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Life In Space, Beyond Earth: Habitability In Question – Between Astrobiology and Aerospace Medicine

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Abstract: The search for life beyond Earth and the possibility of human habitation in space constitute significantly interdisciplinary scientific challenges, especially involving astrobiology and aerospace medicine. Astrobiology investigates the conditions of the emergence of life on Earth and the possible existence of living beings on other worlds, with emphasis on habitability studies for biosignature detection. Aerospace medicine focuses on the physiological and psychological impacts that the space environment, marked by cosmic radiation, microgravity, and confinement, among other aspects, imposes on human beings. This article aims to analyze the contributions of these fields to the contemporary debate on the habitability of extraterrestrial celestial bodies. For these means, an integrative literature review was carried out based on descriptors selected from DeCS, which, when combined, were used for the bibliographic search in PubMed. Twenty-nine articles were selected to compose this current manuscript, whose information was organized into three topics in the Results and Discussion section: (i) "Astrobiology and habitability," (ii) Aerospace medicine and habitability; and (iii) "Syntheses: Life sciences in search of space colonization." The convergence between these disciplines, their integration of knowledge, from identifying potentially habitable exoplanets to ensuring astronaut health, is fundamental to enabling long-duration missions and future space colonization, transforming human activity in the cosmos from a fictional possibility into a sustainable scientific reality, based on collaboration and transdisciplinary innovation.

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1. Introduction

History of humanity is marked by successive revolutions in the way of thinking/acting, from the comprehension of one's own place in the universe to the means by which *Homo sapiens* became conscious of reality, and more than that, self-conscious. From the mastery of fire in prehistory to the space probes of the 20th and 21st centuries, knowledge regarding the stars and Planet Earth has been consolidated. The Greeks used geometry to make the first measurements of the Sun, Earth, and Moon, and precise instruments in the 17th century overturned ideas about the Earth's formation in the cosmos (Sidoli, 2018). The telescope revealed new mysteries to be explored by Newton's theory of gravitation, and later, Einstein's Theory of General Relativity transformed the understanding of reality, revealing that gravity is not just a force, but a curvature of spacetime caused by the presence of mass (Einstein; Infeld, 2017; Siqueira-Batista; Helayël-Neto, 2021). The technique of spectroscopy paved the way for the study of the properties of stars, which ultimately revealed the existence of other galaxies and the expansion of the universe.

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The events briefly mentioned contributed, in one way or another, to the human space adventure, whose milestone was Yuri Gagarin's historic flight in 1961. In a coordinated manner, unmanned probes explore the Solar System, revealing the secrets of planets, comets, and the Sun itself, and satellites provide everyday services, such as weather forecasts and global connections, essential as the energy that lights our homes (Tasker, 2017; Mason, 2008; Pessoa Filho, 2021). This orbital network already moves trillions of dollars, driven by visionary entrepreneurs who promise to saturate the skies with thousands of new devices, taking internet to remote regions and paving the way for colonizing Mars (Tasker, 2017; Pessoa Filho, 2021). The greatest challenge, however, is not technical. In a world fragmented by rivalries, only unprecedented collaboration will allow humanity to transcend its borders – not as a refuge from a planet in crisis, but as proof of the union of forces to preserve the cosmic home and, who knows, to build others to come (Pessoa Filho, 2021).

The identification of the first planet outside the Solar System, PSR *1257+12 b* (named *Poltergeist*) in 1992, orbiting a neutron star (Wolszczan; Frail, 1992), was a historic milestone in astronomy (Ksanfomaliti, 2000). Nevertheless, the true "explosion" of exoplanet discovery occurred from 1995 onwards, when Mayor and Queloz described the exoplanet 51 *Pegasi b*, a Jupiter-like celestial body orbiting a Sun-like star (Mayor; Queloz, 1995). The work, published in *Nature*, opened a new scientific chapter, showing that other planetary systems are much more common than previously thought.

The search for exoplanets has benefited greatly from advances in astronomical observation. The Hubble Space Telescope, with its 2.4-meter mirror, has obtained valuable information on the subject. Yet, the advent of the James Webb Space Telescope (JWST), whose mirror reaches 6.5 meters (Gianopoulos; Dunbar, 2022), promises the description of significant data on other worlds beyond the solar system. In fact, the JWST, launched in December 2021, possesses infrared observation capabilities, allowing the study of exoplanet atmospheres, identification of chemical compounds, and even determination of their temperatures and pressure (Coelho, 2022). Thanks to the JWST, scientists can now investigate the atmospheric composition of planets like WASP-96 b, revealing the presence of molecules such as water, sodium, and potassium (Taylor, 2023). These descriptions not only enrich the understanding of the formation and evolution of planetary systems but also assist in the search for evidence of alien life.

Human space activity has a significant interface with the search for life beyond Earth, one of the most intriguing scientific issues nowadays, which concerns the concept of habitability. In the astrophysical context, habitability refers to the set of characteristics that allow a rocky planet to support life (Kopparapu; Wolf; Meadows, 2019). This does not mean that the planet already harbors life or that it has all the necessary conditions. Habitability, traditionally anchored in terrestrial conditions, expands by considering possibilities that go beyond the known model, integrating a multidisciplinary approach that encompasses astrophysics, geology, chemistry, and biology.

In this context, astrobiology – an interdisciplinary field that combines different areas of science – seeks to understand the conditions necessary for life to emerge and persist on other worlds (GALANTE Et Al. 2016). Astrobiological studies are in a highly dynamic and advanced phase, with significant progress on several fronts, from the search for other worlds on which life might exist (Lipunov, Tarasenkov, Kuznetsov, 2024) to understanding the limits of habitability and the potential for microbial life in extreme environments on Earth and other planets (Airo; Hauber; Van Gasselt, 2023), (Henin, 2024). Simultaneously, aerospace medicine – a multidisciplinary area of knowledge that integrates medicine, physics, chemistry, and aeronautical engineering, studies and mitigates the effects of the aeronautical and space environment, such as low oxygenation, reduced humidity, radiation, noise, time zone changes, and decompression risks on the human body, ensuring the health and safety of crew members, passengers, and astronauts (Sbma, 2024) – supports and investigates the possibilities of habitability of *Homo sapiens* in different contexts, particularly when considering the effects of space travel on human health (Carvalho-E-Silva Et Al. 2023), which provides valuable insights for future manned missions to planets such as Mars (Krittanawong Et Al. 2023).

Based on these preliminary considerations, this article analyzes the possibilities for contributions from astrobiology and aerospace medicine to the current debate on the habitability of celestial bodies beyond Earth.

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2. Methods

2.1. Types of Study

This is bibliographic research of the integrative literature review kind that seeks to organize and summarize research conducted on a defined topic. Souza, Silva, and Carvalho (2010, p. 105) note that "the integrative review has been pointed as a unique tool (...), as it synthesizes available research on a given topic and guides scientific knowledge-based practice."

2.2. Search Strategy

Initially, terms were selected from DeCS (Health Science Descriptors – https://decs.bvsalud.org/), relating "Habitability"; "Aerospace Medicine"; "Astronauts"; "Extraterrestrial Environment"; "Astrobiology"; "Habitability"; "Health" and "Space Flight." These descriptors were combined into search strategies, which were used for the search on PubMed's online library (https://pubmed.ncbi.nlm.nih.gov/), as shown in Table 1 below:

Table 1: Search strategy applied to the literature review in the online library PubMed and its related results.

Search strategy	Number of citations
(Habitability) AND (Aerospace Medicine)	**54**
(Habitability) AND (Astrobiology)	**704**
(Habitability) AND (Astronauts)	**106**
(Habitability) AND (Extraterrestrial Environment)	**476**
(Habitability) AND (Health)	**750**
(Habitability) AND (Space Flight)	**338**
TOTAL	**2428**

Search end date: June 30, 2025

Source: Prepared by the authors

2.3. Characteristics, Selection Criteria, Exclusion/Inclusion of Articles

In order to include articles in this current study, their relevance was verified against the following criteria: manuscripts that presented habitability in their composition, alluding to extreme environments, aerospace medicine, and/or space health, and articles published in Spanish, French, English, and Portuguese. These manuscripts were read in full in order to obtain significant information. Articles that did not meet any of the inclusion criteria were excluded, as well as manuscripts that did not address the topic of habitability.

The studies were selected based on the following inclusion criteria: i) being the original article (prepared with experimental data and/or constructed as an essay); ii) discussing aspects of planetary habitability and possible habitable planets; iii) relating extreme environments with habitability; iv) relating aerospace medicine with planetary habitability. The exclusion criteria were: i) not being the original article (dissertations, theses, abstracts, letters to the editor; literature reviews were included, exceptionally, when they contained new insights on the issue at hand); and ii) not addressing or relating some of the central elements of this study, such as planetary habitability, astrobiology, and aerospace medicine; v) not presenting current scientific perspectives on the theme. Furthermore, articles published in Spanish, French, Italian, English, and Portuguese were selected.

3. Results and Discussion

The application of the search strategy resulted in the recovery of 2,428 citations (Table 1). Duplicates and articles not relevant to the objective of this manuscript were removed, as after reading the titles and abstracts, their inadequacy to the topic was demonstrated. Continuously, the full texts were read, selecting – original review – articles that contained substantive information on the approach of planetary habitability in the context of astrobiology and aerospace medicine. In the end, 29 articles were obtained, which were utilized for systematizing the results and discussion (Table 2), as discussed in the table below.

Table 2. Summary of studies used in literary review

AUTHORS	YEAR	TITLE	OBJECTIVE	CONCLUSION
Mota et al.	2025	How habitable are m dwarf exoplanets? modeling surface conditions and exploring the role of melanins in the survival of *Aspergillus niger* spores under exoplanet-like radiation	To model the surface conditions (temperature and radiation) of M dwarf exoplanets and experimentally test the survival of fungal spores to simulated radiation, focusing on the protective role of melanin.	Proxima b and TRAPPIST-1 are the most likely candidates to have habitable surface conditions. *Aspergillus niger* spores can survive stellar superflares if protected by a Mars-like atmosphere or a thin soil/water layer. Melanin-rich solutions significantly increase spore survival and germination, highlighting the multifunctional role of this pigment in the potential habitability of exoplanets.
Porterfield et al.	2025	Critical investments in bioregenerative life support systems for bioastronautics and sustainable lunar exploration	To analyze NASA and CNSA's lunar exploration plans, highlighting strategic gaps in the U.S. bioregenerative life support systems (BLiSS) and providing recommendations for recovering competitiveness.	China (CNSA) has taken the lead in developing BLiSS, adapting and advancing programs that NASA abandoned. The U.S. faces a critical capability gap that poses a strategic risk. Investments in protoflight habitats, biophysical research, omics systems, and international cooperation are urgently needed to enable long-duration lunar missions.
Cockell et al.	2024	The concept of life on Venus informs the concept of habitability	To discuss how habitability limits are defined, using the clouds of Venus as an example to explore empirical and theoretical criteria for habitable environments.	The most reliable assessment of habitability should be based on already *known* (empirical) biological limits. Nevertheless, speculation about alternative biochemistries is valid to broaden our understanding.
Doran et al.	2024	The COSPAR planetary protection policy for missions to Icy Worlds	To review COSPAR's planetary protection policy, focusing on icy worlds in the outer Solar System, such as Europa, Enceladus, and others. To discuss the risks of terrestrial contamination on these celestial bodies and to propose updated guidelines to protect potential habitats for life.	The work suggests clear scientific parameters, such as minimum temperature and water activity thresholds to support life. It is recommended to revise COSPAR's current policy, incorporating new discoveries about the habitability of these bodies, as well as to emphasize that any return of samples to Earth from these worlds be done with extreme caution, aiming to preserve both the extraterrestrial environments and our own.
Lammer, Scherf and Sproß	2024	Eta-Earth revisited i: a formula for estimating the maximum number of Earth-like habitats	To propose a formula to estimate the maximum number of Earth-like habitats in the galaxy, considering atmospheric and biological	The formula developed minimizes speculative assumptions and prioritizes quantifiable factors (such as atmospheres with N_2-O_2 and CO_2 limits). The existence of

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	2024		parameters essential for complex aerobic life.	Earth-like habitats depends on complex conditions, such as stable geochemical cycles and biosphere-atmosphere interactions. Future observations of exoplanets will assist in refining the calculations.
Lemos et al.	2024	Beyond earth: harnessing marine resources for sustainable space colonization	To explore how marine organisms (algae, microorganisms, invertebrates) and ocean-derived compounds can be used to enable life support systems, food production, pharmaceuticals, biomaterials, and radiation protection in space colonies.	An integration of marine resources with space biotechnology is essential for sustainable colonization. Systems inspired by marine ecosystems, such as microalgae cultivation for oxygen and waste treatment, reduce dependence on terrestrial supplies. Collaboration between marine science and space agencies paves the way for innovation in long-term missions to the Moon and Mars.
Rodriguez et al.	2024	A geological and chemical context for the origins of life on early Earth	To comprehensively review the geology and chemistry of early Earth to understand the contexts that enabled the emergence of life.	Early Earth offered a diversity of environments and chemical processes favorable to the origin of life. The interaction between oceans, atmosphere, and Earth's crust would have created the energy gradients and organic compounds necessary for complex molecules to form.
Sarma and Shelhamer	2024	The human biology of spaceflight	To explore how human biology, based on evolutionary theories and biocultural approaches, can improve spaceflight research.	The integration of evolutionary perspectives and mixed methodologies is essential for understanding human adaptation to space, aiming for safe and sustainable interplanetary missions, besides modeling other extreme environments.
Scherf, Lammer and Sprog	2024	Eta-Earth Revisited II: deriving a maximum number of Earth-like habitats in the galactic disk	To estimate the maximum number of Earth-like habitats (EHs) in the Milky Way, considering quantifiable stellar and planetary parameters.	Earth-like habitats are relatively rare, with up to ~10^5 planets capable of sustaining N_2-O_2 atmospheres. Complex life or extraterrestrial intelligence would be even rarer, invalidating the application of the Copernican Mediocrity Principle.
Styczinski et al.	2024	Assessing habitability beyond Earth	To review the requirements for habitable environments and to evaluate Solar System bodies (such as Mars, Venus, and icy moons) and exoplanets.	The search for life requires multidisciplinary data synthesis. Bodies like Europa and Enceladus are promising, and exoplanet studies assist in contextualizing cosmic habitability.
Gaza et al.	2023	The importance of time-resolved	To develop and validate the *Crew Active*	The CAD has demonstrated effectiveness in providing

		personal dosimetry in space: the ISS Crew Active Dosimeter	*Dosimeter* (CAD), a portable dosimeter for real-time monitoring of radiation exposure for astronauts on the International Space Station (ISS), replacing passive devices and ensuring safety on long-duration missions.	accurate and continuous radiation exposure data on the ISS, with results comparable to instruments such as the RAD and REM2. Its autonomy, low power consumption, and telemetry capabilities make it crucial for future lunar missions (Artemis) and beyond, protecting crew health in complex radiation environments.
Malaterre et al.	2023	Is there such a thing as a biosignature?	To critically review the concept of "biosignature" in astrobiology, highlighting ambiguities and challenges in its definition and use, as well as to propose recommendations to improve clarity and scientific communication.	The term "biosignature" is useful, but it carries much ambiguity. The authors recommend caution in its use, emphasizing the need for explicit definitions and critical questions to avoid false certainties. Clear communication between disciplines and with the public is essential, especially in research into extraterrestrial life, where misinterpretations can generate confusion or unrealistic expectations.
Olsson-Francis et al.	2023	The COSPAR Planetary Protection Policy for Robotic Missions to Mars: a review of current scientific knowledge and future perspectives	To review and update planetary protection policies for Mars missions, considering new scientific data, contamination risks, and the current space exploration landscape.	COSPAR policy should evolve based on new knowledge about Martian conditions (such as radiation and microbial transport). Global cooperation is essential, as are flexible approaches to balancing planetary protection and sustainable exploration.
Wordsworth et al.	2023	Self-sustaining living habitats in extraterrestrial environments	To explore the feasibility of self-sustaining biological habitats in space, overcoming challenges such as pressure, temperature, and radiation, and how this would impact human life and astrobiology.	Biogenic habitats are viable using existing biological materials and can maintain habitable conditions between 1 and 5 AU in the Solar System. This not only supports human expansion into space but also broadens the search for extraterrestrial life.
Wandel	2023	Habitability and subglacial liquid water on planets of M-dwarf stars	To expand the traditional concept of the habitable zone by considering the possibility of subglacial liquid water on planets around M dwarf stars.	Basal melting of ice by geothermal heat or tidal heating can generate subglacial oceans on planets outside the classical habitable zone, especially around M dwarfs. This significantly expands the estimated number of potentially habitable worlds. Furthermore, the ice cover offers protection from intense stellar radiation, which would make these

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				environments even more conducive to the emergence and maintenance of life.
Marazziti et al.	2022	Space missions: psychological and psychopathological issues	To explore the psychological and psychopathological risks of space missions, including the effects of microgravity, radiation, and isolation.	Space missions pose significant mental health risks, such as cognitive changes and depression. It is urgent to develop preventive strategies and create a field of space psychology/psychiatry.
Michael Marge	2022	Preparing individuals with disabilities for space travel and habitation	To propose a research program to ensure accessibility and safety for individuals with disabilities in space travel and habitation.	Including individuals with disabilities in the development of space research and initiatives is crucial. Research projects focused on biomedical risks, training, and technical adaptations are essential to enable their safe participation.
Mitton	2022	A short history of panspermia from antiquity through the mid-1970s	To review the history of the idea of panspermia – the hypothesis that life (or its precursors) may have come from space – from antiquity to the mid-20th century.	Panspermia has traveled a fascinating path from a philosophical hypothesis to a plausible and testable scientific field. By tracing ideas from Anaxagoras, through Epicurus, Giordano Bruno, to 20th-century scientists, the author shows how the notion that life may have a cosmic origin was refined over time. This historical legacy assists in situating modern astrobiology within a continuum of ideas about life in the universe.
Tovy H. Kamine et al.	2022	Spatial volume necessary to perform open appendectomy in a spacecraft	To determine the minimum volume required to perform an open appendectomy in a spacecraft and compare it with existing habitable volumes.	It is technically feasible to perform the procedure in a spacecraft such as the Soyuz (4 m^3), but the required unobstructed volume (2.87–4.3 m^3) requires planning. Microgravity and operational adaptations still need to be investigated.
Avila-Herrera et al.	2020	Crewmember microbiome may influence microbial composition of ISS habitable surfaces	To investigate how the astronauts' microbiome influences the surfaces of habitable environments on the International Space Station (ISS).	The astronauts' skin microbiome is similar to that of the surfaces of habitable environments on the ISS. The diversity of salivary microorganisms decreases during flight, highlighting the importance of microbial monitoring for long-duration missions.
Carrier et al.	2020	Mars extant life: what's next? conference report	To discuss strategies and priority environments for the search for extant life on Mars, focusing on	Caves, deep subsurface, ice, and salts are promising environments for harboring microbial life. Advanced robotic missions with sample return for more

			refuges ("oases") and detection methods.	sensitive analysis are needed. Experiments in extreme environments on Earth (such as caves and permafrost) assist in guiding the search on Mars. The search for life on Mars remains relevant and viable.
Higgins e Cockell	2020	A bioenergetic model to predict habitability, biomass and biosignatures in astrobiology and extreme conditions	To present the NutMEG computational model, which estimates the habitability of extreme environments, including exoplanets, based on available energy, nutrients, and minimum requirements for life.	The NutMEG model can reliably predict microbial behavior based on bioenergetic data. This provides a useful tool for assessing the theoretical habitability of extraterrestrial environments.
Makuch, Heller and Guinan	2020	In search for a planet better than Earth: top contenders for a superhabitable world	To investigate whether there are planets more suitable for life than Earth ("superhabitable") and identify candidates among known exoplanets.	Twenty-four superhabitable planet candidates have been identified, primarily orbiting K dwarf stars. These worlds may have ideal conditions, such as an age between 5-8 billion years, a mass up to 1.5 times that of Earth, and slightly higher temperatures. The search for extraterrestrial life should prioritize these planets, which may harbor greater biodiversity and biomass than Earth.
O'Rourke et al.	2020	Following the astrobiology roadmap: origins, habitability and future exploration	To explore the three major questions of astrobiology (the origin of life, the existence of extraterrestrial life, and the future of life in the universe), analyzing extreme environments on Earth and space missions as models for other worlds.	Microbial adaptation in extreme terrestrial environments offers insights for the search for life on other planets. Planetary protection is crucial to avoid biological contamination. Advanced genomic and chemical technologies are essential to define "habitability."
Sobel and Duncan	2020	Aerospace environmental health: considerations and countermeasures to sustain crew health through vastly reduced transit time to/from Mars	To present an overview of the environmental risks faced by astronauts during space travel, especially on missions to Mars.	It is essential to limit radiation exposure time and apply the ALARA (As Low As Reasonably Achievable) concept. The need for personalized medicine, big data, and bioinformatics tools to prevent disease and anticipate risks is reinforced.
Cekanaviciute, Rosi and Costes	2018	Central nervous system responses to simulated galactic cosmic rays	To review the effects of simulated cosmic radiation on the central nervous system, focusing on neuronal and cognitive damage.	Cosmic radiation causes oxidative stress and neuroinflammation, leading to cognitive deficits. Further studies on combinations of stressors (such as microgravity) and the development of protective therapies are needed.

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Moissl-Eichinger, Cockell and Rettberg	2016	Venturing into new realms? Microorganisms in space	To investigate the ability of terrestrial microorganisms to survive in space environments (such as the ISS) and assess the risks of interplanetary contamination, as well as to explore implications for the search for extraterrestrial life.	Extremophile microorganisms demonstrate remarkable resilience to space conditions, even surviving in simulations of Mars. This reinforces the need for rigorous planetary protection policies and expands the possibilities of finding life on other celestial bodies, as long as they are protected from terrestrial contamination.
Mayberry, James, Ty and Lam	2011	Space toxicology: protecting human health during space operations	To discuss chemical risks in space missions and establish safety standards to protect the health of astronauts.	Managing toxicological risks in space environments requires continuous monitoring, rigorous standards, and innovative technologies, especially for long missions and exploration of celestial bodies, such as the Moon.
Koch e Gerzer	2008	A research facility for habitation questions to be built at the German Aerospace Center in Cologne: future challenges of space medicine	The article describes the construction project of the research facility: *envihab*, of the German Aerospace Center, with the aim of studying the physiological and psychological effects of long-duration space missions and their applications in terrestrial health.	The facility integrates space research with clinical applications on Earth, particularly in the areas of aging, immobilization, and isolation. The project will enable significant advances in both space medicine and terrestrial public health, promoting synergy between science, industry, and society.

Source: prepared by the authors.

The information from the articles listed in Table 2 was reunited into three sections – "Astrobiology and habitability", "Aerospace medicine and habitability" and "Syntheses: life sciences in search of space colonization" – which will be presented below.

3.1. Astrobiology and Habitability

Contemporary astrobiology is anchored in fundamental elements to define planetary habitability: the presence of liquid water, energy sources, and stable atmospheres (Seager, 2013). Nevertheless, this classic view has been challenged by discoveries that expand the concept of "habitable environments." While aqueous solvents remain essential for terrestrial-like biochemistries, alternative solvents, such as methane on Titan or ammonia in subsurface oceans, reveal potential for exotic biochemistries (Stevenson; Lunine; Clancy, 2015; Mckay, 2011). This plurality is endorsed by the study of terrestrial extremophiles, organisms that thrive in extreme conditions of temperature, pH, radiation, and salinity, demonstrating that life can emerge under unusual parameters (Salwan; Sharma, 2020).

The epistemological critique highlighted by Cockell et al. (2024) introduces methodological rigor into this discussion. By categorizing habitability into three levels, *Empirical* (based on observed limits), *Stricto Sensu* (theoretical for terrestrial life), and *Lato Sensu* (hypothetical for alien biochemistries), the authors argue that assessments for astrobiological missions should prioritize empirical criteria. Venus exemplifies this dichotomy: its clouds (30-70°C, 0.4-2 atm) are thermodynamically mild, but ultra-low water activity (≤ 0.004) and extreme acidity (pH ≈ −1) make a known metabolism unviable, preliminarily rejecting it as a viable target for life detection. This approach reinforces the prioritization of environments such as Europa and Enceladus, where subsurface oceans align with terrestrial biological limits.

Simultaneously, planetary protection policies are evolving to safeguard such environments. Doran et al. (2024) update the COSPAR guidelines for "Ice Worlds," defining universal biophysical parameters: minimum temperature for microbial replication (−28°C) and water activity (0.5°C). The risk assessment period is extended to 1,000 years, and missions such as Europa Clipper (Category III) require strict protocols against contamination. This framework operationalizes the conservatism proposed by Cockell et al. (2024), balancing exploration and scientific preservation. Nevertheless, the search for complex life imposes additional constraints. Lammer et al. (2024) and Scherf et al. (2024) reformulate the concept of "Earth Habitats" (EHs) – rocky planets with N2-O2 atmospheres and CO2 ≤ 100 mbar – highlighting "invisible limits" such as CO2 toxicity and the need for oxygen for animal respiration (100–300 mbar). Their modeling indicates that only 60,000–250,000 EHs would exist in the Milky Way, concentrated on K and G-type stars. This rarity, amplified by requirements such as plate tectonics and stable magnetic fields, suggests that Earth is a cosmic exception, challenging the Copernican Principle.

Traditionally inhospitable environments also acquire a new status. Wandel (2023) and Mota et al. (2025) demonstrate that planets orbiting M dwarfs can sustain subglacial oceans beyond the classical habitable zone, thanks to geothermal or tidal heat. This expansion increases the abundance of habitable worlds by two orders of magnitude: (i) the extension of the habitable zone due to subglacial oceans, given that planets closer to the star may have subglacial liquid water on the night side (protected from extreme heat) and more distant planets (with radiative flux as low as 0.1 of Earth's flux) may harbor polar lakes or subglacial oceans (e.g., analogy to Martian lakes); and (ii) the abundance of M dwarf stars. If we considered only G-type stars (like the Sun) as hosts for habitable planets, the estimate would be ~1 habitable planet per 100 stars. When including M dwarfs, this estimate reaches ~1 habitable planet per M dwarf star (Wandel, 2023). In life detection, Malaterre et al. (2023) warn about the ambiguities of biosignatures. Atmospheric oxygen, for example, can be generated abiotically by photolysis, and false positives such as Venusian phosphine expose instrumental limitations. The authors support a probabilistic approach with confidence scales, while Carrier et al. (2020) emphasize strategies for *extant* life on Mars, based on the "Refuge Model": microorganisms would survive in caves, deep subsurface, or salts, where UV radiation and desiccation are mitigated.

Astrobiology, that being said, navigates between the search for empirical evidence and scientific, perhaps fiction, imagination. While studies such as those by Cockell et al. (2024) and Doran et al. (2024) anchor the discipline in observable data, innovative visions, such as biogenic habitats in space (Wordsworth Et Al., 2023) or superhabitable planets (Makuch; Heller; Guinan, 2020), expand conceptual horizons. The integration of marine biotechnology into life support systems (Lemos Et Al., 2024) and lessons from the origin of terrestrial life (Rodriguez Et Al., 2024) offer practical tools for this journey. In this way, the search for life in the cosmos remains a dialogue between the known and the possible, where methodological rigor is as crucial as theoretical boldness.

3.2. Aerospace Medicine and Habitability

Long-term space exploration poses complex challenges to human health, with Aerospace Medicine emerging as a critical discipline for enabling habitability in extraterrestrial environments. Cosmic and solar radiation, combined with the systemic effects of microgravity, constitute the main physiological obstacles. Recent studies corroborate this premise: Carvalho-e-Silva et al. (2023) highlighted that prolonged microgravity induces accelerated bone loss (up to 150 mg of calcium/day), an increased risk of kidney stones due to dehydration, and significant cardiovascular changes, including fluid redistribution during accelerations (+2-3Gx) and a 12% reduction in red blood cell counts over 10 days. Simultaneously, ionizing radiation damages DNA, shortens telomeres, and alters genes related to immunity, increasing the risk of carcinogenesis (Krittanawong et al., 2023; Alcântara et al., 2025). These effects converge synergistically, requiring multidisciplinary approaches for mitigation, from radioprotective drugs to advanced life support systems.

The immunological and microbiological impacts reinforce human vulnerability in space. Castro-Costa et al. (2024) demonstrate that microgravity suppresses *natural killer* (NK) cells, elevates pro-inflammatory cytokines (IL-6, IL-8), and alters the gut microbiota, increasing susceptibility to infections and the reactivation of latent viruses. Avila-Herrera et al. (2020) expand this perspective by revealing, through metagenomics on the ISS, that 97% of microbial species on astronauts' skin contaminate habitable surfaces, with 56% of the human microbiome contributing during stays. This dysbiosis, marked by a significant reduction in salivary diversity ($p < 0.05$, Hill indices) and an increase in *Alloprevotella* (associated with cavities), demands targeted disinfection protocols and real-time monitoring to avoid systemic complications during lunar or Martian missions. Additionally, hypergravity during launches, although temporarily immunostimulatory (Alcantara et al., 2025), does not compensate for chronic immunosuppression in space, requiring strategies such as personalized probiotics and gut-brain axis modulation.

Neurological and psychological risks represent another critical dimension. Marazziti et al. (2022) warn that isolation, confinement, and radiation lead to depression, anxiety, sleep disorders (75% of astronauts use hypnotics such as zolpidem), and cognitive deficits, exacerbated by delays in terrestrial communication (up to 24 minutes on Mars). Cekanaviciute et al. (2018) detail underlying mechanisms: high-energy particles (HZE) damage hippocampal neurons, reduce neurogenesis, and activate microglia via the complement cascade (C3 protein), compromising

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spatial and social memory in animal models. These findings justify the creation of a subfield of *space psychiatry*, integrating continuous psychological support, personalized pharmacological interventions, and biocultural resilience training, especially considering sexual dimorphism in the stress response (Sarma; Shelhamer, 2024).

To face cosmic radiation, technological advances are indispensable. Huff et al. (2023) present the GCRsim simulator, developed by NASA/BNL, which replicates the complex spectrum of galactic cosmic rays (GCR) in the laboratory, including primary and secondary particles with varying LET (*Linear Energy Transfer*) levels. This tool allows testing biological countermeasures and validating materials such as the nanomaterials highlighted by Sales (2025): aluminized polyimides (CPI-T/Al) withstand temperatures up to 451°C and reduce UV transmission after 2,000 hours of exposure, while nanocomposites such as BNTT-Ti reduce neutron transmission by 20%.

Life support systems and *in situ* resource production are pillars of sustainability. Lemos et al. (2024) propose the use of marine resources: microalgae (*Chlorella vulgaris*) reach densities of 20 g/L in simulated Martian regolith, supplying 37.1% of dietary protein and oxygenation, while bacteria (*Nitrosomonas*) treat wastewater with 98% ammonia removal efficiency. Wordsworth et al. (2023) innovate by framing self-sustaining photosynthetic ecosystems based on biopolymers (agarose) and silica aerogels, which regulate pressure (~10 kPa) and temperature (up to 15°C at 5 AU from the Sun) in extraterrestrial habitats. These biogenic solutions reduce dependence on terraforming and conventional technologies, promoting self-sufficiency through closed loops that recycle 90% of the water in space aquaculture systems.

Operational integration between medicine and engineering is crucial for emergencies. Kamine et al. (2022) determine that an open appendectomy requires only 3.8 m^3 of space volume, feasible even in capsules like the Soyuz (4 m^3), , but highlight practical challenges such as patient stabilization in microgravity and fluid containment. Sobel and Duncan (2020) offer a radical solution: nuclear propulsion would reduce the Earth-Mars time to 2–6 days (vs. the conventional 180 days), reducing radiation exposure by >90% and enabling synchronization with solar storm forecasts (45 days). This approach, associated with precision medicine and predictive biomarkers, mitigates cumulative risks and enables safe interplanetary missions, applying the ALARA (*As Low As Reasonably Achievable*) principle to dosimetry.

Habitability in space requires transdisciplinary convergence in terms of aerospace health. As Sarma and Shelhamer (2024) articulate, NASA's "five dangers" (radiation, microgravity, isolation, closed environments, and distance from Earth) interact synergistically, demanding evolutionary models (*Life History Theory*) that consider human diversity and biocultural factors. Facilities like the DLR's envihab (Koch; Gerzer, 2008) exemplify this integration, uniting human centrifuges, telemedicine (*intuVR*), and environmental research within its 3,000 m^2 facility. The inclusion of diverse populations, including people with disabilities, as proposed by Marge (2022), and the development of big data in health reinforce human resilience. Thus, Aerospace Medicine transcends its mitigating function, becoming the cornerstone for transforming science fiction, such as the interstellar journey imagined by Nolan (2014), into sustainable biological reality, where human adaptability is as vital as technological advances.

3.3. Synthesis: Life Sciences in Search of Space Colonization

The search for extraterrestrial life and the habitability of other planets requires an interdisciplinary approach that integrates fields such as astrobiology, aerospace medicine, planetary geology, physics, and chemistry. Astrobiology, for example, studies the biological and chemical processes that could sustain life on other worlds, while aerospace medicine focuses on the effects of space travel on the human body and the development of strategies to mitigate them.

Collaboration between these areas of knowledge is essential to advance space exploration and the search for habitable planets. For example, knowledge about the effects of microgravity on human health can assist in creating safer and more effective space habitats for future missions. Interaction between astrobiologists and aerospace physicians can also lead to the development of new technologies, such as diagnostic systems and advanced medical treatments, adapted for long-duration missions where resources are limited and terrestrial medical care is difficult.

Furthermore, technologies developed to adapt to life in space could, in the near future, be fundamental for the creation of human colonies on other planets. Success in space exploration will depend on a collaborative and interdisciplinary approach that unites life sciences, technology, and space environment studies. Advances in these areas will allow humanity to take the first steps toward space colonization, a crucial step for the future of our species.

4. Conclusion

Habitability on other planets is a fascinating field that encompasses multiple scientific disciplines. Advances in astrobiology and aerospace medicine are getting ever closer to answering the fundamental question: Are humans alone in the universe? As human space activities expand, collaboration between different fields of knowledge is essential to address the challenges and seize the opportunities that arise with the discovery of new habitable worlds. Interdisciplinarity is key to progress in this exciting field, allowing scientists from diverse fields to work together in order to achieve common goals. As advances toward a deeper understanding of habitability on other planets occur, horizons may be opened so that the possibility of living beings – human or otherwise – in space goes beyond the limits of science fiction, creating new realities. And, as in so many moments in human history, life will once again imitate art.

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6. Conflict of Interest

The author declares no competing conflict of interest.

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