during desiccation and nitrogen deprivation, provide a rich landscape for synthetic biologists to engineer enhanced resilience^{29 38 40}.

Comparative Analysis of Model Strains and Application Scenarios

The selection of a specific *Anabaena* strain is a critical decision that profoundly impacts the feasibility and efficiency of any proposed space application. The provided research highlights a clear divergence in performance characteristics between different strains, making a comparative analysis essential for strategic planning. The consensus emerging from recent studies is that *Anabaena* sp. PCC 7938 stands out as the premier chassis for space exploration, particularly for Mars ISRU applications^{2 11 17 32}. Its superiority stems from a confluence of desirable traits: high biomass productivity on Martian regolith simulant, moderate resistance to perchlorates, and, critically, excellent culture homogeneity with minimal aggregation^{2 16 17}. Aggregation poses a significant engineering challenge, as it can lead to clogging in photobioreactors and create internal gradients of light and nutrients, reducing overall system efficiency. The ability to maintain a suspended culture is therefore a major advantage for scalability and process control.

In contrast, other widely studied strains exhibit significant drawbacks for these applications. *Anabaena* sp. PCC 7122, a common model organism, forms extensive biofilms and aggregates, which severely complicates its use in conventional liquid-phase bioreactors^{2 17}. Similarly, PCC 7937 also tends to form aggregates². *Anabaena* sp. PCC 7120, while possessing a mature genetic toolkit, has been observed to cause chlorosis in the higher plant *Lemna* sp. when used as a lysate, making it a less effective feedstock compared to PCC 7938¹⁶. This comparative disadvantage in co-culture applications is a crucial factor, as many advanced BLSS concepts rely on trophic interactions between autotrophs like *Anabaena* and heterotrophs or higher plants. Therefore, while PCC 7120 serves as an invaluable platform for developing genetic tools, PCC 7938 is the clear choice for translating those tools into functional bioprocesses. The genomic relationship between these strains further clarifies their distinct roles: PCC 7938 shares over 99.9% average nucleotide identity with PCC 7122 but possesses unique metabolic pathways and superior phenotypic properties, validating it as a distinct and superior chassis^{2 32}.

These differences dictate distinct application scenarios for each strain. The following table outlines a strategic framework for deploying *Anabaena* in various space exploration contexts.

Application Scenario	Primary Environmental Challenge(s)	Recommended Anabaena Strain	Rationale & Supporting Evidence
Martian Surface Bioproduction	Regolith utilization, perchlorate toxicity, UV radiation, temperature swings.	PCC 7938	Superior biomass yield on regolith; moderate perchlorate tolerance; good homogeneity for potential reactor systems. Must be shielded from direct UV exposure. 2 3 8 17 32
Lunar Base Life Support	Low gravity (0.166g), radiation, thermal cycling (-171° C to 111° C), vacuum.	PCC 7938	Demonstrated viability in low-pressure atmospheres mimicking Mars; strong desiccation tolerance; proven ability to use regolith. Radiation/shielding is the biggest unknown. 26 35 38
Closed-Loop BLSS (e.g., MELiSSA)	Integration with higher plants, nutrient recycling, system stability.	PCC 7938	Excellent feedstock quality for Lemna; avoids chlorosis seen with PCC 7122. Facilitates trophic coupling in multi-compartment systems. 2 16 23 32
Genetic Tool Development	Laboratory-scale research, plasmid construction, transformation protocols.	PCC 7120	Mature and well-characterized genetic toolkit (CRISPR-Cpf1, CRISPRi, CyanoGate). Serves as a platform for developing and optimizing methods before adaptation. 6 7 21

This strategic differentiation underscores the importance of a multi-pronged approach. While PCC 7938 is the ultimate goal for in-situ applications, PCC 7120 remains indispensable for the foundational research and development required to unlock the full potential of the entire genus. The successful deployment of Anabaena in space will depend on leveraging the strengths of each strain appropriately, ultimately culminating in the use of the best chassis, PCC 7938, for the final mission hardware.

System-Level Integration and Engineering Challenges

The transition of Anabaena from a laboratory organism to a functional component of a space habitat requires more than just understanding its individual biology; it demands a systems-level approach that addresses the complex engineering challenges of integrating it into a bioregenerative life support system (BLSS). The provided research identifies several critical bottlenecks that must be overcome to ensure stable, efficient, and scalable operations. One of the most prominent challenges is managing the interaction between the phototrophic culture and the solid matrix of Martian regolith. As established, direct cell-regolith contact is vital for nutrient extraction [3](#) [25](#) [34](#). However, this same

interaction leads to cell aggregation and sedimentation, which can render a suspended culture bioreactor ineffective by preventing adequate mixing and light distribution. This creates a fundamental trade-off: maximizing nutrient access often comes at the cost of operational efficiency. Consequently, photobioreactor design must be carefully tailored to the chosen *Anabaena* strain. For aggregating strains like PCC 7122, bioreactors might require mechanical agitation or specialized flow patterns to keep solids in suspension. For the more favorable PCC 7938, simpler designs might suffice, but the risk of clogging and fouling still exists. Prototyping and testing of novel reactor geometries specifically for *Anabaena* on regolith are underway, highlighting the need for hardware development to proceed in parallel with biological research³³.

Another significant engineering hurdle is light limitation. In a bioreactor containing a dense suspension of cells and regolith particles, light penetration becomes a major issue. Experiments have shown that a relatively low concentration of suspended MGS-1 (20 kg/m³) can reduce photosynthetically active radiation (PAR) to undetectable levels over a short path length (3.3 cm)^{3 25 34}. This phenomenon, known as shading, means that a large portion of the culture volume may exist in a dark zone, unable to contribute to biomass production. To mitigate this, engineers must design reactors with high surface-area-to-volume ratios and potentially incorporate artificial lighting or highly efficient light-diffusing materials. Furthermore, the ability of *Anabaena* to grow under low atmospheric pressure, similar to Mars' surface conditions, is a positive sign for system design^{26 33}. Maintaining the partial pressures of metabolizable gases (CO₂ and N₂) at ambient levels appears to be sufficient for normal growth, which simplifies the requirements for pressure control within the bioreactor³³.

From a systems biology perspective, the integration of *Anabaena* into a larger BLSS, such as the European Space Agency's MELiSSA project, provides a conceptual blueprint^{12 14 20 23}. MELiSSA is structured as a series of interconnected compartments, each performing a specific ecological function, ultimately converting waste products into food, water, and oxygen^{20 23}. In such a framework, *Anabaena* could serve as a primary producer, fixing CO₂ and N₂, while its biomass or soluble exudates could be consumed by heterotrophic bacteria in a subsequent compartment. The successful demonstration of growing duckweed (*Lemna*) on *Anabaena* lysate is a direct proof-of-concept for this type of trophic cascade^{2 11 16 32}. However, scaling this up introduces challenges related to system stability and control. The cost of transporting mass to space is exorbitantly high (\$10,000/kg to LEO, up to \$300,000/kg to Mars), making every gram of equipment and every watt of power a critical resource¹². Therefore, any *Anabaena*-based system must be highly automated, robust, and reliable to justify its inclusion on a mission. Predictive models have been developed to estimate the productivity and resource-efficiency of PCC 7938 on Mars, suggesting a breakeven point could be reached within five years, but these models highlight the need for further refinement and validation through ground-based hardware testing^{24 33}. Ultimately, the success of *Anabaena* in space will depend on solving these intertwined biological and engineering problems through interdisciplinary collaboration.

Knowledge Gaps and Future Directions in a Post-Genomic Era

While the potential of *Anabaena* as a space exploration chassis is undeniable, realizing this potential requires addressing significant knowledge gaps and pushing the field into new frontiers of research. The coming decade promises to be a period of intense investigation aimed at overcoming the remaining scientific and technical hurdles. The most pressing and critical gap is the disconnect between the genetic tools available for *Anabaena* and the premier chassis, PCC 7938. Nearly all advanced genetic technologies, including the powerful CRISPR-Cas12a and CAST systems, have been developed and validated in the model strain PCC 7120^{6 21 28}. Without a corresponding set of tools for PCC 7938, the most promising strain for Mars ISRU, progress is effectively stalled. The immediate priority must be the systematic transfer and optimization of these toolkits to PCC 7938. This involves not only adapting existing vectors and protocols but also developing new ones that are specifically suited to the unique growth characteristics and genetic background of PCC 7938. Success in this area would unlock the ability to rationally engineer the superior phenotype of PCC 7938, combining its innate resilience with targeted enhancements for space applications.

A second major area for future research is the comprehensive characterization of the PCC 7938 genome and transcriptome under a wide range of stress conditions. Although its genome has been sequenced and deposited in GenBank, deeper functional genomics is needed^{2 32}. Whole-genome sequencing confirmed the absence of complete biosynthetic gene clusters for known cyanotoxins, which is reassuring for safety^{2 32}. However, the presence of incomplete clusters for microcystin and saxitoxin warrants further investigation to fully understand any potential risks³². More importantly, a systems-level understanding of how PCC 7938 responds to the combined stresses of low pressure, perchlorates, and high UV radiation is lacking. Directional RNA-seq has provided a detailed view of the response to nitrogen starvation in PCC 7120, identifying key regulators and antisense RNAs⁴⁰. Analogous studies on PCC 7938 under Mars-analog conditions would provide invaluable data for engineering more resilient strains. Identifying the master regulators of the cold shock response, for instance, could allow for the fine-tuning of metabolic pathways to improve performance in the cold Martian nights^{27 36 42}.

Future directions should also explore the untapped potential of phage-host systems. The development of a CRISPR-Cas12a system for genome editing in cyanophages infecting *Anabaena* sp. PCC 7120 opens up the possibility of using phages for biotechnological applications, such as targeted population control in large-scale cultures or as delivery vectors for genetic cargo¹⁵. Exploring the virome of PCC 7938 and developing tools for its manipulation could provide another layer of control and functionality. Furthermore, there is a significant opportunity to develop base-editing technologies for *Anabaena*, which would allow for more subtle and precise genetic modifications without inducing double-strand breaks—a technology that has not yet been reported for this genus⁷. Finally, the integration of *Anabaena* into complex, multi-species consortia for advanced BLSS presents a frontier for synthetic ecology. Understanding the metabolic cross-talk and competitive dynamics between *Anabaena* and other microbes, such as heterotrophic bacteria and fungi, will be crucial for designing stable and productive synthetic ecosystems for long-duration missions. In summary, the next 5 – 10 years will be defined by the convergence of three key trends: the translation of cutting-edge genetic tools to the premier chassis PCC 7938, the deep functional

characterization of its genome under realistic space conditions, and the engineering of complex, multi-component systems that leverage its unique capabilities to create truly regenerative life support for humanity's expansion into the solar system.

Reference

1. Mechanisms of Stress Tolerance in Cyanobacteria under ... <https://www.mdpi.com/2673-7140/2/4/36>
2. Selection of Anabaena sp. PCC 7938 as a ... <https://pmc.ncbi.nlm.nih.gov/articles/PMC9361815/>
3. On the growth dynamics of the cyanobacterium Anabaena ... <https://www.nature.com/articles/s41526-022-00240-5>
4. CRISPR-Cas systems in multicellular cyanobacteria - PMC <https://pmc.ncbi.nlm.nih.gov/articles/PMC6546389/>
5. Efficient Multiplex Genome Editing of the Cyanobacterium ... <https://analyticalsciencejournals.onlinelibrary.wiley.com/doi/10.1002/bit.28910>
6. Expanding the Potential of CRISPR-Cpf1-Based Genome ... <https://pubmed.ncbi.nlm.nih.gov/30525474/>
7. Development of a base editor for convenient and multiplex ... <https://www.nature.com/articles/s42003-024-06696-3>
8. Exposure of phototrophs to 548 days in low Earth orbit <https://pmc.ncbi.nlm.nih.gov/articles/PMC3176519/>
9. Survival of Akinetes (Resting-State Cells of Cyanobacteria) ... <https://link.springer.com/article/10.1007/s11084-009-9167-4>
10. Exposure of cyanobacterium Nostoc sp. to the Mars-like ... <https://www.sciencedirect.com/science/article/pii/S101113442100186X>
11. Cyanobacteria Will be our Best Partner for Living on Mars <https://www.universetoday.com/articles/cyanobacteria-will-be-our-best-partner-for-living-on-mars>
12. Phototrophic microorganisms in bioregenerative life ... <https://www.sciencedirect.com/science/article/abs/pii/S0094576523003570>
13. Survival of Filamentous Cyanobacteria Through Martian ... <https://pmc.ncbi.nlm.nih.gov/articles/PMC12114234/>
14. MELiSSA: The European project of closed life support system https://www.researchgate.net/publication/284789582_MELiSSA_The_European_project_of_closed_life_support_system
15. CRISPR/Cas12a-based genome editing for cyanophage of ... <https://www.sciencedirect.com/science/article/pii/S2405805X24001303>

16. Selection of Anabaena sp. PCC 7938 as a Cyanobacterium ... <https://journals.asm.org/doi/10.1128/aem.00594-22>
17. Selection of Anabaena sp. PCC 7938 as a Cyanobacterium ... <https://journals.asm.org/doi/abs/10.1128/aem.00594-22>
18. CRISPR Tools for Engineering Prokaryotic Systems <https://www.annualreviews.org/content/journals/10.1146/annurev-chembioeng-100522-114706?crawler=true>
19. The Anabaena sp. PCC 7120 Exoproteome: Taking a Peek ... <https://www.mdpi.com/2075-1729/5/1/130>
20. ESA - MELiSSA life support project, an innovation network ... https://www.esa.int/Enabling_Support/Space_Engineering_Technology/MELiSSA_life_support_project_an_innovation_network_in_support_to_space_exploration
21. CRISPR-Based Technologies for Metabolic Engineering in ... [https://www.cell.com/trends/biotechnology/fulltext/S0167-7799\(18\)30146-X](https://www.cell.com/trends/biotechnology/fulltext/S0167-7799(18)30146-X)
22. Current advances in CRISPR-Cas-mediated gene editing and ... <https://bluebiotechnology.biomedcentral.com/articles/10.1186/s44315-024-00009-3>
23. Integration of a Higher Plant Chamber into the European ... <https://ui.adsabs.harvard.edu/abs/2008cosp...37.3437W/abstract>
24. Resource-efficiency of cyanobacterium production on Mars <https://www.sciencedirect.com/science/article/pii/S2211926424004132>
25. On the growth dynamics of the cyanobacterium Anabaena ... <https://pmc.ncbi.nlm.nih.gov/articles/PMC9606272/>
26. Growth of Anabaena sp. under ambient atmosphere (AA) ... https://www.researchgate.net/figure/Growth-of-Anabaena-sp-under-ambient-atmosphere-AA-and-MDA-1-at-cultivation-onset-T_fig3_349338234
27. Regulation of Cold Shock-Induced RNA Helicase Gene ... <https://pmc.ncbi.nlm.nih.gov/articles/PMC94409/>
28. Genome Engineering by RNA-Guided Transposition for ... <https://pubs.acs.org/doi/10.1021/acssynbio.3c00583>
29. Expression and possible role of stress-responsive proteins in <https://www.ias.ac.in/article/fulltext/jbsc/023/04/0399-0406>
30. Recent Developments in Bacterial Cold-Shock Response <https://www.caister.com/cimb/v/v6/125.pdf>
31. Selection of Anabaena sp. PCC 7938 as a ... <https://ouci.dntb.gov.ua/en/works/4wyEVK89/>
32. (PDF) Selection of Anabaena sp. PCC 7938 as a ... https://www.researchgate.net/publication/361932079_Selection_of_Anabaena_sp_PCC_7938_as_a_Cyanobacterium_Model_for_Biological_ISRU_on_Mars

33. Design of Cyanobacterium Photobioreactors for Mars In ... https://www.researchgate.net/publication/392894286_Design_of_Cyanobacterium_Photobioreactors_for_Mars_In-Situ_Resource_Utilisation_Prototyping_and_Testing_with_Anabaena_sp_PCC_7938_to_be_published
34. On the growth dynamics of the cyanobacterium Anabaena ... https://www.researchgate.net/publication/364738706_On_the_growth_dynamics_of_the_cyanobacterium_Anabaena_sp_PCC_7938_in_Martian_regolith
35. Design of Microalgae Photobioreactor Experiments on the Moon <https://ttu-ir.tdl.org/bitstreams/5e80ff18-d5d5-4812-a296-2d7ecafabd3b/download>
36. Regulation of cold shock-induced RNA helicase gene ... <https://pubmed.ncbi.nlm.nih.gov/10671444/>
37. Regulation of cold shock-induced RNA... - ERA <https://era.library.ualberta.ca/items/a46ed29e-3bbf-4c38-8df2-877415c893d3>
38. Gene Expression in the Cyanobacterium Anabaena sp. ... https://www.researchgate.net/publication/8897195_Gene_Expression_in_the_Cyanobacterium_Anabaena_sp_PCC7120_under_Desiccation
39. The DEAD-box RNA helicase CrhB exhibits pleiotropic ... <https://www.sciencedirect.com/science/article/pii/S2772735125000976>
40. Directional RNA deep sequencing sheds new light on the ... <https://bmcbioinformatics.biomedcentral.com/articles/10.1186/1471-2164-12-332>
41. Time course of cold-induced accumulation and warmth- ... https://www.researchgate.net/figure/Time-course-of-cold-induced-accumulation-and-warmth-induced-decay-of-crhC-transcripts_fig2_12644790
42. IEM analysis of cold-stressed Anabaena. A. CrhC... https://www.researchgate.net/figure/EM-analysis-of-cold-stressed-Anabaena-A-CrhC-distribution-within-an-ultrathin-section_fig1_9005222