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Aerospace health: a systematic review and current state of science

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Introduction: The frontier of aerospace health integrates medicine, technology, psychology, and related disciplines. The field has evolved from its earlier emphasis on maintaining crew survival beyond Earth's atmosphere to addressing the fundamental challenge of sustainable human space habitation. Despite the growing body of literature in aerospace health, a gap persists due to an overconcentration on synthesis studies with limited empirical validation and insufficient attention to higher-order human health needs, including psychosocial aspects. By examining existing literature, this systematic review aims to present the current landscape of aerospace health research and its future directions.

Methods: The research paper adopted an integrative review framework developed by Whittemore et al. (Journal of Advanced Nursing, 2005, 52(5), 546–553), comprising five stages: problem identification, literature search, data evaluation, data analysis, and data presentation.

Results and Discussion: The Results and Discussion are organized into three sections that reflect the study's objectives: (1) to focus on bibliometric patterns of the field, (2) to demonstrate study purposes and health-related outcomes, and (3) to conduct keyword network analysis and thematic linkages among the included articles. Findings indicate that most studies reviewed in aerospace health involve multiple authors, show a notable increase after the COVID-19 pandemic, and are primarily concentrated in the Americas. The results can be attributed to the multidisciplinary nature of the aerospace industry, the post-pandemic expansion of space activities, and the dominance of U.S.-led space initiatives. In addition, article purpose and outcomes demonstrate eight themes identified across all articles, covered under: (1) Physiology and Health Risks, (2) Psychology and Behavior, (3) Pharmaceuticals and Interventions, (4) Product and Technology, (5) Profession and Training, (6) Process and Procedures, (7) Place and Environment, and (8) Policy and Strategy. Keywords and network analysis, on the other hand, determine six themes, namely: (1) Health Ecosystem, (2) Health Examination, (3) Health Education, (4) Health Engineering, (5) Health Estimation, and (6) Health Evidence.

Conclusion: Ultimately, the review presents a Torus Model and thematic analyses that map the current landscape of aerospace health research and provide insights for future directions of the field.
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KEYWORDS

aerospace health, network analysis, space flight, space health, systematic review

1 Introduction

Aerospace health is a rapidly developing area of inquiry that examines the physiological, psychological, and technological dimensions of human performance in aviation and space environments. The term "aerospace" encompasses the integrated field of air and space travel, including the science, technology, engineering, and health aspects that enable both. In health contexts, aerospace medicine focuses on the health, safety, and performance of crew members and passengers in air and space vehicles (Davenport et al., 2021). Over the years, human space exploration, along with commercial air travel and long-duration missions, has become increasingly important. Through studies of the space environment and testing of initial capabilities in Earth orbit, over 50 years of human activity in space have yielded benefits that improve society and the quality of life on Earth (NASA, 2013). This is evident in the contributed critical knowledge and advancements in satellite telecommunications, global positioning systems, and weather forecasting. Amidst these, it is well known that the aerospace environment presents extreme conditions for the human body, as exposure to microgravity and ionizing radiation can lead to both short- and long-term health problems (Kapoor et al., 2025). Thus, one major result of this is the creation of deleterious effects and obstacles for long-term space missions.

With the expansion of aerospace exploration, the need for comprehensive healthcare approaches is thus becoming increasingly urgent. Beyond NASA's ongoing efforts, global organizations such as the United Nations Office for Outer Space Affairs (UNOOSA) are also advancing policies that promote the application of space technologies to strengthen global healthcare. Initiatives such as Massive Open Online Courses (MOOCs) on Space and Global Health further support this mission by raising awareness and expanding space and global health education amongst academics and organizations worldwide. Such initiatives are increasingly important because the space environment exerts profound physiological effects that impact nearly every human organ system. Factors in the space environment, such as microgravity, is shown to lead to weakened muscle functions, including the heart, reabsorption of weight-bearing bones (i.e., a major cause of increased fracture risks and kidney stones), reduction in blood volume, and other immunological, reproductive, and sensorimotor changes (Jemison and Olabisi, 2021).

While these physiological risks have been extensively documented in aerospace research, the literature remains fragmented across other fields, such as biomedical engineering and psychological domains. Studies are predominantly focused on clinical countermeasures (Khan et al., 2024) and technological innovations (Sharp et al., 2025), often overlooking broader health contexts, particularly psychosocial dimensions. As a result, current knowledge provides valuable insights into performance and adaptation but fails to offer a comprehensive synthesis as to how healthcare can be delivered systematically in aerospace environments. Currently, most aerospace health research is conducted in simulated or laboratory settings. Since several countries lack their own space agencies, researchers often have limited access to information and must rely on the few that provide open-access data (Rausser et al., 2023). Systematic reviews, integrative syntheses, and conceptual frameworks have become dominant forms of scholarly output, reflecting the field's efforts to organize and interpret emerging research. Despite this increase in synthesized knowledge, a significant gap remains in the empirical validation of findings within actual aerospace environments.

To address these gaps, this systematic review aims to synthesize existing evidence on the current state of research in aerospace health. Specifically, this review (1) describes bibliometric characteristics of published papers, (2) thematizes article purposes and reported outcomes, and (3) performs a keyword network analysis to map conceptual linkages and emerging domains in the field of aerospace health. Beyond documenting biomedical and technological challenges, this analysis's findings highlight the growing recognition that aerospace health requires attention not only to basic survival but also to higher-order human needs and psychosocial wellbeing.

2 Methods

This research paper adopted a systematic review following the stages developed by previous scholars (Whittemore and Knafl, 2005). The review process is outlined as follows: (a) problem identification, (b) literature search, (c) data evaluation, (d) data analysis, and (e) presentation. To ensure quality and consistency throughout the review process, a scoping review guideline, the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) (Moher et al., 2010) was used. This review was registered on OSF.io (embargoed) and received ethical clearance exemption from *** (2025-IERC-00737).

2.1 Stage 1: problem identification

This paper examines the current state of research in the emerging field of aerospace health. As an interdisciplinary domain that integrates medical, biological, and engineering sciences to address the physiological and environmental challenges posed by human activity in space, aerospace health is still in its developmental stage. A systematic review of existing literature is therefore essential to establish a clear understanding of the field's present scope, prevailing limitations, and areas

TABLE 1 Database search strategy.

Database	Search string	Results
Scopus	TITLE-ABS-KEY ("Aerospace Health" OR "Aerospace Wellness" OR "Space Health" OR "Space Wellness" OR "aerospace nursing" OR "Space nursing" OR "spaceflight hygiene" OR "astronautical hygiene") AND [LIMIT-TO (LANGUAGE, "English")] AND [LIMIT-TO (SRCTYPE, "j") OR LIMIT-TO (SRCTYPE, "p")]	217
PubMed	["Aerospace Health" (Title/Abstract) OR "Aerospace Wellness" (Title/Abstract) OR "Space Health" (Title/Abstract) OR "Space Wellness" (Title/Abstract) OR "spaceflight hygiene" (Title/Abstract) OR "astronautical hygiene" (Title/Abstract)]	67
ProQuest	[TI ("aerospace health" OR "aerospace wellness" OR "space health" OR "space wellness" OR "aerospace nursing" OR "space nursing") OR AB ("aerospace health" OR "aerospace wellness" OR "space health" OR "space wellness" OR "aerospace nursing" OR "space nursing") OR SU("aerospace health" OR "aerospace wellness" OR "space health" OR "space wellness" OR "aerospace nursing" OR "space nursing" OR "spaceflight hygiene" OR "astronautical hygiene")] AND stype.exact ("Conference Papers and Proceedings" OR "Scholarly Journals") AND la.exact ("English")	72
Web of Science	[TS = ("aerospace health" OR "aerospace wellness" OR "space health" OR "space wellness" OR "aerospace nursing" OR "space nursing" "spaceflight hygiene" OR "astronautical hygiene")] AND ((DT == ("ARTICLE") AND LA == ("ENGLISH")) NOT (SILOID == ("PPRN") OR SILOID == ("RC")))	143
	Total	499

requiring further development. The following inquiries guided this systematic review: (1) What does the existing published literature describe about aerospace healthcare? (2) What trends and patterns exist in terms of article purpose and outcomes of aerospace healthcare? (3) What themes can be generated to describe the articles on aerospace healthcare?

2.2 Stage 2: literature search

Databases including Scopus, Web of Science, PubMed, and ProQuest were thoroughly searched for existing literature. Keywords, like "aerospace health," "aerospace nursing," "aerospace wellness," are used to identify relevant literature (See Table 1. Database search strategy).

2.3 Stage 3: data evaluation

A systematic review tool, Covidence, was used to assess the validity and methodological appropriateness of the included studies. All retrieved articles from the selected databases were uploaded into the application, where duplicate records were automatically detected and removed, both manually and by the system. Following this, a full-text review was conducted after at least two independent reviewers had completed the title and abstract screening. The principal investigator resolved any discrepancies or divergences among reviewers through data reconciliation and consensus agreement. The following inclusion criteria were then applied to determine the relevance of eligible full-text studies and guide the selection of related literature.

2.3.1 Study design

This review includes both empirical and theoretical research obtained from multiple academic databases. Empirical studies generate findings through the systematic collection of controlled, measurable, and reproducible data (Brass, 2006). Studies with outcomes derived from tested or validated data were therefore included. Theoretical research, such as experience reports, editorial articles, conceptual papers, and review articles, was also incorporated. These studies contribute by developing, refining, or evaluating models and frameworks relevant to the field (Olusegun et al., 2024). Including both empirical and theoretical work thus provides a comprehensive understanding of the current state and future directions of aerospace health research.

2.3.2 Language

Discourse on aerospace health is an emerging trend with a well-documented body of research that frequently cross-references related studies. Therefore, the interpretation of the data and the dissemination of the findings in this paper should be conducted in a medium accessible to the broader scientific community. This project selected articles written only in English to ensure accurate data interpretation and widespread accessibility of the study. The proportion of publications in English within science, mathematics, medicine, and engineering is predominant and continues to increase (Smith, 2003). Moreover, scientific research published in English attains greater visibility in international literature and fosters stronger connections with scientists worldwide (Huttner-Koros and Perera, 2016). Therefore, the selected articles for review are written in English because this is the primary language of global scientific discourse, with most peer-reviewed journals disseminating research in this language.

2.3.3 Focus

For this review, only studies addressing health concerns, health technology, and environment specific to aircraft and spacecraft operations were selected, ensuring that the focus remains on aerospace-related human health. The key difference between aircraft and spacecraft lies in the environments in which they operate. An aircraft is a machine designed or intended for flight, as defined by current regulations (Sheng, 2019). This suggests that aircraft are designed to fly within Earth's atmosphere. Typical examples are airplanes, helicopters, gliders, and paramotors. Spacecraft are designed to operate outside Earth's atmosphere. There are two types of spacecraft: earth-orbiting and deep-space. Their difference lies in that earth-orbiting spacecraft operate around Earth for applications such as communication, weather monitoring, and observation, while deep space spacecraft are typically used for the exploration of other planets and celestial bodies (Birur et al.,

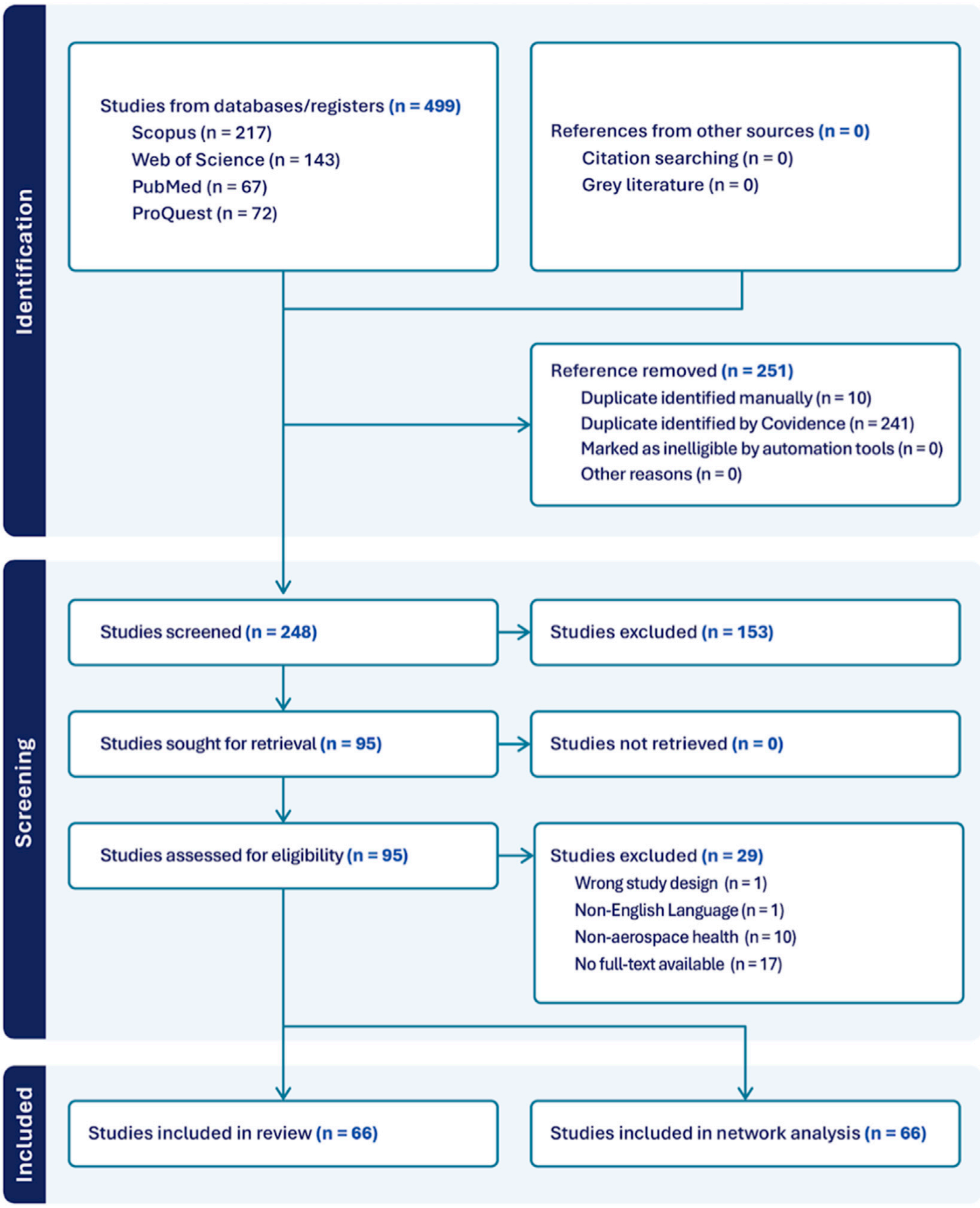

FIGURE 1
PRISMA diagram.

2003). Therefore, articles focusing on aircraft and spacecraft were selected to ensure relevance to human health, technology, and environmental issues in aerospace operations, both within and outside the Earth's atmosphere. Following this, the authors employed the Mixed Methods Appraisal Tool (MMAT) to assess the methodological quality of the empirical studies included in the review. The Authority, Accuracy, Coverage, Objectivity, Date, and Significance (AACODS) checklist was utilized to evaluate the validity and credibility of the theoretical studies collected. Finally, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram was used to illustrate the data evaluation process, depicting the number of studies identified, screened, included, and excluded, along with the reasons for exclusion at each stage.

2.3.4 Keyword rationale

The keyword strategy was developed to align closely with the review's focus on aerospace health, emphasizing terms directly related to health, human performance, and biomedical concerns in aerospace contexts (e.g., "aerospace health," "aerospace medicine," "space health"). Broader space-related terms, including references to specific mission environments such as

TABLE 2 Article bibliometrics.

Article attributes	f	%
Authorship		
Single	14	21.21
Double	8	12.12
Multiple	44	66.67
Journal publication		
Health	46	69.70
Non-health	20	30.30
Year		
1967	1	1.52
1985	1	1.52
1989	2	3.03
2001	1	1.52
2005	2	3.03
2007$	1	1.52
2009	1	1.52
2010	1	1.52
2011	1	1.52
2012	1	1.52
2015	2	3.03
2016	1	1.52
2018	2	3.03
2019	1	1.52
2020	4	6.06
2021	4	6.06
2022	10	15.15
2023	12	18.28
2024	13	19.70
2025	5	7.58
Region		
Americas	38	57.58
European	14	21.21
Southeast Asia	3	4.55
Western Pacific	9	13.64
African	1	1.52
East Mediterranean	1	1.52
Sample size (M = 51.80; SD = 71.16)		
0–10	2	3.03
11–20	0	0
21–30	2	3.03
31–40	0	0
41–50	1	1.52
51 and above	2	3.03
Not mentioned	59	89.39
Topic/research area		
Biology and Life Sciences	8	12.12
Clinical and Medical Specialties	8	12.12
Health Technology and Engineering	12	18.18
Knowledge Synthesis and Reports	38	57.57
Output		
Device	4	6.06
Policy/standard	3	4.54
Theory/model	52	78.78
Practice/process	5	7.57
Tool/platform	2	3.03
Environment		
Aircraft	3	4.54
Spacecraft	2	3.03
Simulated	4	6.06
Laboratory	11	16.66
Community	0	0.00
Clinical	2	3.03
Not mentioned	44	66.66

(Continued in next column)

TABLE 2 (*Continued*) Article bibliometrics.

Low Earth Orbit (LEO), Moon, or Mars, were considered within the overall conceptual landscape of aerospace research. Because the review concentrated on health-focused studies across both aviation and space settings, the final set of keywords was structured around terminology that most consistently reflected this domain.

Figure 1 (PRISMA diagram) illustrates the identification, screening, and inclusion process that was carried out using Covidence. A total of 251 duplicate references were removed from 494 studies in the databases. Ten are identified manually, and 241 are identified as duplicates by Covidence. Of the 243 studies screened, 153 were excluded based on their titles and abstracts because they did not meet the inclusion criteria outlined in Stage 2. From ninety (n = 90) studies that underwent full-text review, 29 were excluded because of wrong study design (n = 1), non-English language (n = 1), non-aerospace health (n = 10), and no full-text available (n = 17). Lastly, 66 studies are included in the review, all of which underwent network analysis.

2.4 Stage 4: data analysis

At least two authors independently extracted data from eligible studies using a systematic, interactive process to identify common patterns and emerging themes across the dataset. The data extracted from the included articles are as follows: (a) Bibliometrics which covered author, year of publication, bibliographic identifiers, article type, authorship, health journal, country of publication, and World Health Organization (WHO) region; (b) Critical Appraisal which included MMAT score for empirical research, AACODS score for theoretical studies, and relevance score; (c) Article Target in terms of topic, subtopic, health focus, health dimension, client status, sample size, and environment; (d) Research Data, which encompassed article purpose, outcome, and direction; and (e) Research Output.

Attaining a collective agreement among the group is given priority in any circumstances of conflicting judgment. Additionally, data reconciliation is facilitated using the Covidence Application to resolve discrepancies during screening and data extraction. Files were safeguarded in institutional databases after being accurately entered into a spreadsheet.

TABLE 3 Thematized purpose and outcomes.

Area	Purpose		Outcomes	
	Themes	Source articles	Themes	Source articles
Physiology and health risks	To identify health risks and physiological changes in the human body in aerospace	(Cain, 2011, 2018, 2010, 2019; Chandler and Polk-Walker, 1989; Chunduri et al., 2022; Cohen, 2022; Krittanawong et al., 2022; Kunitskaya et al., 2022; Moran, 2007; Oluwafemi, 2018; Pagbilao et al., 2023; Pelligra et al., 2025; Polk-Walker, 1989; Rudolf and Hood, 2024; Scheibler et al., 2023; Siagian, 2012; Siagian et al., 2009; Simpson, 2023; Wani et al., 2024; Xiao et al., 2021)	Identified physiological risks (cardio, immune, neuro, mito, renal, musculoskeletal) to the human body in aerospace	(Barbour et al., 2025; Cain, 2011, 2018, 2010, 2019; Chandler and Polk-Walker, 1989; Moran, 2007; Oluwafemi, 2018; Paul et al., 2020; Rasheed et al., 2019; Rudolf and Hood, 2024; Xiao et al., 2021)
Psychology and behavior	To explore psychological and behavioral health status of humans in aerospace	(Barbour et al., 2025; Burles et al., 2023; Rasheed et al., 2019; Sarma et al., 2025)	Discovered mental health insights and phenomenon (depression, neuroplasticity, stress, adaptation)	(Burles et al., 2023; Rasheed et al., 2019; Rivera et al., 2024)
Pharmaceuticals and interventions	To develop resilient pharmaceutical products for humans in aerospace	(Aziz et al., 2022; Bokhari et al., 2022; Paul et al., 2020; Tran et al., 2022; Vallota-Eastman et al., 2023; Wang et al., 2025)	Piloted therapies and interventions (radiation, immunity, microbiota, infection, drug stability) with promising results	(Bokhari et al., 2022; Tran et al., 2022; Vallota-Eastman et al., 2023; Wang et al., 2025)
Product and technology	To design technology and tools for human survival and exploration in aerospace	(Alemaryeen et al., 2015; Bokhari et al., 2022; Chu and Tsia, 2023; Chua et al., 2024; Elam et al., 2005; Pulvirenti, 2024; Tavakol et al., 2023; Vallota-Eastman et al., 2023)	Tested biomedical tools (antennas, XR, exosuits, sensors, PHM, engineered tissues) in simulated aerospace environment	(Alemaryeen et al., 2015; Chu and Tsia, 2023; Gupta and Ghosh, 2025; Pulvirenti, 2024; Tavakol et al., 2023)
Profession and training	To design competency framework for allied health professionals	(Borges et al., 2022; Paula et al., 2024; Polk-Walker, 1989; Rivera et al., 2024; Siagian, 2012; Siagian et al., 2009; Sjner, 1967)	Proposed competency frameworks (CBRN, disaster response, frameworks, occupational health) and call to action	(Borges et al., 2022; Paula et al., 2024; Rivera et al., 2024)
Process and procedures	To examine utility of advanced technologies (Data, AI, and Informatics) for process improvement for aerospace applications	(Dewey and DeVries, 2020; Gupta and Ghosh, 2025; Martinez et al., 2016; McGregor, 2021; Nuryatno et al., 2023; Scott et al., 2023; Waisberg et al., 2023)	Generated refined procedures using digital health tools (AI, LLMs, data mining, autonomy, decision support) in aerospace applications	(Martinez et al., 2016; McGregor, 2021; Scott et al., 2023; Waisberg et al., 2023)
Place and environment	To investigate potential changes in environment for human acclimatization in aerospace	(Abi-Ramia Silva et al., 2024; Alemaryeen et al., 2015; Sobel and Duncan, 2020)	Evaluated the performance and efficacy of certain tools under extreme aerospace conditions (gases, noise, radiation)	(Abi-Ramia Silva et al., 2024; Siagian, 2012; Siagian et al., 2009)
Policy and strategy	To propose standards for policy and strategy development	(Kutch, 1985; Madani and McGregor, 2024; Rudge, 1995; Scheibler et al., 2023; Sjner, 1967)	Showcased strategic frameworks (admin, cybersecurity, editorial trends, readiness) for aerospace health	(Kutch, 1985; Madani and McGregor, 2024; Rudge, 1995)

2.5 Stage 5: data presentation

Findings were organized into thematic tables and conceptual models, allowing the researchers to observe relationships, variations, and emerging patterns across the included studies. These models illustrate the mapped thematic areas and depict the overall landscape of aerospace health research.

3 Results

3.1 Article bibliometrics

Table 2 presents the bibliometric data for the 61 articles included in this study, covering the period from 1967 to 2025. The majority of this research is conducted by multiple authors (n = 44; 66.67%). Despite the aerospace nature of the topics, the reviewed articles are primarily published in health journals (n = 46; 69.70%). Geographically, the American region produced the most studies with (n = 38; 57.58%). Notably, most articles focus on creating Knowledge Synthesis and Reports (n = 38; 57.57%), thereby producing more Theory and Models (n = 52; 78.78%) than other output types. For the studies not focusing on creating synthesis and reports, most are set in a laboratory setting (n = 11; 16.66%).

3.2 Article purpose and outcomes

The present literature review included 61 articles that assessed the current state of research on aerospace health from 1967 to 2025. Two primary areas were evaluated, specifically examining the purposes and outcomes of each study in relation to their key

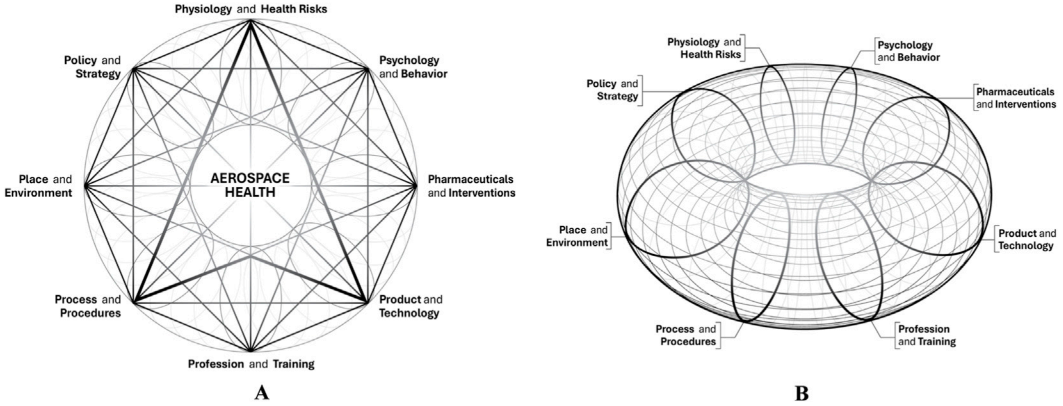

FIGURE 2
Torus Model representing the themes on Aerospace health articles' purpose and outcomes. **(A)** Top view of the model, **(B)** angled view of the Torus.

objectives and results. This ranges from research article titles and corresponding authors to quality checks via MMAT and AACODS, as well as purpose and outcome. To establish a clear distinction of emerging patterns, Table 3 synthesizes this individual information into thematized clusters that identify research trends. In terms of purpose, studies were classified into eight areas: (1) Physiology and Health Risks, (2) Psychology and Behavior, (3) Pharmaceuticals and Interventions, (4) Product and Technology, (5) Profession and Training, (6) Process and Procedures, (7) Place and Environment, and (8) Policy and Strategy. These thematic areas correspond to individual themes on both article purpose and outcomes, spanning the identification of health risks and physiological changes in the human body, mental health phenomena, resilience of pharmaceutical products, technology innovations, competency frameworks for health professionals, digital health tools, environmental changes, and finally, policy and strategy development for aerospace-related health. A comprehensive overview of the included studies is provided in the supplementary file.

MMAT appraisal reveals that 25 studies were evaluated. Among these, eight studies (32%) achieved a score of 100%, indicating high methodological quality. Another twelve studies (48%) were rated at 80%, reflecting moderate quality, while five studies (20%) scored 60%, suggesting notable methodological limitations. Using the AACODS checklist, 41 non-empirical or grey literature sources were assessed. These generally rated highly in terms of Authority and Accuracy, as they were authored by domain experts and supported by credible evidence. However, variation was observed in Currency and Significance, with some studies providing outdated insights or limited applicability to aerospace healthcare.

While Table 3 summarizes the themes derived from the purposes and outcomes of the aerospace health articles and corresponding articles, Figure 2 illustrates these themes in a "torus" model—a fundamental geometric form found in nature at multiple scales and often viewed as a symbol of balance, renewal, and interconnectedness. Figure 2A shows a top view of the torus, where eight themes are arranged radially around a center, characterizing the themes of aerospace health research. This perspective was chosen to allow integration with symbolic shapes such as the octagon and delta, which symbolize "space." On the other hand, Figure 2B illustrates an angled view of the model. The toroidal geometry model reflects how existing literature on aerospace health integrates knowledge in a self-sustaining loop across eight interconnected domains. It specifically provides a balanced framework in which areas (e.g., physiology, policy, technology) maintain their distinctions while being united by the flow of knowledge through continuous feedback loops. This emphasizes that themes bound research in the field of aerospace health but evolve endlessly through integrated insights.

3.3 Article keyword network analysis

Figure 3 is a co-occurrence network of article keywords that reveals six thematic clusters (Table 4) from the systematic review, illustrating the characteristics of the existing literature on aerospace healthcare. The network showed that some of the most frequently occurring keywords include "human," "space health," "space research," and "extraterrestrial environment," represented by node sizes proportional to word frequency and lines indicating co-occurrence strength. Six keyword clusters, particularly "Health Ecosystem," "Health Examination," "Health Education," "Health Engineering," "Health Estimation," and "Health Evidence." The first cluster encompasses discussions on aerospace environments and their impacts on health. The second cluster is centered on health diagnostics. The third cluster relates to information on physiology, practice, and process. The fourth cluster addresses approaches for improving health and wellbeing through potential modifications in body system factors. The fifth cluster highlights health indicators, metrics, and measures. Finally, the sixth cluster pertains to health research, biomarkers, and functional assessment in aerospace. Together, these clusters provide a comprehensive view of the field, reflecting both foundational biomedical concerns and emerging directions in aerospace health.

4 Discussion

4.1 Article bibliometrics

Aerospace health studies predominantly featured multiple authors from both health and non-health scholars. One key

FIGURE 3
Article keywords network map.

contributor to this finding is the consistent increase in multiple authorship in aerospace health, spanning disciplines such as physical sciences, including physics and space sciences. For instance, despite some fluctuations in 2006, 2009, and 2010, authorship in physical science-related aerospace health shows an upward trend. From 1967 to 2019, publications in aerospace health were relatively sparse, with most years contributing one or two articles and occasional small peaks (e.g., 1989 and 2005 with two articles each). Beginning in 2020, there was a noticeable increase in research output, rising from four articles in 2020 and 2021 to 10 in 2022, peaking at 13 in 2024, and slightly decreasing to five in 2025 (Table 2). Other than years of publication, research in physics-related aerospace health is the largest, followed by space science (King, 2013). As an inherently interdisciplinary domain, aerospace health demands a comprehensive understanding that integrates health, technology, physics, and space science into a unified framework. In addition, space medicine is a field of study that seeks to understand medical challenges with space travel by applying multiple scientific approaches (Gunga, 2021). Hence, another contributing factor to the result is that aerospace health is an inherently interdisciplinary and multidisciplinary field that requires collaboration among various fields of study (medicine, engineering, physics, and astronomy). The results suggest that the advancement of allied disciplines (technology, physics, biomedicine, space chemistry, and space science) is integral to the development of aerospace health. Therefore, it is recommended to evaluate the current developments of related disciplines, as this provides a basis for projecting the future direction of aerospace health. Future trends may involve recalibrating the curriculum to include courses on aerospace health or developing academic programs tailored to professional practice in space medicine. New research methods must be designed for aerospace health-related investigations.

Findings reveal a growing number of publications on aerospace health from 2020 to the present. A steady rise was observed from 2020 to 2021, peaking from 2022 to 2023. This trend can be attributed to several factors, including the parallels between human health conditions during the COVID-19 pandemic and those experienced in spaceflight, recent discoveries suggesting the possibility of life on other planets, the undertaking of long-duration space missions, and the emergence of space tourism. There has been a surge of studies focused on aviation and aerospace health following the COVID-19 pandemic. Given the significant impact of this health crisis across all areas of life, many studies have examined its role and

TABLE 4 Aerospace health article keyword clusters and themes.

Cluster	Keywords	Theme	Description
1	3D Printing, Advanced Material Technology, Antibiotics, Bandwidth, Big Data Data Handling, Bioactive Compounds, Biodiversity, Biomonitoring, Bone Loss, Clinical Care and Research, Colonisation, Common Ground, Cosmology, Crucial Parameters, Cybersecurity, Data Analytics, Deep Space, Material Degradation, Disease, Drug Delivery Systems, Earth (planet), Ecosystems, Epidemiology, Extreme Environment, Digital Platforms and Infrastructure, Genetic Basis Genetic Disorders, Health Data, Health Risks, Healthcare Systems, Human Space Exploration, Human Health, Human Society, Space Habitation, Implants (Surgical), Internet Of Things, Interplanetary Flight, Key Solution, Knowledge Management, Large Groups, Long Duration, Machine Learning and Modelling, Martian Surface Analysis, Microgravity Processing, Microorganisms, Neonatal Care and Monitoring, Mission Control and Traffic, Optical Communication, Orbits, Paradigm Shifts, Pharmacokinetics and Pharmacodynamics, Physiology, Pipelines, Planets, Psychological Response, Radiation Hazards, Rare Disease, Regenerative Medicine, Remote Health Monitoring, Research Communities, Resupply, Small Sample Size, Space Medicines, Space Missions, Space Research, Spacecraft Equipment, Substantial Distances, Time Dependent, Virtual Storage, Wellbeing	Health Ecosystem	Article keyword cluster related to aerospace environments and its impact on health
2	3.0 T MRI Scanner, Actigraph Accelerometer, Aged, Anthropometry, Bed Rest (Head-Down Tilt), Blood Sampling, Blood Volume, Body Composition, Body Equilibrium, Bone Density (DXA, pQCT), Caloric Intake, Canada, Cardiopulmonary Exercise, Cardiorespiratory Fitness, Cardiovascular Assessments, Cognition, Computer Assisted Tomography, Diet Supplementation, Dynamometer Jamar, Electroencephalogram (EEG), Neurological and Sensorimotor Assessments, Exercise and Countermeasures, Fat Mass, Feces Analysis, Female, Fluid-Attenuated Inversion, Human Experiment, Loss Of Appetite, Mental Health and Performance, Metamax 3b-R2, Middle Aged, Muscle Biopsy, Musculoskeletal Function and Strength, Normal Human, Older Adults, Oral Glucose Tolerance Test, Oxygen Saturation, Physical Examination, Quality Of Life, Randomized Controlled Trial, Resting Metabolic Rate, Saliva Analysis, Sleep Quality, T1 Weighted Imaging, T2 Weighted Imaging, Urine Sampling	Health Examination	Article keyword cluster related to health diagnostics
3	Adaptation, Behavior, Aerospace, Article, Astronaut Health, Astronauts, Astronomy, Augmented Reality, Authorship, Aviation, Basic Needs, Biological Adaptation, Conceptual Model, Cosmonaut, Cultural Background, Data Base, Education, Educational Status, England, Environment, Environmental Health, Extended Reality, Extraterrestrial Environment, Fatigue, Flight, Fluid Shift. France, Health, Health Practitioner, Health Promotion, Human Immersive Technology, Israel, Knowledge Base, Long-Distance Spaceflight, Mental Stress, Microclimate, Mixed Reality Mood, Multidisciplinary Team, Narrative Noise, North America, Nursing, Nursing As A Profession, Nursing Care, Nursing Role, Nursing Theory, Orbit Score, Periodicals, Plasma Volume, Problem Solving, Psychology, Publication Residence Characteristics, Review, Russia, Sleep Disorder, Social Aspect, Space Flight, Space Nursing, Spaceflight Specialties, Nursing, Stress, Stress - Psychological, Systematic Review, Virtual Reality	Health Education	Article keyword cluster related to information on physiology, practice, and process
4	3d Tissue, Acute Lymphoblastic, Leukemia, Adeno Associated Virus Vector, Adverse Event, Angiogenesis, Antagomir, Antivirus Agent, Biomaterial, Blindness, Blood Vessel Graft, Blood Vessel Injury, Cardiovascular Disease, Cardiovascular System, Cell Selection, Cellular Apoptosis, Susceptibility Protein, Clustered Regularly Inter:, Coronavirus Disease 2019, Dna *Drosophila Melanogaster*, Drug Targeting, Endothelium Cell, Extremophile, Fluorescence Activated Cell, Sorting, Futurology, Gastrointestinal Tract, Government, Guide Rna, Hematopoietic System, High Mobility Group B1 Protein, *In Vivo* Study Investment, Luxturna, Magnetic Activated Cell Sorting, Messenger Rna, Microbiome Moon, Nanoligomer, Nanoparticle, Nanotechnology, Nervous System, Nervous System Inflammation, New Drug, Nucleic Acid, Nucleotide, Nucleotide-Based Approaches, Oligomer, Organoid Oxygen, Pattern Recognition Receptor, Polymer, Protein Inhibitor, Radiation Countermeasures, Radiation Hazard, Radiation Injury, Radiation Protection, Risk Assessment, Rna Vaccine, Severe Acute Respiratory, Silicon, Small Intestine Disease, Small Intestine Epithelium, Small Untranslated Rna, Tissue Engineering, Translational Research, Viral Gene Therapy, Voretigene Neparvovec	Health Engineering	Article keyword cluster related to improving health and wellbeing via potential modification in body system factors

(Continued on following page)

TABLE 4 (*Continued*) Aerospace health article keyword clusters and themes.

Cluster	Keywords	Theme	Description
5	Ab Sciex Ic-Ms System G, Agilent, Bioanalyzer 2100, Animal, Animal, Experiment, Animal Model, Animal Tissue, Animals, Bacterial Metabolism, Bacteroidetes, Claudin 1, Cytoflex Flow, Cytometer, Differential Gene Expression, DNA Sequencing, Drug Effect, Enzyme, Linked Immunosorbent Assay, Fatty Acid, Metabolism, Firmicutes, Flow Cytometry, Gastrointestinal Microbiome, Gene Expression, Ginseng, Ginseng Saponin, Ginseng Total Saponins, Ginsenoside, Ginsenosides, Graphpad Prism 8, Hindlimb Suspension, Histology, Homeostasis, Illumina Hiseq Sequence, Illumina Miseq, Immobilization, Immunity, Inflammation, Interleukin 6, Intestinal Homeostasis, Intestine, Intestine Flora, Intestine Injury, Intestines, Liquid Chromatography, Microbial Community, Microbial Diversity, Occludin, Panax, Rat, Rats, Rats, Sprague-Dawley, Real Time, Polymerase Chain Reaction, Rna 16s, Rna Sequencing, Short Chain Fatty Acid, Short-Chain Fatty Acids, Sprague Dawley Rat, Tight Junction Protein, Transcriptome, Sequencil, Transcriptomics, Tumor Necrosis Factor, Ultra DNA Library Prep Kit, Ultra Performance Liquid Chromatography, Weightlessness, Weightlessness Simulation	Health Estimation	Article keyword cluster related to health indicators, metrics, and measures
6	25 Hydroxyvitamin D, Adult, Aerobic, Capacity, Aging, Air Force, Aircraft Noise, Airplane Pilot, Alanine, Aminotransferase, Army, Biodex-System 3, Body Mass, Body Weight, C Reactive, Protein, Cardiovascular Function, Case, Control Study, Cholesterol Blood Level, Clinical Article, Clinical Assessment, Confidence Interval, Controlled Study, Cycling, Diastolic Blood Pressure, Exposure, Follow Up, Glucose Blood Level, Health Center, High Density, Lipoprotein, Hospitalization, Hydrocortisone, Hypertension, Indonesia, Iron, Iron Blood Level, Lean Body Weight, Lode Corival Cpet, Low Density Lipoprotein, Lunar Prodigy, Male, Medical Record, Military Pilots, Muscle, Isometric Contraction, Non Invasive, Procedure, Odds Ratio, Orthostatic, Hypotension, Parathyroid Hormone, Physiotherapy Pilots, Population Based Case Control Study, Pulse Rate, Quark Cpet, Resistance Training, Resting Pulse Rate, Risk Factor Self Evaluation, Systolic Blood Pressure, Testosterone Thyrotropin, Total Body Fat, Waist Circumference, Working Time, Young Adult	Health Evidence	Article keyword cluster related to health research, biomarkers, and functional assessment in aerospace

effects (Sun et al., 2021). This research addition spanned multiple academic venues, including aviation-specific conferences and journals, transportation and health-related publications, and economics and law journals (Sun et al., 2022). Research in aerospace medicine identified pandemic-related impacts as a critical focus area, with the field receiving numerous submissions related to the effects of SARS-CoV-2 on flight (Scheibler et al., 2023). For instance, knowledge on disease prevention and protocols for human spaceflight (Petersen et al., 2021), development of new clinical and operational guidelines for flight crew members (Osborn et al., 2020), and advances in space medicine research were specifically applied to pandemic management on Earth, with aerospace medical research serving as a resource to improve terrestrial medical care during COVID-19 (Cinelli and Russomano, 2021).

Moreover, the interconnectedness of human health conditions in space bears a striking resemblance to the observed condition of humans during a pandemic (COVID-19). The increase in aerospace health publications during the COVID-19 pandemic may be attributable to the recognition that some of the human body's responses in space share similarities with those seen in COVID-19. Both spaceflight and COVID-19 involve changes in the immune system, including increases in specific inflammation markers, such as interleukin-6 (IL-6) (Melnick et al., 2020). IL-6 has been widely studied during the pandemic because it is associated with more severe illness and has also been observed to rise during spaceflight due to stressors such as microgravity and radiation (Smith, 2018; Wang et al., 2022). This overlap prompted researchers to compare astronaut health with COVID-19, leading to greater interest in topics such as immune function, inflammation, and countermeasures. As a result, space medicine was increasingly viewed as relevant to broader public health challenges, contributing to the growth of aerospace health research during the pandemic years.

Ongoing developments in Mars exploration have provided promising insights into the possibility of extraterrestrial life, prompting further studies on the planet's habitability and potential for future human colonization. The Perseverance Rover, deployed during the Mars 2020 mission to explore the planet's ancient habitability through geological sampling (Thanadulsatit et al., 2024), has identified various mineral, chemical, and organic patterns that point to the possibility of biosignatures within the bright-toned outcrop observed on the northern margin of Neretva Vallis called Bright Angel formation (Hurowitz et al., 2025). While this discovery still requires verification through subsequent rock sampling and analysis, this provides the most prominent indication of life on another planet to date. As a result, studies emphasizing human adaptation and colonization in the aerospace environment have significantly expanded. The ongoing expansion of long-duration space missions from 2020 to the present may have contributed to the significant growth in interest in aerospace health. Artemis 1 started in 2022, during which time they tested out the ground systems, rocket, and spacecraft without a crew (Krishna, 2025). The further development of this project leads to Artemis 2, in which humans will be sent around the moon. The Artemis program represents a shift from Apollo's temporary lunar missions toward developing a sustainable human presence on the moon. The project aims to learn how to survive and work in the moon's environment (Krishna, 2025). This project alone led to the development of multiple studies exploring ways to survive in the aerospace environment, potentially for space tourism.

Space tourism was first introduced when Denis Tito successfully visited the International Space Station in 2001, and before that, only federal astronauts were permitted to travel to space (Chang, 2015). Space tourism gained significant popularity in 2021 with the emergence of various private space ventures. In July 2021, Blue Origin successfully conducted its first launch, followed by Virgin Galactic. Moving on to September 2021, SpaceX achieved another milestone with the launch of Dragon Resilience (Pallathadka and Pallathadka, 2022). More recently, Blue Origin's all-female space mission, featuring celebrities, further highlighted the growing accessibility and appeal of commercial space travel (Jessen, 2025). These privately funded space programs are a turning point for space tourism. This implies that multiple studies on aerospace health have arisen from this trend to assess the feasibility of human spaceflight (by determining risk and hazard). Therefore, the increase in aerospace health studies runs parallel with the growing demand for long-duration space travel, and the increase in aerospace health research output since 2020 can be interpreted as a transitional phase to heightened interest and a more defined research field, marking the shift of space exploration from a mere aspiration to a recognized public need. Thus, it is recommended that the scientific community foster aerospace health research by developing promising theories and models to meet the growing needs of space exploration.

Results also showed that among all World Health Organization (WHO) regions, the Americas are the predominant contributor to aerospace health research, primarily from the United States of America. This outcome may be linked to the United States of America's position as a frontrunner in aerospace exploration, which also extends to aerospace health. In addition, a majority of leading initiatives in space exploration are spearheaded by NASA (National Aeronautics and Space Administration) and major commercial companies such as SpaceX, Blue Origin, and Axiom Space, all based in the United States of America. According to NASA's Annual Highlights Report for 2024, bibliometric analyses revealed that the United States accounted for 23% of international collaborations in space research, making it the leading country in global space research partnerships. The same report documented 361 publications for fiscal year 2024, of which 80% were sponsored by NASA and the Japan Aerospace Exploration Agency (NASA, 2025). This implies that aerospace research is highly concentrated in the United States, reflecting the country's technological advancements, funding capacity, and institutional dominance in space science. As the United States has shaped the discourse on aerospace health, a global collaboration among other WHO regions is encouraged to globalize aerospace research. Publications were categorized according to the World Health Organization (WHO) regional classification system, and this approach causes an overrepresentation of the Americas since, under that region, the United States (a country that produces significant aerospace research) is included, even though other countries in the same region do not engage in aerospace research to the same extent. Hence, it is recommended for future analyses to consider alternative regional or country-specific classifications to ensure a more balanced representation of global research contributions.

Research in aerospace health is primarily driven by the synthesis and review of previously published articles. Space exploration limitations hinder the collection of additional data samples, as aerospace research is costly. Aerospace health is still in an exploratory infancy stage (navigating the "unknown"), and currently, NASA faces challenges such as reduced government funding, leading to increased reliance on private funding sources (Rausser et al., 2023). Additionally, environmental issues, including the accumulation of debris in low-Earth orbit, pose collision risks and threaten to make orbital environments economically unsustainable (Smith, 2023). Further use of existing studies can help develop ways to overcome space exploration limitations, such as funding and resource constraints, and to leverage modern technological innovations to bypass low-Earth-orbit debris. For the time being, simulated environments for "earth-based" studies in aerospace health should be considered to support continuous efforts in this area.

4.2 Article purpose and outcomes

The summary article's purpose and outcomes communicate various themes that encompass the objectives and results of all included studies in the present literature review. First, it was conveyed that aerospace health research primarily focuses on safeguarding and maintaining human physical health, hygiene, and stability during space missions. A potential association may be found in the fact that human safety is the top priority, in which ensuring the wellbeing of astronauts and humans beyond Earth's bounds, as well as low-orbit satellites, is crucial for the next level of development in longer, deeper space travel. Health risks from deep-space exposure remain uncertain and poorly understood, and technologies to mitigate them are underdeveloped. Along with isolation from expert care, health monitoring and prevention are therefore key priorities for ensuring human safety and health during space missions (Rajput et al., 2023). This implies that the uncertainty of the space environment makes it crucial that astronaut and personnel health monitoring be prioritized in aerospace healthcare. To enhance astronaut safety, future studies should focus on understanding and mitigating the risks currently identified in space environments.

It was found that advancements in the development of policies and procedures for aerospace health are relatively limited. Given the limited progress in developing policies and procedures in aerospace health over the years, there is a clear need for further advancement in this area. Limitations in advancing aerospace health policies may be attributed to the novelty of human space exploration, a relatively small and specialized population eligible for study, and logistical barriers to health research (Dev et al., 2024; Kahn et al., 2014; Lester and Robinson, 2009). At the scientific level, this constrains the development of standardized research and affects the integration of biomedical theories into practice. Ethically, this lack of robust policies creates uncertainty about astronaut health, undermining public trust and slowing broader participation in human space exploration (Detsis, 2022). A global approach is hence necessary in developing policies and standards. It will be helpful for future efforts to prioritize establishing clear, evidence-based health procedures that can be adopted across disciplines in aerospace health. This will strengthen astronaut safety and build public trust, both of which are necessary for the sustainability of long-duration space missions.

Findings also revealed that there are limited studies that review the role of medical practitioners and personnel. Even within aerospace medicine, research has prioritized engineering-oriented approaches in managing healthcare in space. Streamlined healthcare delivery systems extend healthcare reach to remote and underserved areas with round-the-clock availability (Anawade et al., 2024), including space. Biosensors, for instance, are leading a revolution in healthcare and ultimately, in life itself. This technological advancement marks a shift toward a more proactive, preventive approach to medical care (Vo and Trinh, 2024). This involves the further application of systems engineering principles that draw on best practices, as well as the adaptability of existing systems to better manage healthcare risks (Aujla et al., 2024). However, despite this growing reliance on technology-driven approaches, there remains a shortage of system engineers who are skilled in the healthcare domain and its unique challenges (Ferreira et al., 2023). Healthcare development relies on an engineering-based approach to enable the proactive identification and management of risks, particularly in situations where patients or subjects, such as astronauts, are beyond the direct care of medical professionals. It is critical to develop a balanced approach to health technology development, involving collaboration between healthcare professionals and system engineers, and to establish a competency framework to guide human resources training for health.

Lastly, it was observed that pharmaceutical and biomedical interventions have primarily been tested in simulated environments and/or on animal subjects due to the significant risks and safety concerns associated with involving human participants. These limitations are further driven by ethical and logistical constraints in conducting experimental interventions directly on astronauts. Given the limited number of trained and certified astronauts, ensuring their safety remains the foremost priority in aerospace health research. The small number of individuals who have ventured into space represents an invaluable data source that can inform future safety measures and enhance the success of upcoming space missions (Corlett et al., 2020). These findings underscore the critical importance of astronaut health and safety, not only for maintaining scientific integrity and mission success, but also for providing unique data essential to advancing human space exploration. Consequently, specialized protocols for pharmaceutical and biomedical applications in aerospace contexts may be necessary. Moreover, with the recent commercialization of space travel, broader participation could generate additional data on the physiological effects of space exposure, including polypharmacy and drug–drug interactions, which represent promising areas for future research.

In the eight themes summarized by Figures 2A,B, the Torus Model encapsulates geometric forms that visually represent how current knowledge on aerospace health operates as an interconnected system. The top-view torus displays eight key research areas: 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, all arranged radially around a center. The circular geometry emphasizes that every domain contributes equally to the core of research on aerospace health and that no single area functions in isolation. The radial symmetry, also highlighted by the delta and octagon, reflects the balanced contribution of each area. Correspondingly, the angled view of the toroidal shape symbolizes an ongoing, cyclical process in which knowledge circulates among all eight academic areas through a continuous feedback loop. This mirrors the real-world nature of research in this field, where advancements in one facet often drive the rise of new procedures, policies, or adaptations. Complementing this geometric structure, the network of lines that generally connects these domains further illustrates how research in one area consistently informs and strengthens findings in others. For instance, studies in Physiology and Health Risks often intersect with Psychology and Behavior (e.g., stress responses), Pharmaceuticals and Interventions (e.g., countermeasures), and Product and Technology (e.g., equipment performance). Fundamentally, the Torus Model's geometric forms depict the non-linear, multidirectional flow of knowledge across the eight research disciplines, which align with the integrative nature of aerospace health knowledge.

4.3 Article keyword network analysis

Thematic assessment of keyword network analysis revealed that aerospace health research is organized around ecosystems, diagnostics, education, biomedical engineering, health indicators, and empirical evidence. This may stem from the condition that aerospace health is multidimensional, with heavy influence from other non-health fields. Addressing astronaut health requires a systems-level perspective, in which expertise from medicine, engineering, behavioral sciences, and education converge to develop adaptive, evidence-based strategies. Given that aerospace health research is inherently multidisciplinary, diverse challenges from diagnostics and biomedical engineering to education and health indicators require specialized lines of inquiry (Chen et al., 2025). Apart from this, fragmented institutional priorities at the early stage of development of these fields may also have contributed to the clustering of research across various areas. Just as medical education seeks to unify basic science and clinical practice through systems thinking, aerospace health demands a similar integrative approach that synthesizes adaptive strategies for aerospace care in evolving environments (Aron, 2017).

Outcomes in this area suggest that improvement in aerospace health research requires not only continued advances in the hard sciences and engineering but also deliberate attention to the psychosocial dimensions of aerospace healthcare. This reflects the "Maslow's Effect," where scientific development follows the pattern of Maslow's Hierarchy of Human Needs, addressing basic physiological and safety needs with high priority before belongingness and self-actualization. For instance, the field of robotics initially focused on core functions, such as stability and locomotion, but has since expanded to higher-order concerns, including emotional intelligence and human-robot interactions (Dino et al., 2022; Mahdi et al., 2022). Similarly, the development of digital technologies has evolved beyond automation to support complex fields such as forensic sciences, serving human-centered needs by protecting human welfare, justice, and safety (Dino et al., 2025). Public health, which initially focused on controlling infectious diseases, sanitation, and vaccination in the early years, later evolved to emphasize mental health and quality of life to better understand human health needs (Tulchinsky and Varavikova, 2014). Therefore, future researchers in the field of aerospace health are expected to focus on higher-order needs such as Love and Belonging, Esteem, and Self-Actualization (Kenrick et al., 2010) to support holistic wellbeing and long-term mission success.

5 Conclusion

This systematic review on aerospace health research aimed to (1) describe bibliometric characteristics of published papers, (2) thematize article purposes and reported outcomes, and (3) perform a keyword network analysis to map conceptual linkages and emerging domains in the field of aerospace health. Bibliometric analysis revealed that aerospace health research is increasingly multi-authored and interdisciplinary, with publications rising since 2020, peaking in 2022–2023, and led predominantly by scholars from the Americas (i.e., the United States). The field also remains primarily driven by reviews and syntheses rather than empirical studies, reflecting its ongoing consolidation. In terms of purpose and outcomes, eight themes emerged that summarize the areas of research in aerospace health: 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. Building on these results, a conceptual model was generated using a space-inspired geometric figure, the Torus Model, to visually represent how these eight themes form an interconnected, self-sustaining system of knowledge within aerospace health research. Finally, keyword network analysis demonstrated that research in the field is structured around six interrelated themes: Health Ecosystem, Health Examination, Health Education, Health Engineering, Health Estimation, and Health Evidence. While aerospace health is still in its formative or infancy stage, this review may serve as a reference for policy and standards development and for developing a roadmap for aerospace health and associated healthcare provider competencies. This study also offers critical insights to inform future research and innovation in health technologies. Future developments should extend beyond basic survival measures to integrate psychosocial support systems that foster higher-order human wellbeing and mission resilience.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

MD: Conceptualization, Funding acquisition, Validation, Resources, Visualization, Project administration, Data curation, Methodology, Writing – review and editing, Formal Analysis, Software, Supervision, Investigation, Writing – original draft. CV: Validation, Resources, Conceptualization, Project administration, Writing – review and editing, Data curation, Formal Analysis, Software, Funding acquisition, Writing – original draft, Methodology, Investigation, Supervision, Visualization. JP: Writing – review and editing, Conceptualization, Supervision, Software, Writing – original draft, Methodology, Investigation, Resources, Project administration, Visualization, Funding acquisition, Data curation, Formal Analysis, Validation. JS: Writing – review and editing, Validation, Software, Resources, Investigation, Funding acquisition, Visualization, Methodology, Data curation, Project administration, Writing – original draft, Formal Analysis, Conceptualization, Supervision. JV: Funding acquisition, Software, Writing – review and editing, Resources, Investigation, Visualization, Formal Analysis, Writing – original draft, Validation, Data curation, Conceptualization, Supervision, Project administration, Methodology. DH: Software, Supervision, Funding acquisition, Writing – original draft, Writing – review and editing, Resources, Formal Analysis, Methodology, Data curation, Visualization, Investigation, Project administration, Conceptualization, Validation. LT: Visualization, Funding acquisition, Formal Analysis, Resources, Project administration, Conceptualization, Validation, Data curation, Software, Methodology, Writing – review and editing, Supervision, Investigation, Writing – original draft. VD: Funding acquisition, Supervision, Writing – review and editing, Conceptualization, Software, Project administration, Formal Analysis, Writing – original draft, Methodology, Resources, Data curation, Visualization, Investigation, Validation. MS: Data curation, Software, Project administration, Conceptualization, Visualization, Validation, Methodology, Writing – review and editing, Supervision, Funding acquisition, Writing – original draft, Investigation, Resources, Formal Analysis. LC: Writing – original draft, Resources, Formal Analysis, Funding acquisition, Writing – review and editing, Visualization, Project administration, Methodology, Software, Data curation, Conceptualization, Supervision, Investigation, Validation. ML: Funding acquisition, Writing – original draft, Writing – review and editing, Software, Resources, Visualization, Formal Analysis, Project administration, Conceptualization, Supervision, Validation, Methodology, Data curation, Investigation. JR: Validation, Writing – review and editing, Conceptualization, Methodology, Funding acquisition, Supervision, Investigation, Resources, Software, Formal Analysis, Project administration, Writing – original draft, Data curation, Visualization. RD: Resources, Funding acquisition, Visualization, Formal Analysis, Software, Writing – review and editing, Data curation, Writing – original draft, Conceptualization, Methodology, Validation, Project administration, Supervision, Investigation. JM: Investigation, Writing – review and editing,

Conceptualization, Funding acquisition, Supervision, Resources, Writing – original draft, Software, Project administration, Validation, Visualization, Methodology, Data curation, Formal Analysis.

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References

Abi-Ramia Silva, T., Burisch, F., and Güntner, A. T. (2024). Gas sensing for space: health and environmental monitoring. *TrAC Trends Anal. Chem.* 177, 117790. doi:10.1016/j.trac.2024.117790

Alemaryeen, A., Noghanian, S., and Fazel-Rezai, R. (2015). "EBG integrated textile monopole antenna for space health monitoring application," in 2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, 1209–1210. doi:10.1109/APS.2015.7304993

Anawade, P. A., Sharma, D., and Gahane, S. (2024). A comprehensive review on exploring the impact of telemedicine on healthcare accessibility. *Cureus* 16, e55996. doi:10.7759/cureus.55996

Aron, D. C. (2017). Developing a complex systems perspective for medical education to facilitate the integration of basic science and clinical medicine. *J. Eval. Clin. Pract.* 23 (2), 460–466. doi:10.1111/jep.12528

Aujla, N., Tooman, T., Arakelyan, S., Kerby, T., Hartley, L., O'Donnell, A., et al. (2024). New horizons in systems engineering and thinking to improve health and social care for older people. *Age Ageing* 53 (10), afae238. doi:10.1093/ageing/afae238

Aziz, S., Raza, M. A., Noreen, M., Iqbal, M. Z., and Raza, S. M. (2022). Astropharmacy: roles for the pharmacist in space. *INNOVATIONS Pharm.* 13 (3), 13. doi:10.24926/iip.v13i3.4956

Barbour, B. N., Twardowska, K., Favero, N., Ghoddousi, P., and Hodkinson, P. (2025). Biopsychosocial health considerations for astronauts in long-duration spaceflight: a narrative review. *Wilderness Environ. Med.* 36 (1_Suppl. l), 123S–137S. doi:10.1177/10806032241289106

Birur, G. C., Siebes, G., and Swanson, T. D. (2003). "Spacecraft thermal control," in *Encyclopedia of physical science and technology* (Elsevier), 485–505. doi:10.1016/B0-12-227410-5/00900-5

Bokhari, R. S., Beheshti, A., Blutt, S. E., Bowles, D. E., Brenner, D., Britton, R., et al. (2022). Looking on the horizon; potential and unique approaches to developing radiation countermeasures for deep space travel. *Life Sci. Space Res.* 35, 105–112. doi:10.1016/j.lssr.2022.08.003

Borges, L. L., Haberland, D. F., Guimarães, C. C. V., Felipe, L. A. D. F., and Aguiar, B. G. C. (2022). Training of nursing in chemical, biological, radiological and nuclear defense for aeromedical evacuation in the pandemic. *Rev. Gaúcha Enferm.* 43, e20200458. doi:10.1590/1983-1447.2022.20200458.en

Brass, J. (2006). *Methods of research on teaching the English language arts: the methodology chapters from the handbook of research on teaching the English language arts*. 2nd ed., 639–640. doi:10.1017/S0272263106250290

Burles, F., Williams, R., Berger, L., Pike, G. B., Lebel, C., and Iaria, G. (2023). The unresolved methodological challenge of detecting neuroplastic changes in astronauts. *Life* 13 (2), 500. doi:10.3390/life13020500

Cain, J. R. (2010). Lunar dust: the hazard and astronaut exposure risks. *Earth, Moon, Planets* 107 (1), 107–125. doi:10.1007/s11038-010-9365-0

Cain, J. (2011). Astronautical hygiene—A new discipline to protect the health of astronauts working in space. *J. Br. Interplanet. Soc.* 64, 179–185.

Cain, J. (2018). Mars colonisation: the health hazards and exposure control. *J. Br. Interplanet. Soc.* 71, 178–185.

Cain, J. R. (2019). Martian dust: the formation composition astronaut exposure health risks and measures to mitigate exposure. *J. BIS* 72, 167–171.

Chandler, J. V., and Polk-Walker, G. C. (1989). Health problems in the extraterrestrial environment. *Orthop. Nurs.* 8 (5), 51–55. doi:10.1097/00006416-198909000-00012

Chang, Y.-W. (2015). The first decade of commercial space tourism. *Acta Astronaut.* 108, 79–91. doi:10.1016/j.actaastro.2014.12.004

Chen, M.-L., Hsieh, K.-L., Hsieh, S.-L., Hsieh, M.-C., Lo, D. C.-T., and Hsu, J.-L. (2025). Barriers to using Mobile app-based cognitive testing in older adults with probable alzheimer's disease: a qualitative study. *Brain Sci.* 15 (5), 464. doi:10.3390/brainsci15050464

Chu, W. Y., and Tsia, K. K. (2023). EuniceScope: low-cost imaging platform for studying microgravity cell biology. *IEEE Open J. Eng. Med. Biol.* 4, 204–211. doi:10.1109/OJEMB.2023.3257991

Chua, C. Y. X., Jimenez, M., Mozneb, M., Traverso, G., Lugo, R., Sharma, A., et al. (2024). Advanced material technologies for space and terrestrial medicine. *Nat. Rev. Mater.* 9 (11), 808–821. doi:10.1038/s41578-024-00691-0

Chunduri, R., Aritra, R., Das, P., Simon, A., and Nanda, R. R. (2022). Space travel and its impact on human physiology: is space truly for all? Available online at: https://www.researchgate.net/publication/364355809_Space_Travel_and_its_Impact_on_Human_Physiology_Is_Space_Truly_for_All.

Cinelli, I., and Russomano, T. (2021). Advances in space medicine applied to pandemics on Earth. *Space Sci. Technol.* 2021, 2021–9821480. doi:10.34133/2021/9821480

Cohen, E. (2022). Outer space mobilities and human health. *Tour. Geogr.* 24 (6–7), 1123–1133. doi:10.1080/14616688.2020.1868020

Corlett, T., Stavnichuk, M., and Komarova, S. V. (2020). Population analysis of space travelers. *Life Sci. Space Res.* 27, 1–5. doi:10.1016/j.lssr.2020.06.003

Davenport, E., Palileo, E., and Gore, S. (2021). Cardiovascular screening for pilots, aircrew, and high performance & spaceflight passengers. *REACH* 21–22, 100040. doi:10.1016/j.reach.2021.100040

Detsis, E. (2022). "Ethics in space: the case for future space exploration," in *Ethics, integrity and policymaking*. Editors D. O'Mathúna and R. Iphofen (Springer International Publishing), 9, 111–121. doi:10.1007/978-3-031-15746-2_9

Dev, S. I., Khader, A. M., Begerowski, S. R., Anderson, S. R., Clément, G., and Bell, S. T. (2024). Cognitive performance in ISS astronauts on 6-month low earth orbit missions. *Front. Physiology* 15, 1451269. doi:10.3389/fphys.2024.1451269

Dewey, H. H., and DeVries, D. R. (2020). *Application of a physics-of-failure mentality for aerospace health management systems* in 2020 IEEE Aerospace Conference, 1–7. doi:10.1109/AERO47225.2020.9172352

Dino, M. J. S., Davidson, P. M., Dion, K. W., Szanton, S. L., and Ong, I. L. (2022). Nursing and human-computer interaction in healthcare robots for older people: an integrative review. *Int. J. Nurs. Stud. Adv.* 4, 100072. doi:10.1016/j.ijnsa.2022.100072

Dino, M. J., Balbin, P. T., Villafuerte, C. M. R., Magat-Pangilinan, M. S., David, J., Tee, P. A., et al. (2025). Extended reality in forensic sciences: an integrative review. *Sci. Justice* 65 (6), 101339. doi:10.1016/j.scijus.2025.101339

Elam, A., Gibson, C., Metwalli, Z., Robb, R., Rooney, T., Liebschner, M., et al. (2005). "Advanced space health maintenance system: technology enabling extended manned space exploration," in Space 2005. *Space 2005*. California: Long Beach. doi:10.2514/6.2005-6788

Ferreira, S., Phelps, E., Abolmaali, S., Reed, G., and Greilich, P. (2023). Opportunities to apply systems engineering to healthcare interprofessional education. *Front. Med.* 10, 1241041. doi:10.3389/fmed.2023.1241041

Gunga, H.-C. (2021). "Space," in *Human physiology in extreme environments* (Elsevier), 285–324. doi:10.1016/B978-0-12-815942-2.00007-9

Gupta, R., and Ghosh, P. S. (2025). Advancements in health monitoring technologies for astronauts in deep space missions: a review. *Life Sci. Space Res.* 47, 190–196. doi:10.1016/j.lssr.2025.06.011

Hurowitz, J. A., Tice, M. M., Allwood, A. C., Cable, M. L., Hand, K. P., Murphy, A. E., et al. (2025). Redox-driven mineral and organic associations in Jezero Crater, Mars. *Nature* 645 (8080), 332–340. doi:10.1038/s41586-025-09413-0

Huttner-Koros, A., and Perera, S. (2016). Communicating science in English: a preliminary exploration into the professional self-perceptions of Australian scientists from language backgrounds other than English. *J. Sci. Commun.* 15 (06), A03. doi:10.22323/2.15060203

Jemison, M., and Olabisi, R. (2021). Biomaterials for human space exploration: a review of their untapped potential. *Acta Biomater.* 128, 77–99. doi:10.1016/j.actbio.2021.04.033

Jessen, J. (2025). How sustainable is blue origin's new shepard space flight? Sustainability magazine, diversity&Inclusion (D&I). Available online at: https://sustainabilitymag.com/articles/diversity-circularity-blue-origins-all-women-crew?utm_source=chatgpt.com.

Kahn, J., Liverman, C., and McCoy, M. (2014). *Health standards for long duration and exploration spaceflight: ethics principles, responsibilities, and decision framework*. Washington, DC: Institute of Medicine of the National Academies. doi:10.17226/18576

Kapoor, P., Yadav, R. B., Agrawal, N., Gaur, S., and Arora, R. (2025). Long duration space missions: challenges and prospects in sustaining humans in space. *Life Sci. Space Res.* 47, 14–31. doi:10.1016/j.lssr.2025.05.001

Kenrick, D. T., Griskevicius, V., Neuberg, S. L., and Schaller, M. (2010). Renovating the pyramid of needs: contemporary extensions built upon ancient foundations. *Perspect. Psychol. Sci.* 5 (3), 292–314. doi:10.1177/1745691610369469

Khan, S. U. E., Varghese, R. J., Kassanos, P., Farina, D., and Burdet, E. (2024). Space physiology and technology: musculoskeletal adaptations, countermeasures, and opportunities for wearable systems (version 2). *arXiv*. doi:10.48550/ARXIV.2404.03363

King, C. (2013). *Multiauthor papers: onward and upward*, 4. Ontario, Canada: Thomson Reuters.

Krishna, S. (2025). The farthest journey in human history is about to begin NASA's artemis II mission could happen as early as February. Here's why this flight will be one to watch. *Natl. Geogr.* Available online at: https://www.nationalgeographic.com/science/article/artemis-2-moon-mission-astronauts.

Krittanawong, C., Singh, N. K., Scheuring, R. A., Urquieta, E., Bershad, E. M., Macaulay, T. R., et al. (2022). Human health during space travel: state-of-the-art review. *Cells* 12 (1), 40. doi:10.3390/cells12010040

Kunitskaya, A., Piret, J. M., Buckley, N., and Low-Décarie, E. (2022). Meta-analysis of health research data from greater than three months international space station missions. *Acta Astronaut.* 201, 420–430. doi:10.1016/j.actaastro.2022.09.019

Kutch, J. M. (1985). Aerospace health services administration: strategic concepts and requirements. *Mil. Med.* 150 (12), 670–672. doi:10.1093/milmed/150.12.670

Lester, D. F., and Robinson, M. (2009). Visions of exploration. *Space Policy* 25 (4), 236–243. doi:10.1016/j.spacepol.2009.07.001

Madani, P., and McGregor, C. (2024). "Cybersecurity issues in space optical communication networks and future of secure space health systems," in 2024 IEEE Aerospace Conference, 1–8. doi:10.1109/AERO58975.2024.10521087

Mahdi, H., Akgun, S. A., Saleh, S., and Dautenhahn, K. (2022). A survey on the design and evolution of social robots—Past, present and future. *Robotics Aut. Syst.* 156, 104193. doi:10.1016/j.robot.2022.104193

Martinez, J., Donati, A., Damann, V., Biancat, J., Brighenti, C., Brighenti, A., et al. (2016). "Data mining for astronauts medical autonomy," in SpaceOps 2016 Conference (Daejeon, Korea). doi:10.2514/6.2016-2382

McGregor, C. (2021). "A platform for real-time space health analytics as a service utilizing space data relays," in 2021 IEEE Aerospace Conference, 1–14. doi:10.1109/AERO50100.2021.9438475

Melnick, A., Mason, C., and Lyden, D. (2020). *Studies reveal clues about preventing spaceflight-related risks*. New York, NY: Weill Cornell Medicine. Available online at: https://news.weill.cornell.edu/news/2020/11/studies-reveal-clues-about-preventing-spaceflight-related-risks.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G.PRISMA Group (2010). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Int. J. Surg.* 8 (5), 336–341. doi:10.1016/j.ijsu.2010.02.007

Moran, M. E. (2007). The urologist's guide to the galaxy. *AIP Conf. Proc.* 900, 383–388. doi:10.1063/1.2723601

NASA (2013). *Benefits stemming from space exploration*. Washington, DC: National Aeronautics and Space Administration.

NASA (2025). *Annual highlights of results from the international space station*. Washington, DC: National Aeronautics and Space Administration. Available online at: https://www.nasa.gov/wp-content/uploads/2025/02/ahr-2024-final.pdf?emrc=519fad&utm_source=chatgpt.com.

Nuryatno, E. T., Datumaya Wahyudi Sumari, A., Ayuningtyas, A., Kusumaningrum, A., Pujiastuti, A., and Wintolo, H. (2023). "A preliminary study in exploring aerospace health informatics core competencies: grounded theory perspective," in 2023 International Conference on Electrical and Information Technology (IEIT), 12–18. doi:10.1109/IEIT59852.2023.10335569

Olusegun, A., Omotayo, O., Taiwo, F., and Olorunleke, D. (2024). Theoretical and conceptual review: an essential part of social and management sciences research process. *Int. J. Soc. Sci. Relig. (IJSSR)* 10 (5).

Oluwafemi, F. A. (2018). "Astronautical hygiene: a communal discipline to space medicine and a preventive measure to space diseases," in *IAF/IAA SPACE LIFE SCIENCES SYMPOSIUM (A1) medical care for humans in space (3). 69th international astronautical congress 2018.*

Osborn, L., Meyer, D., Dahm, P., Ferguson, B., Cabrera, R., Sanger, D., et al. (2020). Integration of aeromedicine in the response to the COVID-19 pandemic. *JACEP Open* 1 (4), 557–562. doi:10.1002/emp2.12117

Pagbilao, S., Anne Therese, M., Pfeifer, P., C. Cainguitan, S. M., Felipe, F., Macalling, M., L., et al. (2023). Building a community of practice in a sustained culture of lesson study: the case of Saguday, Philippines. *Am. J. Educ. Res.* 11 (12), 783–791. doi:10.12691/education-11-12-1

Pallathadka, H., and Pallathadka, L. K. (2022). A detailed study of space X vs. Blue origin vs. Virgin galactic and the future of space travel. *Integr. J. Res. Arts Humanit.* 2 (6), 195–201. doi:10.55544/ijrah.2.6.26

Paul, A. M., Cheng-Campbell, M., Blaber, E. A., Anand, S., Bhattacharya, S., Zwart, S. R., et al. (2020). Beyond low-earth orbit: characterizing immune and microRNA differentials following simulated deep spaceflight conditions in mice. *iScience* 23 (12), 101747. doi:10.1016/j.isci.2020.101747

Paula, B. A. C. D., Haberland, D. F., Guilherme, F. J. D. A., Barbosa, B. L., Oliveira, A. B. D., and Silva, T. A. S. M. D. (2024). Aerospace nurses' competencies in disaster situations: a scoping review. *Rev. Latino-Americana Enferm.* 32, e4326. doi:10.1590/1518-8345.7421.4326

Pelligra, S., Casstevens, E. A., Matthews, M. J., and Edemekong, P. F. (2025). "Aerospace health maintenance wellness," in *StatPearls* (StatPearls, FL: StatPearls Publishing). Available online at: http://www.ncbi.nlm.nih.gov/books/NBK441915/.

Petersen, E., Pattarini, J. M., Mulcahy, R. A., Beger, S. B., Mitchell, M. R., Hu, Y. D., et al. (2021). Adapting disease prevention protocols for human spaceflight during COVID-19. *Aerosp. Med. Hum. Perform.* 92 (7), 597–602. doi:10.3357/AMHP.5832.2021

Polk-Walker, G. C. (1989). Aerospace nursing. *J. Prof. Nurs.* 5 (4), 224–230. doi:10.1016/S8755-7223(89)80055-9

Pulvirenti, E. (2024). Advancing space health: towards a soft wearable hypogravity exosuit (hexsuit) for enhanced mobility in martian conditions. *IAF Hum. Spacefl. Symp.*, 574–582. doi:10.52202/078364-0065

Rajput, S., Mayor, I., Diamond, M., Rosenberg, M., Cole, V., Bhakare, N., et al. (2023). Medical ethics of long-duration spaceflight. *Npj Microgravity* 9 (1), 85. doi:10.1038/s41526-023-00333-9

Rasheed, S. P., Younas, A., and Sundus, A. (2019). Self-awareness in nursing: a scoping review. *J. Clin. Nurs.* 28 (5–6), 762–774. doi:10.1111/jocn.14708

Rausser, G., Choi, E., and Bayen, A. (2023). Public–private partnerships in fostering outer space innovations. *Proc. Natl. Acad. Sci.* 120 (43), e2222013120. doi:10.1073/pnas.2222013120

Rivera, M. V., Vargas, M., Cornejo, J., Plascencia, P. V., Guillen, K., Maquera, E., et al. (2024). Space nursing for the future management of astronaut health in other planets: a literature review. *Open Nurs. J.* 18 (1), e18744346289848. doi:10.2174/0118744346289848240328074640

Rudge, F. W. (1995). A review of articles published in aviation, space, and environmental medicine, 1975-94. *Aviat. Space, Environ. Med.* 66 (10), 1005–1009.

Rudolf, A. M., and Hood, W. R. (2024). Mitochondrial stress in the spaceflight environment. *Mitochondrion* 76, 101855. doi:10.1016/j.mito.2024.101855

Sarma, M. S., Niclou, A. M., and Hurd, K. J. (2025). Methodologic opportunities for space health research: integrating biological anthropology methods in human research for precision space health and medical data. *Wilderness Environ. Med.* 36 (1_Suppl. l), 104S–112S. doi:10.1177/10806032251349436

Scheibler, C., Crane-Godreau, M. A., and McNeely, E. (2023). Editorial: aerospace health and safety: today and the future, volume I. *Front. Public Health* 11, 1264524. doi:10.3389/fpubh.2023.1264524

Scott, R. T., Sanders, L. M., Antonsen, E. L., Hastings, J. J. A., Park, S., Mackintosh, G., et al. (2023). Biomonitoring and precision health in deep space supported by artificial intelligence. *Nat. Mach. Intell.* 5 (3), 196–207. doi:10.1038/s42256-023-00617-5

Sharp, J., Kelson, J., South, D., Saliba, A., and Kabir, M. A. (2025). Virtual reality and artificial intelligence as psychological countermeasures in space and other isolated and confined environments: a scoping review (version 1). *arXiv*. doi:10.48550/ARXIV.2504.01366

Sheng, R. (2019). "Systems engineering fundamentals," in *Systems engineering for aerospace* (Elsevier), 113–206. doi:10.1016/B978-0-12-816458-7.00007-7

Siagian, M. (2012). Hypertension in Indonesian air force pilots. *Med. J. Indonesia* 38, 38. doi:10.13181/mji.v21i1.477

Siagian, M., Basuki, B., and Kusmana, D. (2009). High intensity interior aircraft noise increases the risk of high diastolic blood pressure in Indonesian air force pilots. *Med. J. Indonesia* 276, 276. doi:10.13181/mji.v18i4.375

Simpson, A. C. (2023). Challenges and opportunities for bioactive compound and antibiotic discovery in deep space. *J. Indian Inst. Sci.* 103 (3), 819–832. doi:10.1007/s41745-023-00385-6

Sjner, J. C. (1967). Science and technology in space nursing. *AORN J.* 5 (1), 71–75. doi:10.1016/S0001-2092(08)71358-9

Smith, L. E. (2003). "English language, role in international communications," in *Encyclopedia of international media and communications* (Elsevier), 523–528. doi:10.1016/B0-12-387670-2/00081-9

Smith, J. K. (2018). IL-6 and the dysregulation of immune, bone, muscle, and metabolic homeostasis during spaceflight. *Npj Microgravity* 4 (1), 24. doi:10.1038/s41526-018-0057-9

Smith, H. (2023). Near, far, wherever we are: space exploration urgently needs an ethics-informed planning revolution. *Adv. Astronautics Sci. Technol.* 6 (1), 47–55. doi:10.1007/s42423-023-00135-x

Sobel, A., and Duncan, R. (2020). Aerospace environmental health: considerations and countermeasures to sustain crew health through vastly reduced transit time to/From Mars. *Front. Public Health* 8, 327. doi:10.3389/fpubh.2020.00327

Sun, T., Xu, Y., Xie, H., Ma, Z., and Wang, Y. (2021). Intelligent personalized exercise prescription based on an eHealth promotion system to improve health outcomes of middle-aged and older adult community dwellers: pretest-posttest study. *J. Med. INTERNET Res.* 23 (5), e28221. doi:10.2196/28221

Sun, X., Wandelt, S., and Zhang, A. (2022). COVID-19 pandemic and air transportation: summary of recent research, policy consideration and future research directions. *Transp. Res. Interdiscip. Perspect.* 16, 100718. doi:10.1016/j.trip.2022.100718

Tavakol, D. N., Nash, T. R., Kim, Y., He, S., Fleischer, S., Graney, P. L., et al. (2023). Modeling and countering the effects of cosmic radiation using bioengineered human tissues. *Biomaterials* 301, 122267. doi:10.1016/j.biomaterials.2023.122267

Thanadulsatit, T., Bualert, P., Deschanin, S., Ruxthawonwong, T., Rueankham, S., Wongsawat, S., et al. (2024). A review of structural and system design of mars rover curiosity and perseverance. *Suranaree J. Sci. Technol.* 31 (2), 010294. doi:10.55766/sujst-2024-02-e01241

Tran, Q. D., Tran, V., Toh, L. S., Williams, P. M., Tran, N. N., and Hessel, V. (2022). Space medicines for space health. *ACS Med. Chem. Lett.* 13 (8), 1231–1247. doi:10.1021/acsmedchemlett.1c00681

Tulchinsky, T. H., and Varavikova, E. A. (2014). "A history of public health," in *The new public health* (Elsevier), 1–42. doi:10.1016/B978-0-12-415766-8.00001-X

Vallota-Eastman, A., Bui, C., Williams, P. M., Valentine, D. L., Loftus, D., and Rothschild, L. (2023). Bacillus subtilis engineered for aerospace medicine: a platform for on-demand production of pharmaceutical peptides. *Front. Space Technol.* 4, 1181843. doi:10.3389/frspt.2023.1181843

Vo, D.-K., and Trinh, K. T. L. (2024). Advances in wearable biosensors for healthcare: current trends, applications, and future perspectives. *Biosensors* 14 (11), 560. doi:10.3390/bios14110560

Waisberg, E., Ong, J., Masalkhi, M., Zaman, N., Kamran, S. A., Sarker, P., et al. (2023). Generative pre-trained transformers (GPT) and space health: a potential frontier in astronaut health during exploration missions. *Prehospital Disaster Med.* 38 (4), 532–536. doi:10.1017/S1049023X23005848

Wang, X., Tang, G., Liu, Y., Zhang, L., Chen, B., Han, Y., et al. (2022). The role of IL-6 in coronavirus, especially in COVID-19. *Front. Pharmacol.* 13, 1033674. doi:10.3389/fphar.2022.1033674

Wang, Y., Wang, L., and Siau, K. L. (2025). Human-centered interaction in virtual worlds: a new era of generative artificial intelligence and metaverse. *Int. J. Human–Computer Interact.* 41 (2), 1459–1501. doi:10.1080/10447318.2024.2316376

Wani, A., Prabhakar, B., and Shende, P. (2024). Strategic aspects of space medicine: a journey from conventional to futuristic requisites. *Space Sci. Technol.* 4, 0123. doi:10.34133/space.0123

Whittemore, R., and Knafl, K. (2005). The integrative review: updated methodology. *J. Adv. Nurs.* 52 (5), 546–553. doi:10.1111/j.1365-2648.2005.03621.x

Xiao, Y., Luo, Q., Yu, Y., Cao, B., Wu, M., Luo, Y., et al. (2021). Effect of baduanjin on the fall and balance function in middle-aged and elderly people: a protocol for systematic review and meta-analysis. *Medicine* 100 (37), e27250. doi:10.1097/MD.0000000000027250