Journal of Nature Studies 25(1): 38-55
Online ISSN: 2244-5226

SPACE BIOLOGY IN THE PHILIPPINES: A NARRATIVE REVIEW OF RESEARCH POTENTIALS AND FUTURE DIRECTIONS

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ABSTRACT – Space biology is emerging as one of the most consequential scientific frontiers of the twenty-first century. This paper presents a narrative review of foundational concepts and current trends in space biology, examines their relevance for Philippine higher education institutions, and proposes a transdisciplinary roadmap for developing space biology education and research capacity in the country. The review draws on a secondary analysis of publicly available bibliometric network data describing the global space bioscience literature, together with a synthesis of peer-reviewed evidence on planetary analog research and space health science. It argues that the Philippines possesses a distinctive opportunity to contribute to global space bioscience through strategic investment in microbial studies, plant biology, cell and molecular biology, cross-disciplinary integration with artificial intelligence (AI) and synthetic biology, and aerospace nursing. The proposed roadmap identifies priority research areas, foreseeable challenges, future directions, and a phased academic architecture suited to the current capacity of Philippine research institutions.

Keywords: aerospace nursing, microgravity, Philippines, space biology, space biosciences

INTRODUCTION

The exploration of space has never been purely an engineering endeavor. From the earliest Sputnik-era biological payloads to current long-duration missions aboard the International Space Station (ISS), life science has been central to determining whether and how humans can survive and thrive beyond Earth. In recent years, the field of "space biology" (broadly understood as the scientific study of how living organisms respond, adapt, and evolve under the conditions of spaceflight) has expanded dramatically in scope, funding, and global participation, creating an increasingly well-defined body of knowledge, methodology, and international infrastructure that new entrants can draw upon.

Considerable groundwork has already been established for understanding this field. Recent bibliometric mapping of the global space bioscience literature has clarified how the field is organized, identified its most active subdisciplines, and highlighted remaining thematic gaps. Complementary research on planetary analog environments and the physiological and psychological effects of long-duration spaceflight provides a substantial evidence base to guide countries newly entering the field in setting research priorities.

To cite this paper: Hernandez, J.P.T. 2026. Space Biology in the Philippines: A Narrative Review of Research Potentials and Future Directions. *Journal of Nature Studies, 25*(1), 38-55.

For the Philippines, however, considerable gaps remain. Despite the establishment of the Philippine Space Agency (PhilSA) in 2019 under the Philippine Space Act (Republic Act No. 11363) and growing national investment in space-related science and technology, engagement with the life sciences of space exploration, as distinct from engineering and remote sensing, remains limited. The country's substantial biodiversity, internationally distributed nursing and health sciences workforce, and globally connected research diaspora represent underutilized assets for this emerging field. However, no structured framework currently exists to guide the strategic entry of Philippine higher education institutions into space bioscience research.

This paper addresses that gap. It presents a narrative review of foundational concepts and current trends in space biology, combined with a conceptual synthesis of secondary bibliometric and empirical literature, and proposes a roadmap for how Philippine higher education institutions might build space biology research and education capacity. The paper does not report original empirical data collection; rather, it synthesizes existing, publicly available evidence into an orienting framework that institutions can adapt to their own capacity and priorities.

The remainder of the paper proceeds as follows. The review first states its objectives, then describes how the literature was identified, reviewed, and synthesized, including the secondary network analysis of bibliometric data. It then presents the results and discussion, organized around four themes: the biological foundations of space biology (foundational concepts, key disciplinary findings, analog-environment research, and human health science); Philippine strengths and opportunities; priority research areas; and a proposed roadmap and institutional strategy. The review closes with a discussion of its limitations, followed by a summary, conclusion, and recommendations for future research and institutional development.

OBJECTIVES

This review pursues three objectives: (1) to synthesize the foundational concepts and current trends in space biology; (2) to examine the relevance of space biology research for Philippine higher education institutions in shaping future research directions; and (3) to propose a transdisciplinary pathway and roadmap for developing space biology research and education capacity within Philippine higher education.

MATERIALS AND METHODS

Design

This paper is a narrative review combined with a conceptual synthesis and roadmap. It does not follow a systematic-review protocol (e.g., PRISMA) with pre-registered search strings and dual independent screening; rather, literature was identified purposively around three anchor sources that between them span the major subdisciplines of space bioscience: a comprehensive bibliometric mapping of the field (Berliner et al., 2024), a major space agency's consolidated summary of spaceflight biology findings and research gaps (Sato, 2020), and recent peer-reviewed work on planetary analog environments (Foucher et al., 2021; Arrigo, 2022) and spaceflight-related human health outcomes (Yin et al., 2023). Additional peer-reviewed sources published primarily between 2020 and 2024 were incorporated where they extended or illustrated findings from these anchor sources. This approach is appropriate to the paper's purpose of orienting a research community that is new to the field, but it is not a substitute for a systematic review, a limitation discussed further in the Limitations section below.

Secondary Network Analysis of Bibliometric Data

A secondary (i.e., re-analysis of previously published, not newly collected) network analysis was constructed directly from Table 1 of Berliner et al. (2024), which reports the count and prevalence of the 20 most common author keywords within each of three discipline corpora, Astrobiology (AB, n = 49,792 keyword instances), Bioastronautics (BA, n = 27,650), and Space Bioprocess Engineering (SBE, n = 1,071), drawn from their Scopus-based bibliometric analysis. Each keyword was represented as a three-dimensional discipline-prevalence profile using the published percentage values directly (Table 1). A fully connected, weighted graph was then built over the 20 keywords in Python (NetworkX 3.6.1), with the edge weight between each pair of keywords defined as the cosine similarity of their discipline-prevalence profiles (bounded 0 to 1); no co-occurrence threshold was applied, so every keyword pair is connected, an explicit modeling choice that also reproduces the fully connected structure reported for the retained output of the original analysis (discussed further below). Degree, betweenness, and closeness centrality were computed with NetworkX's standard implementations. Community detection used the Louvain algorithm (networkx.algorithms.community.louvain_communities, weighted, resolution = 1.0, seed = 42).

Table 1. Prevalence (P, %) of the 20 highest-prevalence author keywords within each disciplinary corpus.

Keyword	P_{AB} (%)	P_{BA} (%)	P_{SBE} (%)	Scaled P (%)
Astrobiology	4.49	0.09	0.93	1.84
Microgravity	0.04	4.56	0.37	1.66
Mars	1.44	0.31	1.68	1.14
Origin of life	3.01	0.00	0.09	1.03
Spaceflight	0.02	2.39	0.09	0.83
Prebiotic chemistry	1.32	0.00	0.00	0.44
In situ resource utilization	0.00	0.03	1.21	0.42
International space station	0.06	0.60	0.47	0.38
Moon	0.12	0.26	0.65	0.34
Space exploration	0.06	0.22	0.75	0.34
Cyanobacteria	0.12	0.03	0.84	0.33
RNA world	0.89	0.00	0.00	0.30
ISRU	0.00	0.03	0.84	0.29
Synthetic biology	0.10	0.01	0.75	0.29
SETI	0.84	0.00	0.00	0.28
Space	0.04	0.46	0.28	0.26
Weightlessness	0.00	0.76	0.00	0.25
Equivalent system mass	0.00	0.01	0.75	0.25
Extremophiles	0.28	0.00	0.47	0.25
Space medicine	0.00	0.63	0.09	0.24

Note. AB = Astrobiology; BA = Bioastronautics; SBE = Space Bioprocess Engineering. Data transcribed from Berliner et al. (2024) and used as input for the secondary network analysis.

An additional exploratory analysis applied a quantum-annealing-style optimization to the same network, formulated as a modularity-maximization QUBO (Quadratic Unconstrained Binary Optimization) Hamiltonian, the formulation used in published quantum-annealing community-detection studies. No quantum annealing hardware or vendor software development kit was accessible for this review, so the

QUBO was solved with a self-implemented classical simulated-annealing sampler (Metropolis-Hastings updates, geometric cooling, 30,000 sweeps), the standard classical stand-in for prototyping this type of problem before it runs on genuine quantum hardware. This is presented later in this paper as an illustrative application of an alternative computational approach rather than a validated method, given the small and preliminary literature on quantum approaches to bibliometric network analysis.

Synthesis and Roadmap Development

Findings from the anchor sources and supporting literature were organized thematically below and then interpreted against the documented strengths, existing expertise, and stated national priorities of Philippine higher education institutions and government agencies, drawing on publicly available institutional and agency information. The resulting roadmap was developed by the author through iterative conceptual mapping, identifying priority research areas where the literature indicates clear gaps and Philippine institutions plausibly have comparative advantages or existing capacity, rather than through stakeholder consultation or a formal Delphi or prioritization exercise. This is noted as a limitation later in this paper. A structured, multi-day expert workshop, of the kind used by the French Space Agency and the Institute for Space Medicine and Physiology to build their own biomedical research roadmap for deep-space missions, is one plausible model that Philippine institutions could adopt to validate and refine the priorities proposed here in future work (Martínez et al., 2026).

RESULTS AND DISCUSSION

Foundational Concepts and Current Trends in Space Biology

The Landscape of Space Biosciences

Berliner et al. (2024) provide a comprehensive contemporary mapping of space life science domains, charting the historical and geographic distribution of research output across the fields constituting the broader “space biosciences.” Their analysis distinguishes three major and partially overlapping domains: **Space Life Science Research** encompasses the broadest study of life in the universe, including research on origin, evolution, and distribution, both current and prospective. **Space Biology** focuses specifically on the biological effects of spaceflight, studying physiological and psychological impacts on living organisms with particular emphasis on human subjects. **Space Biosciences** takes a systems-level approach to the biological aspects of space exploration.

Within these domains, three subdisciplines merit special attention for researchers newly entering the field:

- **Astrobiology**: the study of life’s origin, evolution, and distribution in the universe; the search for habitable environments; detection of prebiotic chemistry and microbial biosignatures; and examination of the potential impacts of extraterrestrial life.
- **Bioastronautics**: examination of spaceflight effects on biological systems, including the physiological and psychological impacts of spaceflight and the development of life-support systems and countermeasures.
- **Space Bioprocess Engineering**: the development of biotechnology for space exploration, including in situ resource utilization (ISRU), loop-closure systems, in situ manufacturing, and food and pharmaceutical synthesis.

Secondary Network Analysis of Space Bioscience Keywords

As described above, the resulting keyword network was fully connected (Figure 1), meaning that every keyword was directly linked to every other keyword by a similarity-weighted edge. Consequently, all keywords had identical degree centrality (the number of direct connections) and closeness centrality (the average distance to all other keywords), both equal to 1, whereas betweenness centrality (the extent to which a keyword lies on the shortest paths between other keywords) was 0 for every keyword. This pattern indicates a dense, highly interconnected network in which no keyword serves as a unique bridge or bottleneck. Because all keywords are directly connected, these centrality measures cannot distinguish their relative importance. Instead, edge weights, which indicate the strength of relationships between keywords, and community structure, which identifies groups of closely related keywords, provide more informative insights into the organization of the research domain.

Louvain community detection (an algorithm that finds densely connected groups of nodes by optimizing modularity) detected three communities, with a modularity of $Q = 0.262$ (a measure of how strongly a network is divided into distinct communities). One community grouped “astrobiology,” “origin of life,” “prebiotic chemistry,” “RNA world,” “SETI,” and “mars,” reflecting Astrobiology’s characteristic emphasis on the origins and distribution of life. A second grouped “international space station,” “microgravity,” “space,” “space medicine,” “spaceflight,” and “weightlessness,” reflecting Bioastronautics’ human-spaceflight focus. A third grouped “cyanobacteria,” “equivalent system mass,” “extremophiles,” “in situ resource utilization,” “ISRU,” “moon,” “space exploration,” and “synthetic biology,” combining the resource utilization and engineered-biology themes characteristic of Space Bioprocess Engineering. The highest-weighted pairs were, as expected, near-synonymous or tightly linked terms: “in situ resource utilization” with “ISRU” and with “equivalent system mass” (both 0.9999), an aerospace metric combining physical mass with the mass equivalent of energy and resources needed for spacecraft operation (Ho et al., 2022); “cyanobacteria” with “synthetic biology” (0.9997); and “spaceflight” with “weightlessness” (0.9993) and “microgravity” (0.9991).

The quantum-annealing-style reanalysis described above was performed on the full network (Figure 2). Across five independent runs with different random initializations, the analysis consistently produced the same two-community partition (modularity, $Q = 0.195$, for this coarser two-way partition). The keywords “astrobiology,” “extremophiles,” “mars,” “origin of life,” “prebiotic chemistry,” “RNA world,” and “SETI” always formed one stable community, separate from the remaining thirteen keywords associated with the human-spaceflight and resource-utilization themes. This result independently confirms the Astrobiology-themed community identified by the classical Louvain algorithm, providing converging evidence from two different clustering methods that this thematic boundary is robust. However, because the two-community partition has a lower resolution, it combines the Bioastronautics and Space Bioprocess Engineering communities into a single group. Therefore, this analysis is presented as an exploratory illustration rather than a replacement for the higher-resolution Louvain community detection.

Semantic Relationships Among Core Terms

The hierarchical and lateral relationships among key disciplinary labels merit clarification because terminology in this field is not yet fully standardized. “Space life science research” is the broadest umbrella, encompassing questions of life’s origins and its cosmic distribution. “Space biology” sits within this umbrella, concentrating on the measurable biological effects of spaceflight on defined organisms. “Space biosciences” takes a systems-level view, bridging the molecular detail of biology with the operational realities of space exploration. Each of these frames a slightly different set of research questions and

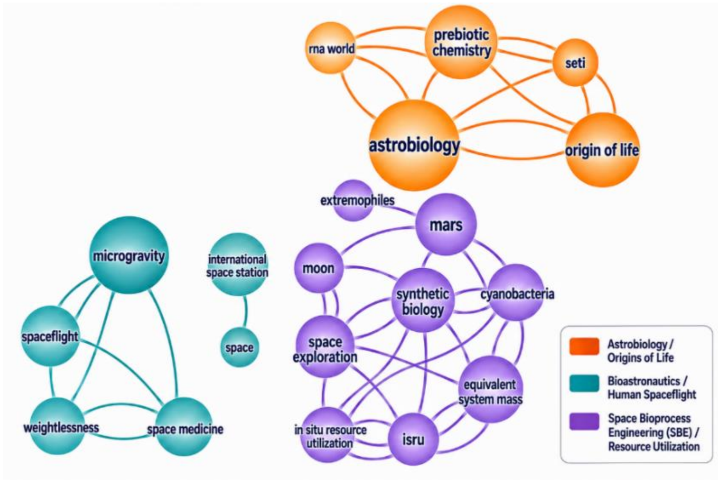

Figure 1. Reconstructed space bioscience keyword network (20 keywords) based on cosine similarity from Table 1. Node size reflects combined keyword prevalence, node color indicates Louvain communities, and only the strongest 18% of edges are shown for clarity.

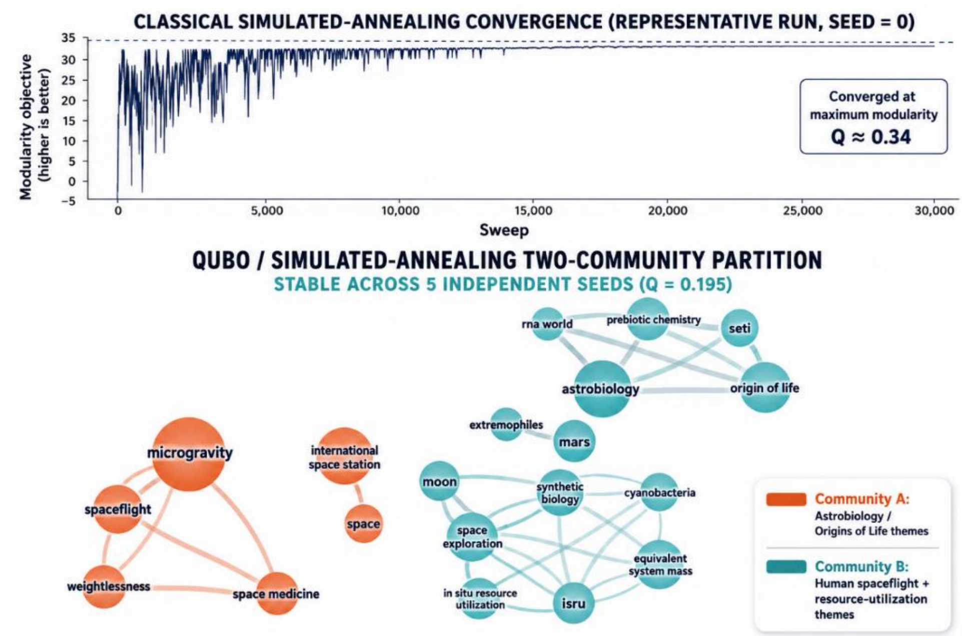

Figure 2. QUBO optimization reveals two major research communities in the space bioscience keyword network.

methodological approaches, and Philippine institutions entering this field would benefit from clarity about which level a given curriculum or research agenda primarily occupies.

Key Findings Across Space Biology Disciplines

Microbiology. A substantial body of spaceflight microbiology has accumulated over the past three decades. Sato (2020) summarizes several replicated findings: microbes reach higher population densities under microgravity than in ground controls; certain bacterial species develop enhanced antibiotic resistance during spaceflight; *Salmonella typhimurium* cultured in space demonstrates greater virulence than ground-grown cultures; microbial biofilms form structurally distinct configurations in microgravity and resist antimicrobials more effectively; and *Candida albicans* activates virulence-associated genes and enters a hyphal growth stage in response to spaceflight conditions.

Cell and Molecular Biology. At the cellular level, microgravity inhibits the Rel/NF-κB signaling pathway during T-cell activation, a finding with direct implications for immune surveillance during long-duration missions. Plant cell vacuoles have been found to operate as independent compartments whose fusion is regulated by phosphoinositides, and a calcium-based signaling mechanism has been characterized that can relay information from root to leaf tip, findings relevant to the design of space agriculture systems. Root waving and skewing movements in plants do not require gravity, suggesting a degree of robustness in plant tropisms under altered-gravity conditions.

Plant Biology. Photosynthesis proceeds normally in microgravity given adequate light, water, and nutrients, an encouraging result for space agriculture. Darwin's theory of circumnutation in plant stems has been validated in spaceflight experiments. However, space-grown plants display increased susceptibility to pathogens, attributable to altered cell wall composition, and red-light-based phototropism in Arabidopsis seedling stems is attenuated at fractional gravity levels (Sato 2020).

Key Research Gaps. Despite substantial progress, significant gaps remain (Sato, 2020): long-duration, multigenerational growth of microorganisms in microgravity is poorly characterized; the effects of spaceflight on viral pathogen dynamics are largely unknown; the mechanisms underlying microgravity-induced immune dysfunction, beyond the T-cell activation finding, require further elucidation; cellular gravity-sensing mechanisms remain incompletely described; long-term cellular and molecular consequences of prolonged spaceflight exposure have not been systematically characterized; and the ability of plants to complete multiple life cycles under altered gravity demands further study. Each of these gaps represents a plausible entry point for new research programs, though the ease of entry will vary considerably depending on the equipment, funding, and international partnerships each requires.

Analog Environments and Their Role in Space Biology

Planetary Analogs

Because spaceflight experiments remain expensive, logistically complex, and rare, analog environments on Earth play an important role in advancing space biology. Foucher et al. (2021) describe the definition and use of functional analogs in planetary exploration, that is, terrestrial environments that approximate one or more key features of extraterrestrial environments (extreme temperature, pressure, radiation, aridity, chemical composition), as useful proxies for studying biological responses that are otherwise difficult to replicate outside actual spaceflight. The Philippines, with its diverse volcanic, hydrothermal, deep-sea, and high-altitude environments, is well positioned to contribute analog research sites for regional and international collaboration, subject to the logistical, funding, and partnership constraints discussed in the Limitations section below.

Ocean Worlds and Hydrothermal Analogs

Arrigo (2022) documents how analog environments relevant to ocean worlds, the ice-covered subsurface oceans of moons such as Europa and Enceladus, are studied to understand the potential for life in environments with limited sunlight, high pressure, and chemical energy sources. Hydrothermal vents, polar sea ice, and anoxic deep-ocean basins serve as terrestrial proxies. Researchers with expertise in extremophile microbiology or marine ecology at Philippine institutions would find plausible entry points into this research area, building on existing marine science strengths.

Space Biology and Human Health: Key Research Findings

Physiological Adaptations to Spaceflight

Long-duration spaceflight produces substantial, well-documented physiological effects. The cardiovascular system undergoes a headward fluid shift that increases intracranial pressure, reduces lower-limb venous return, and alters cerebral hemodynamics during acute microgravity exposure. Lower-limb venous pooling may persist despite exercise and artificial-gravity countermeasures. Neurologically, spaceflight is associated with Spaceflight-Associated Neuro-ocular Syndrome (SANS), characterized by optic disc edema, hyperopic shifts, and choroidal folds resulting from altered intracranial fluid dynamics. Brain fluid drainage and lymphatic function are also affected, hippocampal volume changes have been observed, and cognitive performance, particularly sustained attention and working memory, may be impaired (Yin et al., 2023).

Psychological Effects and Cognitive Impairment

Yin et al. (2023) conducted a systematic review examining how long-term spaceflight composite stress, encompassing microgravity, radiation, isolation, confinement, circadian rhythm disruption, and workload, is associated with depression and cognitive impairment, with insights drawn from neuroplasticity research. Their structural analysis indicates a direct effect of radiation exposure on physiological changes and a strong direct effect of microgravity on physiological changes, both of which in turn are associated with psychological outcomes and long-duration mission performance; psychological effects appear to partially mediate the relationship between physiological change and mission performance. Healthcare delivery showed a moderate direct association with long-duration mission outcomes in their model, a finding that underscores the potential importance of nursing and medical systems in mission planning, though as with any structural model these are statistical associations rather than demonstrated causal mechanisms.

Countermeasures and Technologies

Countermeasure development spans exercise protocols (combined exercise and artificial gravity regimens, evaluations of different exercise modalities, and muscle- and bone-preservation strategies), monitoring systems (wearable technologies, remote health monitoring, telemedicine and teledentistry, and novel imaging techniques), and biological models for mechanistic research (the Astro-fly *Drosophila* model, rodent models of radiation effects, cellular gene expression studies, and anhydrobiotic yeast models for radiation biology). A 2023 workshop organized by the *Centre National d'Études Spatiales* (CNES) and the *Institut de Médecine et de Physiologie Spatiales* (MEDES) identified an integrated, artificial intelligence (AI)-supported onboard health system and individual astronaut digital twins, virtual models that combine physiological, psychological, and behavioral data for continuous monitoring and predictive analytics, as leading near-term priorities for crew health countermeasures during deep-space missions (Martínez et al., 2026). Induced torpor and hibernation-inspired strategies are also being actively studied as a countermeasure against radiation exposure and resource consumption on long-duration missions, an effort formalized through a dedicated ESA Topical Team for Torpor and Hibernation (Martínez et al., 2026).

Radiation Biology

Radiation is one of the two primary hazards of deep-space missions, alongside microgravity. Documented biological effects include gastrointestinal tract injury, systemic genomic alterations, and region-specific brain changes. Countermeasure research includes studies of melanin as a natural radiation shield, a direction of particular relevance given interest in fungal melanins found in radiotrophic organisms, and the development of protective materials; monitoring systems for radiation exposure continue to advance (Dadachova et al., 2007; Averesch et al., 2022; Vasileiou, Summerer, 2020; Caffrey, Hamby, 2011).

An example of the intersection of radiation biology, art, and public science communication is described by Vermeulen et al. (2022): "Ēngines of Ēternity," an artistic inquiry using experiments with bdelloid rotifers (*Adineta vaga*) aboard the ISS, produced data-driven visualizations illustrating how scientific data from space biology can be translated into public-facing artistic forms. Related computational work by Perrot et al. (2024) simulated the impact of radiation on *Adineta vaga*, extending the biological findings through in silico modeling.

Philippine Strengths and Opportunities

Alignment with Existing Expertise

Philippine higher education institutions with established programs in biology already harbor expertise in microbiology, plant biology, cell and molecular biology, and ecology, the very disciplines at the core of space biology. The key transition required is not a wholesale change of research subject matter but a reorientation of research questions: rather than studying biological phenomena purely in terrestrial contexts, researchers would ask *how the same biological systems respond to the conditions of spaceflight (microgravity, radiation, confinement, altered circadian rhythms)* and *what implications these responses carry for both space exploration and Earth-based biotechnology*.

This transition is not purely hypothetical. Philippine-based researchers, working with international collaborators, have already begun contributing to the aerospace health literature. A systematic review coauthored by teams from Our Lady of Fatima University, De La Salle University, and the University of Santo Tomas screened 499 records down to 66 included studies and mapped the current state of aerospace health research using an integrative review framework. The review organized study purposes and outcomes into eight themes (Physiology and Health Risks, Psychology and Behavior, Pharmaceuticals and Interventions, Product and Technology, Profession and Training, Process and Procedures, Place and Environment, and Policy and Strategy) and, through a separate keyword and network analysis, identified six recurring thematic clusters it labeled Health Ecosystem, Health Examination, Health Education, Health Engineering, Health Estimation, and Health Evidence (Dino et al., 2026). The same review found that the field remains overconcentrated on synthesis studies with limited empirical validation and gives insufficient attention to higher-order human health needs, including psychosocial aspects, a gap it framed as a "Maslow's Effect" in which the field has so far prioritized basic physiological and safety concerns over belonging, esteem, and self-actualization. This gap mirrors the priority research areas proposed below and suggests that Philippine institutions already have a foothold from which to expand into empirical space biology research rather than starting entirely from zero. Notably, the review recommends that universities integrate aerospace health into their curricula and establish academic programs for space medicine. These recommendations align with the Phase 1 curriculum development activities proposed in the Structural

Recommendations discussed below (Dino et al., 2026).

Priority Research Areas

Based on the gaps identified in the literature reviewed above, three priority research areas are proposed:

- **Microbial Studies**: antibiotic resistance development under spaceflight conditions; pathogen virulence mechanisms in microgravity; biofilm formation under space conditions, with implications for both crew health and engineered life-support systems.
- **Plant Biology**: crop adaptation to microgravity and altered radiation environments; plant disease resistance in space; nutrient uptake and metabolic processes under altered gravity.
- **Cell and Molecular Biology**: immune-system responses to spaceflight stressors; cellular gravity-sensing mechanisms; long-term cellular adaptation to chronic microgravity and radiation exposure.

Distinctive Niche Opportunities

The network analysis described above shows that resource utilization and engineered biology concepts, including synthetic biology, cyanobacteria-based bioprocessing, and ISRU, already cluster as a single community rather than occupying separate, weakly connected areas of the literature. Philippine researchers could plausibly occupy a distinctive niche by developing ISRU-relevant biological systems using organisms adapted to Philippine environmental conditions, including candidate radiotrophic and extremophile microorganisms from the country's volcanic and hydrothermal environments, building on this already-recognized thematic proximity rather than needing to bridge two disparate research areas, though this remains a conceptual opportunity that would need to be validated through dedicated bioprospecting and characterization studies rather than an established research program.

Roadmap and Institutional Strategy

Cross-disciplinary Integration

Building a meaningful space biology research program will require active cross-disciplinary integration across five domains: AI and machine learning (for data analysis, simulation, and autonomous biological research platforms); advanced materials science (for radiation shielding, bioreactor design, and habitat construction); synthetic biology (for engineering organisms with enhanced resilience to spaceflight stressors); environmental science (for analog-environment characterization and life-support ecology); and bioengineering (for the design and validation of biological closed-loop life-support systems).

Immediate Challenges

Four immediate challenges must be addressed. First, the long-term effects of the space environment on biological systems remain incompletely characterized, meaning that researchers entering this field will need to engage with a rapidly evolving evidence base. Second, integrating AI with biological experiments, that is, designing systems that can autonomously monitor, adjust, and respond to biological processes in space, requires interdisciplinary training bridging biology, computer science, and engineering. Third, developing autonomous biological research platforms (biorobots, closed bioreactors, AI-monitored culture systems) demands investment in both hardware and software expertise. Fourth, scaling space-based biological manufacturing from proof of concept to operationally relevant deployment remains an unresolved engineering and biological challenge.

Future Opportunities

Future opportunities span both applied and basic science: commercial space biology ventures producing high-value biologics under microgravity conditions; drug discovery leveraging the distinctive protein crystallization and cellular behavior patterns observed in microgravity; advanced materials development using biologically produced polymers, composites, and structural materials; and sustainable space-habitat technologies, including closed biological life-support systems capable of supporting human communities on long-duration missions.

Major Future Research Directions

- **Biological Manufacturing**: space-based production of pharmaceuticals, materials, and other high-value products using microgravity conditions, which alter protein folding, crystal formation, and cellular behavior in ways that can yield bioproducts with superior purity or yield compared to ground-based production.
- **Advanced Life Support**: development of self-sustaining biological systems for long-duration space missions, including closed-loop systems that recycle waste, produce food and oxygen, and support crew psychological health through interaction with living organisms.
- **Genetic Adaptation**: understanding and engineering organisms for space environments, encompassing directed evolution, synthetic biology approaches, and CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats)-based interventions aimed at enhanced radiation resistance, microgravity tolerance, and metabolic efficiency.
- **Radiation Protection**: developing biological solutions for radiation shielding and repair. Radiotrophic fungi, melanin-based shields, and DNA-repair-enhancement strategies represent a promising suite of approaches, with Philippine biodiversity assets as a potential resource base.
- **Terraforming Technologies**: using biological systems for planetary habitat modification, including cyanobacteria-based oxygen production, soil formation through microbial weathering, and plant-based ecosystem bootstrapping.
- **Induced Torpor and Metabolic Depression**: understanding the physiological and molecular basis of hibernation-like states in mammals, with potential application as a countermeasure for radiation exposure, resource consumption, and psychological strain on long-duration missions. This is a young but internationally prioritized research area, and though the Philippines lacks native hibernating mammals, comparative physiological research on local species capable of torpor-like metabolic depression, such as some bat species, could offer a modest entry point into this literature (Martínez et al., 2026).

Potential Applications and Immediate Impact

Applications that could plausibly be pursued with existing infrastructure at capable Philippine institutions include: space agriculture research building on existing plant biology capabilities; biomanufacturing studies using ground-based clinostat and random-positioning-machine analogs before seeking access to real spaceflight platforms; disease-prevention and drug-development work leveraging the altered virulence and cellular behavior documented in spaceflight microbiology; and closed-loop life-support system design, drawing on existing ecology and environmental science expertise. International experience suggests such investments carry near-term ground value beyond the space application itself:

space-derived telemedicine and portable AI-assisted diagnostic tools have been proposed for adaptation to underserved and disaster-affected areas, and multi-sensory well-being environments developed for astronauts have been proposed for use in hospitals, elder care, and other high-stress settings, illustrating the kind of dual-use benefit Philippine institutions could similarly target (Martínez et al., 2026).

A Transdisciplinary Pathway

Space biology cannot be owned by any single discipline. Its questions are inherently interdisciplinary, requiring biology, physics, chemistry, engineering, medicine, psychology, and increasingly the social sciences and humanities. A transdisciplinary framework goes one step further: it integrates not just multiple academic disciplines but also non-academic knowledge systems, practical stakeholder expertise, and real-world applications. For Philippine higher education institutions to develop a meaningful and sustainable space biology program, this broader orientation is likely to be necessary rather than optional.

Disciplinary Contributions to the Framework

Engineering. The development of life-support systems, bioprocessing hardware, habitat technologies, and spacecraft subsystems that interact with biological payloads. Philippine engineering departments can contribute modular bioprocessing and embedded-systems design expertise.

Medicine. Research on the medical challenges of spaceflight, including disease prevention under the suppressed immunity of microgravity, emergency medical response in isolated environments, pharmacokinetics in altered gravity, and the development of space pharmacovigilance systems.

Nursing. Applying established nursing theories to the challenges of altered gravity and prolonged isolation. The theories of Martha Rogers (Science of Unitary Human Beings) and Florence Nightingale (Environmental Theory) offer conceptual frameworks for understanding how altered environments affect human health and well-being in space. Rivera et al. (2024) describe a growing case for formal nurse roles in space operations, encompassing health monitoring, crew psychological support, and telemedicine. Data sonification, which converts multidimensional physiological datasets into auditory representations, is one methodological tool that could be adapted for space biology research and patient monitoring; Hernandez (2024) proposes one such “aerospace nursing metaparadigm model” as an illustrative framework, though it has not yet been empirically validated in a spaceflight or analog setting. International precedent for this direction already exists: a CNES and MEDES expert workshop identified individual and collective behavioral health monitoring, together with AI-supported digital twins combining physiological, psychological, and behavioral data, as priority areas for crew health support on deep-space missions, lending plausibility to a nursing role built around similar continuous, multidimensional monitoring (Martínez et al., 2026).

A wave of recent nursing scholarship reinforces that “aerospace nursing” is an actively consolidating specialty rather than a purely speculative one. A PubMed-based historical mapping review of aerospace nursing literature from 1946 to 2025 traced the field’s evolution from survival-focused aeromedical transport care toward habitation-oriented support for longer-duration and civilian missions, and found that the literature has historically been dominated by a medical model centered on physiological survival and emergency response rather than nursing’s more holistic model of care, a gap the roadmap proposed here is intended to help address (Kubota et al., 2026). Complementary scoping work has begun to map the specific knowledge, skills, and attitudes nurses need for spaceflight contexts (Braga et al., 2026), while system-specific reviews, such as one examining the spaceflight-altered respiratory system from a nursing perspective, illustrate how existing critical care nursing expertise can be extended to spaceflight-specific physiological changes (Mampre et al., 2025). A broader literature analysis of 45 studies published between 1975 and 2024 organized this evidence around four objectives directly relevant to the roadmap proposed here: identifying clinical and operational challenges, evaluating required skills and training, assessing nurses' roles in crew well-being and safety, and informing curriculum development for aerospace nursing education (Hernandez, 2025).

Development Communication. Creating evidence-based strategies to communicate space biology research findings to the public, policymakers, and funding bodies, a capacity relevant for sustaining the long-term political and financial support that a nascent Philippine space biology program would require.

Arts. Using artistic expression, including data visualization, data sonification, installation art, and science communication media, to engage public interest in space biology. The Ēngines of Ēternity project (Vermeulen et al., 2022) exemplifies how biological data from spaceflight experiments can become the raw material for publicly resonant art that communicates scientific findings and helps build support for the discipline.

Structural Recommendations

Phase 1: Foundation Building. Establish a dedicated space biology working group; develop and pilot an introductory space biology course; initiate analog-environment studies using Philippine extreme environments; and build bilateral relationships with established space biology programs abroad through academic exchange and co-authorship.

Phase 2: Research Capability Development. Acquire ground-based microgravity simulation equipment (clinostats, random positioning machines); establish a culture of interdisciplinary space biology seminars; submit to international funding calls; and recruit cross-disciplinary graduate students.

Phase 3: International Engagement. Pursue access to spaceflight platforms through CubeSat and ISS research mechanisms; establish formal partnerships with relevant national agencies, including for radiation-biology research; develop intellectual property and commercialization pathways for space-derived bioproducts; and work toward becoming a recognized center for space biology education and research in the Philippines.

The roadmap proposed in Figure 3 gains additional near-term relevance from a national development external to this review: in his fifth State of the Nation Address (SONA) on July 27, 2026, President Ferdinand R. Marcos Jr. announced a sounding rocket launch test from Cagayan in 2027, undertaken in partnership with a South Korean aerospace company and positioning the province as the country's planned first spaceport (CNBC-TV18 2026). The bilateral technology-transfer and training arrangement underlying this effort offers a national-scale precedent for the academic exchange partnerships proposed in Phase 1, while a future domestic launch capability could, in time, support Phase 3's goal of Philippine-based access to spaceflight platforms rather than reliance on foreign launch providers alone. This development is properly understood as engineering and launch-infrastructure progress rather than a life-science commitment, and its significance for the roadmap proposed here lies chiefly in the favorable political momentum and public visibility it lends to space activity in the Philippines, not in any direct alignment with space biology research.

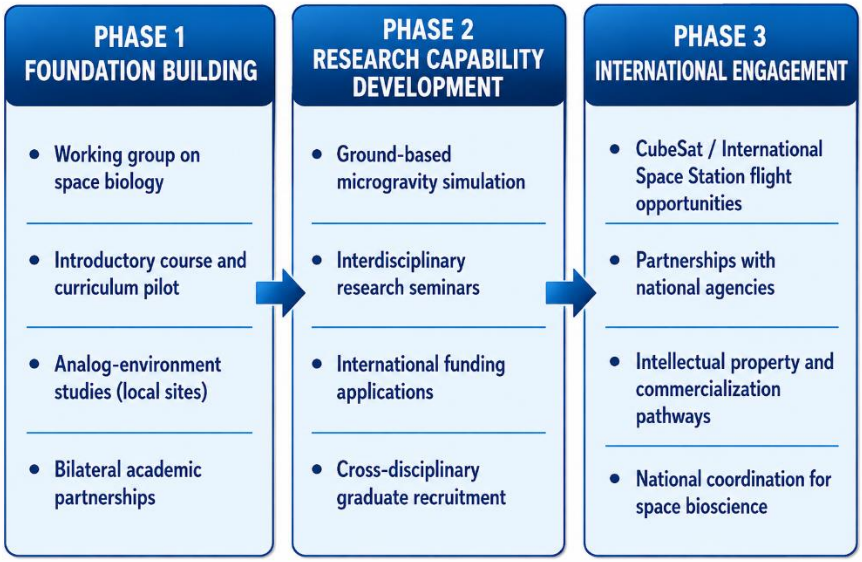

Figure 3. Strategic roadmap for developing institutional capacity in space biology research across Philippine higher education institutions.

NASA ISS Utilization Opportunities Relevant to Curriculum and Training Pipeline Development

NASA's Research Opportunities for International Space Station Utilization solicitation offers concrete reference points for a Philippine space biology training pipeline. It traces the ISS National Laboratory concept to the 2005 NASA Authorization Act, which directed NASA to broaden non-NASA utilization of the station (NASA, 2026). NASA already offers a no-fee Spaceflight Technologies, Application, and Research (STAR) Program course on the effects of microgravity on biosciences investigations, a resource that could inform the introductory course proposed for Phase 1 of the roadmap (NASA, 2026). Its Focus Area 6, seeking next-generation DNA and RNA sequencing capability aboard the ISS, signals growing demand for genomics expertise relevant to the priority research areas identified above (NASA, 2026). The solicitation also lists university-affiliated business and policy programs (Arizona State University's Thunderbird School, Embry-Riddle's Space Operations Management program, and Oxfor's Said School of Business Space Initiative) that model the transdisciplinary training envisioned above (NASA, 2026).

A realistic funding constraint applies: foreign entities, including Philippine institutions, are not eligible for direct NASA funding and are expected to participate on a no-exchange-of-funds basis. NASA funding also cannot be used to support subcontracted research by non-U.S. organizations, although the direct purchase of non-research supplies is permitted (NASA, 2026). Philippine institutions implementing the Phase 2 activities described above should therefore expect early NASA engagement to take the form of no-cost collaboration, while reserving direct funding efforts for agencies that permit international participation or for cost-sharing through a sponsoring U.S. partner.

Limitations

Several limitations should be kept in mind when interpreting this review. First, the literature synthesis is a narrative rather than a systematic review: sources were selected purposively around a small number of anchor publications rather than through a pre-registered, exhaustive search protocol, and the paper does not report the number of records screened, included, or excluded. Second, the network analysis described above is a secondary re-analysis built directly and reproducibly from Table 1 of Berliner et al. (2024) using an explicitly stated method described earlier, and it inherits any limitations of that underlying table, most notably that it reports only the 20 keywords with the highest combined prevalence and their prevalence within each of three discipline corpora rather than pairwise co-occurrence counts within individual publications; the cosine-similarity edge weights used here are accordingly a documented proxy for thematic association rather than a direct measure of how often two keywords appeared together in the same paper. The related quantum-annealing-style re-analysis is, by the same token, an illustrative application of an alternative computational approach on this proxy network rather than a validated method, particularly given the small and preliminary literature on quantum approaches to bibliometric analysis. Third, several conclusions in this review, particularly those identifying “distinctive niches” or “underexplored” opportunities for Philippine institutions, are conceptual and speculative rather than empirically demonstrated; they are intended as hypotheses to guide future investigation rather than established findings. Fourth, the proposed roadmap was developed through the author’s own conceptual synthesis rather than through consultation with Philippine institutional stakeholders, funding agencies, or a structured prioritization exercise, and its feasibility, sequencing, and resource requirements would benefit from validation by the institutions expected to implement it. Finally, because this is a review and roadmap paper rather than a report of original experimental or field data, its claims about the Philippines’ comparative advantages in space bioscience remain to be tested empirically.

CONCLUSION AND RECOMMENDATIONS

This review has summarized current concepts and trends in space biology, examined their relevance for Philippine higher education institutions, and proposed a transdisciplinary roadmap for developing space biology research and education capacity in the country. The picture that emerges is of a field that is mature enough to offer identifiable entry points for new participants, while remaining dynamic enough that even institutions with modest resources could make original contributions, provided the limitations noted above are addressed as the work progresses.

Several strategic considerations deserve emphasis, offered here as hypotheses for further investigation rather than settled conclusions. Philippine extremophile and radiotrophic microorganisms, found in the country’s volcanic, hydrothermal, and deep-marine environments, represent a potentially underexplored reservoir of candidate organisms for space bioscience applications, particularly radiation protection and ISRU, pending dedicated bioprospecting studies. The Philippines’ large and globally distributed nursing workforce could plausibly support the development of aerospace nursing as a subspecialty, though this would require formal curriculum development and validation of proposed frameworks such as the one discussed above. Growing national capacity in computational biology, bioinformatics, and access to cloud-based AI and quantum computing platforms suggests that Philippine researchers could contribute to space biology through simulation, modeling, and secondary analysis of existing spaceflight datasets even without direct access to spaceflight platforms.

Space biology need not be treated as a distant specialty reserved for established spacefaring nations. It is a young and developing field in which the specific knowledge assets of the Philippines, namely biodiversity, nursing expertise, computational capacity, and a globally connected overseas scientific community, could plausibly support meaningful contributions, subject to the validation, resourcing, and stakeholder engagement this review has flagged as still needed. For future work, three practical next steps are recommended: (1) convert the priority research areas identified above into pilot studies with defined, achievable scopes suited to current institutional capacity; (2) engage relevant Philippine institutions, agencies, and funding bodies in validating and refining the proposed roadmap before it is treated as an implementation plan; and (3) pursue at least one international partnership or funding application in the near term to test the practical feasibility of the phased strategy proposed above. The roadmap proposed here is offered not as a rigid prescription but as a starting framework for the conversations within Philippine higher education, across national agencies, and with international partners, that will shape the country's future engagement with space biology.

ACKNOWLEDGMENT

The author gratefully acknowledges Dr. Inocencio E. Buot Jr., Professor Emeritus of Botany, Ecology, and Environmental Science, Institute of Biological Sciences, College of Arts and Sciences, University of the Philippines Los Baños (UPLB), for his openness to engage in this endeavor and for his support in conceptualizing a proposed special topics course on space biology within the Institute's curriculum. The author also thanks the Institute of Biological Sciences (IBS), College of Arts and Sciences (CAS) at UPLB, for hosting the first "Forum on Space Biology" on December 18, 2024, at which this work was presented.

CODE AVAILABILITY

The Python scripts used to construct and analyze the secondary keyword network described above (network construction and Louvain community detection; the classical simulated-annealing QUBO re-analysis), together with their corresponding output data files (table1_network_results.json and qubo_full_network_results.json), are openly available at https://github.com/jphernandezrn/space-bioscience-keyword-network. The analysis was developed and run using Python 3.12.3, with NetworkX 3.6.1, NumPy 2.4.4, and Matplotlib 3.10.8 as the principal dependencies.

STATEMENT OF AUTHORSHIP

The author confirms sole responsibility for the following: conceptualization and design of the review, literature synthesis and secondary network analysis, development of the proposed roadmap, and preparation of the final manuscript.

DECLARATION OF ORIGINALITY AND ETHICAL COMPLIANCE

The author declares that this manuscript is an original work, has not been previously published, and is not under consideration for publication elsewhere, in whole or in part. This paper is a narrative review and conceptual roadmap; it does not report new data collected from human participants or animal subjects, and therefore did not require review by an institutional ethics review board or institutional animal care and use committee. The secondary network analysis described above reuses publicly available data, specifically Table 1 of Berliner et al. (2024), which is distributed under a Creative Commons Attribution 4.0 International (CC BY 4.0) license, with full attribution provided in-text and in the reference list; no new primary data were generated beyond the derived analysis outputs documented in the Code Availability section. The author declares no known conflicts of interest and affirms that the manuscript, including all cited sources, is free from plagiarism and any other ethical concerns, in accordance with the editorial policies of the Journal of Nature Studies.

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