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Beyond Hardware: Why Life is the Primary Infrastructure for Space Settlement

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2 SPACE DEVELOPMENT, 2.3.2 Space Habitat

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ABSTRACT

Earth is not merely the place we come from - it is the most sophisticated life-support system ever built. It is a self-regulating biosphere hurtling through vacuum, and it has kept us alive for millions of years not through machinery but through the seamless integration of living systems. As humanity transitions from short-term orbital missions to sustained settlement in cislunar space and beyond, we face a choice that is as much philosophical as it is engineering: do we export a sterile, hardware-centric outpost, or do we commit to extending the living system into our concealed habitats of which we are an irreducible part?

This paper argues that human survival and quality of life in space depend on treating biology not as a peripheral experiment, but as primary infrastructure. Humans do not travel alone. Our physiological health, psychological resilience, and cultural continuity are deeply entangled with biological partners, from our internal microbiomes to the photosynthetic pioneers that first terraformed the Earth's atmosphere. Drawing on recent research into pioneer organisms - mosses, algae, and lichens - the paper explores how these resilient living layers can serve as 'biological hardware': functional components that generate oxygen, filter water, recycle waste, and provide the green presence essential for mitigating the profound psychological isolation of the space environment.

The paper further examines a critical systems gap: even as our scientific understanding of individual biological components matures, the engineering integration of bioregenerative life support with broader habitat architecture remains unsolved. By designing settlements as extended concealed biospheres rather than pressurized machines, we can move beyond conventional performance metrics to recognise the subtler signals of a thriving community, one where beauty, ecological reciprocity, and human dignity are hardwired into the mission from the outset. The next space age will not be won by better machines alone, but by our willingness to bring the living world with us.

PAPER

1 Introduction: The Choice We Have Not Yet Made

Every human who has ever lived in space has done so inside a machine. The International Space Station is, at its core, an extraordinary feat of mechanical engineering, a pressurized vessel whose atmosphere is maintained by pumps and filters, whose water is recycled by centrifuges and chemical processors, whose food arrives shrink-wrapped from Earth. It works, and it works impressively. But it is also fragile in a way that is easy to overlook: the moment the machines stop, life stops too. There is no redundancy in biology on the ISS. There is no self-repair, no adaptive response, no living buffer between a valve failure and a crew emergency.

This is not a criticism of the engineers who built it. It reflects the mission profile it was designed for: short rotations, reliable resupply, proximity to Earth. But as we plan settlements in cislunar space, on the lunar surface, and eventually on Mars, those conditions will no longer apply. Resupply windows close. Communication delays grow. And the crews who live in those places will need more than survival; they will need a quality of life that can sustain not just their bodies, but their minds and their sense of meaning across years, not months.

The central argument of this paper is straightforward: we need to stop thinking of biology as a passenger on the space mission and start treating it as the engine. Life is not an amenity to be added once the hard engineering is done. It is the primary infrastructure - the layer upon which everything else depends.

2 Earth as Prototype: The Original Life-Support System

It is worth pausing on what Earth actually is, seen from the outside. It is a rocky body of moderate size orbiting an average star, remarkable primarily because of what covers its surface: a thin, self-regulating biosphere that has maintained habitable conditions for over three billion years. This is not an accident of chemistry. It is the result of constant biological activity; the photosynthetic transformation of an early atmosphere, the stabilization of carbon cycles by forests and oceans, the microbial management of nutrient loops in soil and water. Life built its own habitat, and then kept rebuilding it as conditions changed.

The implication for space settlement is significant. We have never actually designed a life-support system from scratch; we have always lived inside one that was already working. The challenge is not to invent something new, but to understand what we are already embedded in well enough to reproduce its essential functions in a new place. This requires us to think ecologically: to ask not just “what does a human need?” but “what does the system that sustains a human need?” The answer, in every case on Earth, involves other living organisms. Specifically, it involves the kind of pioneer organisms - mosses, algae, lichens, and microbial communities - that established the first stable ground-level ecosystems on a previously barren planet.

There is a deep symmetry here that is worth naming explicitly. Bryophytes - mosses and liverworts - were among the first organisms to colonize terrestrial environments from aquatic ones, roughly 470 million years ago. They are not evolutionary relics. They are pioneers in the truest sense: organisms that create the conditions under which more complex life becomes possible. In thinking about how to establish life in space, we would do well to follow the sequence that worked on Earth.

3 Biological Hardware: The Case for Pioneer Organisms

3.1 Functional Roles

The term 'biological hardware' is deliberate. It is intended to reframe the way we categorize living system components in the design of space habitats, placing them on the same operational level as pumps, filters, and pressure vessels. Pioneer organisms, far from being decorative or experimental, perform a suite of functions that are directly mission-critical.

Research published in 2025 by Amitrano et al. in *Frontiers in Plant Science* demonstrated the viability of three aquatic moss species - Taxiphyllum barbieri, Leptodictyum riparium, and Vesicularia montagnei - as biofilters and resource regenerators in Bioregenerative Life Support Systems (BLSS).[1] Under controlled conditions designed to simulate space habitat environments, T. barbieri emerged as the strongest performer: exhibiting the highest net photosynthesis rates, pigment accumulation, and biofiltration efficiency. L. riparium, meanwhile, proved most effective at removing nitrogen compounds and heavy metals such as zinc - complementary roles that suggest a multi-species moss layer could serve as a comprehensive biological filter within a closed water recovery loop.

ESA's subsequent communication of this 'Moss on Mars' project highlighted a further remarkable finding: when exposed to low-dose ionizing radiation (1 Gray of X-ray), T. barbieri did not merely survive, it outperformed non-irradiated controls, exhibiting higher photosynthesis and electron transport rates. This phenomenon, known as radiation hormesis, suggests that the organisms best suited to the space environment may not be those that merely tolerate radiation, but those that are actively stimulated by it.[2]

The evidence for moss resilience extends beyond laboratory simulation. In a landmark study published in *iScience* in November 2025, Maeng et al. exposed spores of the model moss *Physcomitrium patens* to nine months of open space conditions outside the International Space Station.[3] Upon return to Earth, over 86 percent of the spores germinated successfully. The sporangium, a natural protective enclosure, proved sufficient to shield the spores from the combined stresses of vacuum, ultraviolet radiation, extreme temperature cycling, and cosmic ray bombardment. This result is not merely remarkable in biological terms; it is architecturally significant. It means that moss spores are a viable candidate for transport to future lunar or Martian habitats, where they could be cultivated in situ to establish the biological substrate of a living life-support layer.

3.2 The Psychological Dimension: Green Presence as Infrastructure

The functional argument for biological integration - oxygen production, water filtration, waste recycling - is compelling on its own. But it is incomplete. Humans are not simply metabolic systems that need air and water. We are beings whose psychological well-being depends, in ways that are increasingly well documented, on contact with living things.

Research from analog habitat studies, Antarctic stations, submarine deployments, and long-duration isolation experiments consistently identifies the absence of nature as a significant psychological stressor. Astronauts returning from extended ISS missions frequently cite the lack of green, the absence of non-uniform textures, and organic smells as among the most disorienting aspects of life in space. This is not sentimentality. Biophilia, the evolved human affinity for living systems, has measurable effects on cortisol levels, sleep quality, cognitive performance, and social cohesion.

Pioneer organisms are particularly well suited to address this need precisely because they are low-maintenance and spatially flexible. A moss wall does not require a dedicated agricultural bay. It can be integrated into the living surfaces of a habitat, on walls, in corridors, as part of the visual and tactile environment of everyday life. The “green presence” it provides is not decorative. It is part of the habitat's psychological life-support function, as mission-critical as any mechanical subsystem, and far cheaper to maintain.

4 The Integration Gap: Where the Science Still Falls Short

It would be intellectually dishonest to present the case for biological integration without acknowledging the significant gap that remains between demonstrating individual components and deploying a coherent, functioning system. This gap is not merely a matter of engineering readiness; it is a conceptual and organizational challenge that the field has not yet resolved.

A review published in *Frontiers in Microbiology* in May 2026 by Esposito et al. exposes the current state of the art with uncomfortable clarity.[4] The review examines the relationship between In-Situ Resource Utilization (ISRU) - the extraction of local planetary resources - and Bioregenerative Life Support Systems (BLSS). Its central finding is that these two domains are “operationally distinct but architecturally coupled”: they share material and energy flows in ways that are not yet coordinated. The most realistic path toward sustainable human settlements, the authors conclude, lies in coupled ISRU-BLSS architectures, but such architectures do not yet exist in integrated form. Large-scale programs like ESA's MELiSSA loop and NASA's Advanced Life Support projects have advanced individual subsystems considerably, but the integrated coupling problem remains unsolved.

This is not a counsel of despair. It is a clear articulation of where the work needs to happen. The science of individual biological components - mosses, algae, microbiomes, higher plants - is maturing rapidly. What is needed now is the systems-level thinking to connect them: to understand how a moss biofilter couples with a water recovery loop, how a microbial waste recycler interfaces with a plant growth chamber, how the psychological function of a green habitat layer interacts with the social dynamics of a small, isolated crew. These are questions that no single discipline can answer. They require the kind of integrative thinking that this conference is precisely positioned to foster.

There is also a measurement problem embedded in the integration gap. Current BLSS performance metrics are largely quantitative: oxygen production rates, water recovery percentages, and carbon dioxide removal efficiency. These are necessary, but they are not sufficient. A system can meet all its KPIs and still feel, to the humans living inside it, like a machine rather than a home. We need to develop the capacity to read “weak signals” - the subtle ecological and relational cues that indicate a habitat is thriving rather than merely operating within acceptable parameters.

5 Designing for Flourishing: Beyond the KPI Horizon

The language of space settlement is dominated by engineering and logistics. Mission architectures, launch windows, payload fractions, system reliability; these are the categories in which most planning takes place, and rightly so. But they are insufficient for what we are actually trying to build. A settlement is not only a system, it is also a community. And communities are sustained not only by the resources they consume, but by the meanings they generate.

This is the deeper argument for biological integration. When we design a habitat that includes living systems, not as a research module, but as a constitutive part of the living space, we are making a statement about what kind of place this is and what kind of people we intend to be here. A corridor lined with moss is not just a biofilter. It is an assertion that beauty matters, that ecological reciprocity is a value, that the humans who live here are not guests in a machine but inhabitants of a world. The difference is not cosmetic; it is civilizational.

The concept of the Space Renaissance is useful here precisely because it insists on this broader frame. The Renaissance on Earth was not merely a period of technological advance; it was a reintegration of art, science, and human dignity into a shared vision of what it means to live well. The next space age calls for something similar: a vision of settlement that does not merely extend human survival beyond Earth, but extends human flourishing. That means designing habitats where people can grow food they have tended, where the air carries the faint biological signatures of life, where the visual environment is not uniform grey but varied, organic, and alive.

From a systems perspective, this means incorporating metrics of habitat health that go beyond resource throughput. What is the level of spontaneous social interaction among crew members? What is the frequency with which individuals seek out the green areas of the habitat? How do biological subsystem cycles - the growth rhythms of plants, the seasonal cues that can be simulated through lighting - affect crew circadian regulation and mood? These are not soft questions. They are operational questions with direct implications for mission success. A crew that is psychologically thriving makes better decisions, handles emergencies more effectively, and sustains its own cohesion across the long arc of a multi-year mission.

6 Conclusion: Bringing the Living World With Us

The evidence reviewed in this paper points in a consistent direction. Pioneer organisms - and bryophytes in particular - are not merely interesting biological curiosities. They are robust, radiation-tolerant, multifunctional components that are increasingly well characterized for space habitat applications. The scientific case for their integration into life-support architecture is solid and growing stronger. The gap that remains is not one of biological knowledge but of systems integration and design philosophy.

That design philosophy needs to shift. For as long as we think of space habitats as machines that happen to contain humans, we will keep designing them as machines, and we will keep arriving at the same result: environments that sustain life in the narrowest physiological sense, while steadily eroding the psychological and cultural conditions that make that life worth sustaining. The alternative is to design space settlements as extended biospheres: places where the living layer is not bolted on after the engineering is complete, but is woven into the architecture from the beginning.

The next step, the unsettled work before us, is to bridge the coupling gap that Esposito and colleagues have identified: to develop the integrated ISRU-BLSS architectures that can support a genuinely closed-loop settlement, and to embed within that architecture the biological and aesthetic richness that makes a community rather than an outpost. The moss will grow. The question is whether we are bold enough to let it.

ACRONYMS

Acronym	Description
BLSS	Bioregenerative Life Support System
CELSS	Closed (Controlled) Ecological Life Support System
ECLSS	Environmental Control and Life Support System
ESA	European Space Agency
ISS	International Space Station
ISRU	In-Situ Resource Utilisation
KPI	Key Performance Indicator
LEO	Low Earth Orbit
MELiSSA	Micro-Ecological Life Support System Alternative
NASA	National Aeronautics and Space Administration

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