Astropharmacy: Consensus-integrated space health model and potential action plans

Muhammad Ahmer Raza, PhD Student, M.Pharm., Pharm.D.[1,2]
[1]INNOVATIONS in pharmacy Editorial Member
[2]The University of Faisalabad

Astropharmacy, an emerging discipline at the intersection of pharmacy and space medicine, requires structured models to guide knowledge dissemination, education, and practice. In our prior publications in Innovations in Pharmacy, we proposed the Participation, Action, Research (PAR) model and established the framework for a Space Pharmacy Council[1]. Additionally, we explored Space Pharmacy education for pharmacists through the Teeter-Totter Model, If-Then Logic Model, and the Socio-Ecological Framework, laying the foundation for systematic training in this novel field[2]. Then in a commentary article, we discussed the multifaceted roles of pharmacists across the space mission pathway[3]. Pharmacists are uniquely positioned to optimize medication management, reduce the risk to enhance and validate safety measures, and provide expertise in pharmacokinetics, pharmacodynamics, and drug stability under space conditions. Their responsibilities span pre-mission preparation, in-mission medication oversight, and post-mission health evaluations. This framework highlighted the need for structured educational programs and governance strategies to formalize pharmacists' contributions in extraterrestrial settings. Building on these foundational efforts, I aim to introduce the Consensus-Integrated Space Health Model (CISHM) and outline potential action plans for astropharmacy. The CISHM is designed to provide a structured, evidence-informed framework that integrates multidisciplinary expertise to optimize astronaut health outcomes across the mission lifecycle.

Theoretical Rationale of the Consensus-Integrated Space Health Model

The CISHM in Figure 1 proposed as a conceptual and operational framework to address the growing complexity of healthcare delivery during space missions. As human spaceflight advances toward longer-duration missions and increased autonomy from Earth-based support, traditional hierarchical healthcare models become insufficient[4].

Corresponding Author:
Muhammad Ahmer Raza
INNOVATIONS in pharmacy Editorial Member
The University of Faisalabad
ahmerraza313@yahoo.com

Space medicine operates under extreme constraints, including delayed communication, limited medical resources, altered human physiology, and high uncertainty[5]. Within this context, pharmaceutical decision-making cannot remain siloed or unidirectional. Instead, it must be embedded within a dynamic, collaborative system that integrates expertise, clinical judgment, and operational experience. The CISHM responds to this need by positioning pharmacists, physicians, and astronauts as interdependent stakeholders engaged in continuous, evidence-informed, and feedback-driven decision-making.

The rationale behind this model is grounded in three core principles: shared accountability, adaptive learning, and transparency. Unlike terrestrial healthcare settings, where redundancy and rapid escalation are often possible, space missions demand anticipatory planning and collective responsibility[3]. Medication-related decisions in space - ranging from drug selection and storage to dose adjustment and adverse event management - carry amplified risk due to physiological changes induced by microgravity and radiation exposure[6]. The model therefore emphasizes consensus-based decision-making rather than unilateral authority, ensuring that no single professional perspective dominates complex clinical scenarios. By integrating pre-mission review, in-mission feedback, and post-mission evaluation, the model creates a closed-loop system that continuously refines pharmaceutical and clinical practices across missions. Conceptualizing space health through these theoretical lenses provides a robust foundation for governance, structured education, and operational protocols in astropharmacy, translating expert consensus into actionable strategies that safeguard astronaut well-being while advancing the professional scope of pharmacists in extraterrestrial settings.

Consensus-Integrated Space Health Model

Within the CISHM model (Figure 1), pharmacists occupy a central role as the primary stewards of medication expertise. Their responsibilities extend beyond conventional pharmaceutical functions to include pre-mission protocol evaluation, risk assessment, and independent transparency reviews. Pharmacists assess medication stability under space-specific conditions, evaluate pharmacokinetic and pharmacodynamic uncertainties, and identify potential conflicts of interest or biases in protocol development[3,6]. Through pre-mission knowledge transfer, they translate complex pharmaceutical evidence into operationally relevant guidance for physicians and astronauts. Importantly, pharmacists remain engaged throughout the mission lifecycle,

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contributing to real-time medication adjustments based on astronaut feedback and clinical updates. Their role is not static but adaptive, ensuring that pharmaceutical decision-making remains evidence-based, unbiased, and responsive to emerging data.

Physicians, on the other hand, serve as the clinical integrators within the model, bridging pharmaceutical expertise with diagnostic reasoning and therapeutic decision-making. Their role is centered on contextualizing pharmacist recommendations within the broader clinical and mission-specific landscape. Physicians interpret pharmaceutical guidance through the lens of astronaut physiology, mission demands, and diagnostic uncertainty, ensuring that treatment plans remain both medically sound and operationally feasible[7]. During missions, physicians collaborate closely with astronauts and pharmacists to manage adverse events, adjust dosing strategies, and respond to evolving health conditions. Post-mission, physicians contribute to independent audits and outcome evaluations, helping to assess whether clinical and pharmaceutical decisions aligned with intended objectives and produced favorable health outcomes.

Astronauts, traditionally viewed as passive recipients of medical care, are repositioned in this model as active contributors and operational feedback providers. Their role reflects the reality that astronauts are the only healthcare actors physically present in the space environment. Through structured training, astronauts can gain the competence required to implement medication regimens, recognize adverse effects, and report real-time observations. In-mission feedback from astronauts will serve as a critical data source, informing medication adjustments and clinical decision-making. Post-mission debriefings will further enable astronauts to contribute experiential insights that may not be captured through quantitative data alone, such as challenges related to adherence, usability of medication systems, or cognitive and physical constraints. This elevation of the astronaut's role can enhance autonomy while maintaining safety through consensus oversight.

At the core of the model lies shared decision-making, represented as a central node connecting pharmacists, physicians, and astronauts. This shared space reflects the integration of pharmaceutical evidence, clinical judgment, and operational experience. Decision-making is not confined to a single mission phase but spans the entire mission lifecycle. Prior to missions, pre-mission transparency reviews can ensure protocol robustness and ethical integrity. During missions, real-time feedback loops enable dynamic adjustments based on emerging data and astronaut experiences. Following missions, structured debriefings and independent audits support learning, protocol refinement, and training updates. The inclusion of independent evaluation mechanisms further strengthens the model by promoting accountability, minimizing bias, and enabling outcome-based assessment of decisions.

A critical strength of the model is the involvement of unbiased and independent experts in shared decision-making processes, particularly during pre-mission transparency reviews and post-mission evaluations. In high-stakes environments such as space missions, professional hierarchies, institutional pressures, or mission-driven optimism can unintentionally bias decision-making. The inclusion of independent experts - who are not directly embedded within mission command structures - serves as a safeguard against such biases. These experts provide objective assessments of protocols, identify overlooked risks, and challenge assumptions that may otherwise go unquestioned. Their involvement enhances epistemic rigor, strengthens ethical integrity, and reinforces trust among stakeholders. By institutionalizing independent expertise within the consensus framework, the model balances collaboration with critical oversight, ensuring that shared decision-making remains both inclusive and scientifically robust.

Advantages of CISHM

The Consensus-Integrated Space Health Model offers several distinct advantages. By integrating pharmacists as equal partners, the model elevates medication safety and pharmaceutical governance within space medicine. Continuous feedback and evaluation loops promote adaptive learning and reduce the likelihood of repeated errors across missions. Shared accountability mitigates professional silos and aligns clinical, pharmaceutical, and operational objectives. Transparency mechanisms enhance trust and ethical compliance, while independent evaluation supports evidence-based refinement of practices. Collectively, these features position the model as a scalable and resilient framework capable of supporting the future of human space exploration.

Despite its strengths, the model also raises important questions that warrant further discussion and inquiry. How can transparency and consensus be maintained during acute medical emergencies when rapid decisions are required? What governance structures are necessary to formalize the role of independent experts in mission-critical decision-making? How can digital decision-support systems and artificial intelligence be integrated into transparency and feedback loops without diminishing professional accountability? As mission autonomy increases, how should the balance between expert oversight and astronaut self-management evolve? Addressing these questions will be essential for refining the model and ensuring its applicability to increasingly complex space missions.

Astropharmacy: Potential Action Plans

The operationalization of astropharmacy demands a structured, multidimensional framework that translates theoretical knowledge into practice across the educational, scientific, and regulatory domains of space medicine[1,2]. As space missions evolve from short-term expeditions to long-duration habitation, the pharmaceutical dimension becomes central to sustaining astronaut health and mission success. Unlike terrestrial pharmacy, space pharmacotherapy must address unprecedented challenges—ranging from altered pharmacokinetics and drug degradation under microgravity to limited medical resources and communication delays. Thus, the establishment of astropharmacy is not merely an academic pursuit but an operational necessity for ensuring the safety, autonomy, and resilience of future space crews.

To achieve this, a set of coordinated action plans is required to bridge the gap between pharmaceutical science and space operations. These plans collectively aim to build capacity through education and training, establish regulatory and governance frameworks, strengthen interdisciplinary collaboration, promote targeted pharmaceutical research, and develop digital systems for medication monitoring and knowledge transfer. Furthermore, ongoing evaluation, advocacy, and public engagement are essential to maintain scientific rigor, ethical integrity, and global participation. To achieve this goal, the following seven action plans propose a strategic roadmap aimed at transforming astropharmacy from an emerging concept into a functional and sustainable pillar of space healthcare. A summary of these plans is presented in Table 1, while their interconnections are illustrated in Figure 2.

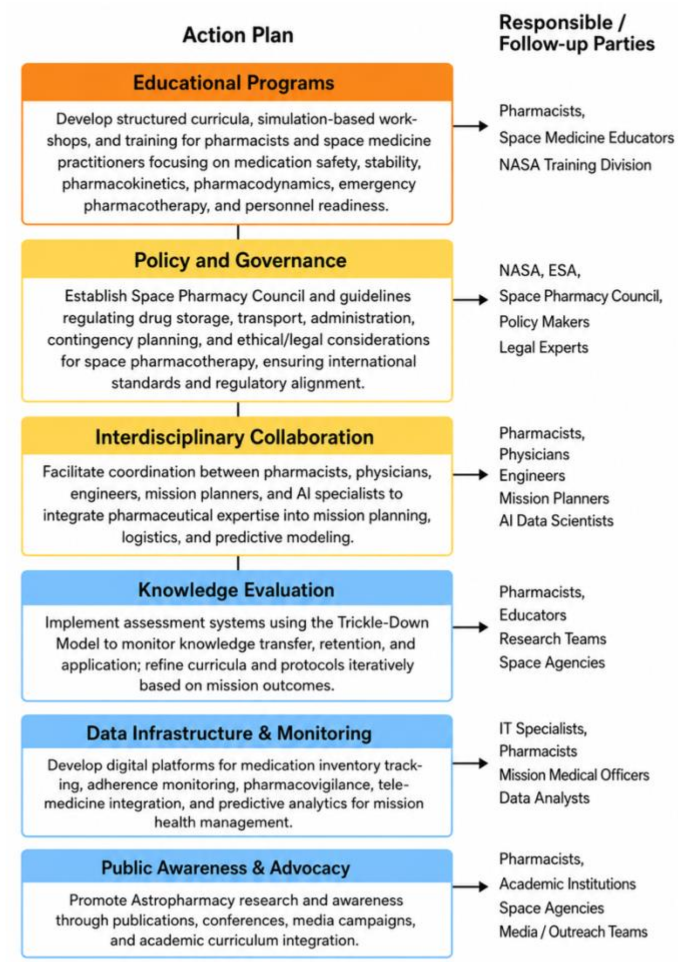
Educational programs

The development of structured educational programs is a foundational step in operationalizing astropharmacy[8]. These programs should encompass specialized curricula and simulation-based workshops designed for pharmacists and space medicine practitioners. They must address the challenges of selection and drug stability under microgravity, exposure to cosmic radiation, and extreme temperature variations, as well as pharmacokinetic and pharmacodynamic alterations observed in astronauts during spaceflight. In addition, training should cover emergency pharmacotherapy, adverse event management, and personalized medicine approaches applicable to long-duration missions. The design and delivery of these programs require collaboration among pharmacists, who provide subject matter expertise, space medicine educators responsible for integrating content into astronaut training programs, and space agencies such as National Aeronautics and Space Administration (NASA), which provide necessary resources, infrastructure, and certification systems to ensure competence and readiness.

Policy and governance

Establishing a robust policy and governance framework is essential for ensuring safe and standardized pharmaceutical practices in space. The creation of a Space Pharmacy Council will centralize oversight and define standardized protocols for drug storage, transport, and administration. Policies should also address contingency planning for controlled substances, medication shortages, stability issues, and unforeseen emergencies.

Figure 2. *Illustration of interconnections in potential action plans for astropharmacy*



Abbreviations: AI, artificial intelligence; ESA, European Space Agency; IT, information technology; NASA, National Aeronautics and Space Administration

Furthermore, ethical, legal, and regulatory considerations for space pharmacotherapy must be integrated, particularly in the context of international collaboration and joint missions. Responsibility for policy development and enforcement should be shared among space agencies such as NASA and European Space Agency (ESA), referring to the Space Pharmacy Council for drafting unbiased guidelines, and seeking legal and policy experts to ensure compliance with ethical and international regulatory standards.

Interdisciplinary collaboration

Interdisciplinary collaboration is critical to integrate pharmaceutical expertise into comprehensive mission planning[1]. Pharmacists must work with physicians to define clinical priorities and anticipate astronaut health needs. Engineers play a pivotal role in designing storage and delivery systems capable of withstanding microgravity and radiation

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exposure, while mission planners ensure pharmaceutical logistics are integrated into supply chains and emergency reserves. Additionally, artificial intelligence (AI) specialists and data scientists can support predictive modeling for medication usage, adverse event risk, and individualized treatment planning. Effective collaboration ensures holistic medical preparedness, with responsibilities shared across pharmacists, physicians, engineers, mission planners, and AI experts.

Knowledge evaluation

Evaluation of knowledge transfer is essential to ensure that educational interventions translate into operational competence[1]. The Trickle-Down Model can be employed to monitor learning outcomes across multiple levels, from trainees to operational teams to astronauts in mission settings. Pre- and post-training assessments enable quantification of knowledge retention, comprehension, and practical application of space pharmacotherapy principles. Continuous feedback loops allow for iterative refinement of curricula and mission protocols. Pharmacists and educators are responsible for assessment design, research teams for data analysis, and space agencies for integrating outcomes into mission readiness strategies.

Pharmaceutical research and development

Focused research and development are necessary to address the unique wellness preservation, health restoration, and pharmacological challenges of space environments. Investigations should initially prioritize long-acting drug formulation prior to departure drug stability under microgravity, radiation exposure, and temperature variations[6]. Development of space-stable formulations, including lyophilized or solid-dose alternatives, for medications that treat acute medical ailments is critical for long-duration missions. Personalized pharmacotherapy approaches, supported by AI-driven predictive models, can optimize safety and efficacy for individual astronauts. Pharmacists and pharmaceutical scientists should lead these studies, while research institutes provide laboratory and analytical infrastructure. Space agencies play a central role in funding and operational support for research conducted in analog environments or in orbit.

Data infrastructure and monitoring

Robust data infrastructure is essential for effective medication management and astronaut safety. Digital systems can enable real-time tracking of drug inventories, adherence monitoring, and pharmacovigilance. Telemedicine platforms facilitate remote monitoring of therapeutic outcomes, while predictive analytics can forecast future medication needs. Responsibilities for system development lie with information technology (IT) clinical specialists and data scientists, whereas pharmacists and mission medical officers utilize these tools for operational monitoring. Mission data analysts are tasked with interpreting collected data to inform future mission planning and improve pharmacotherapy strategies.

Public awareness and advocacy

Promotion of astropharmacy research and awareness is vital for attracting interdisciplinary talent, funding, and collaboration. Dissemination of research findings through peer-reviewed publications, conferences, and public engagement initiatives enhances recognition of the field. Academic institutions can integrate astropharmacy into pharmacy and space medicine curricula, while media outreach increases public understanding of its importance. Pharmacists, academic institutions, space agencies, and public engagement teams share responsibility for advocacy, ensuring sustained growth and support for the emerging discipline.

Conclusion

Astropharmacy is an essential component of future space healthcare, addressing the complex pharmaceutical challenges of long-duration and autonomous missions. The Consensus-Integrated Space Health Model provides a coherent framework that unites pharmacists, physicians, and astronauts within a transparent, feedback-driven, and evidence-based decision-making system. By integrating continuous evaluation, expert oversight, and structured learning loops, the model enhances medication safety, clinical effectiveness, and trust across mission phases. Together with the proposed action plans, this approach supports the transition of astropharmacy from an emerging concept to a sustainable and operational pillar of space medicine.

List of abbreviations

NASA	National Aeronautics and Space Administration
ESA	European Space Agency
AI	Artificial Intelligence
PAR	Participation, Action, Research
IT	Information Technology

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Figure 1. Consensus-Integrated Space Health Model (CISH Model)

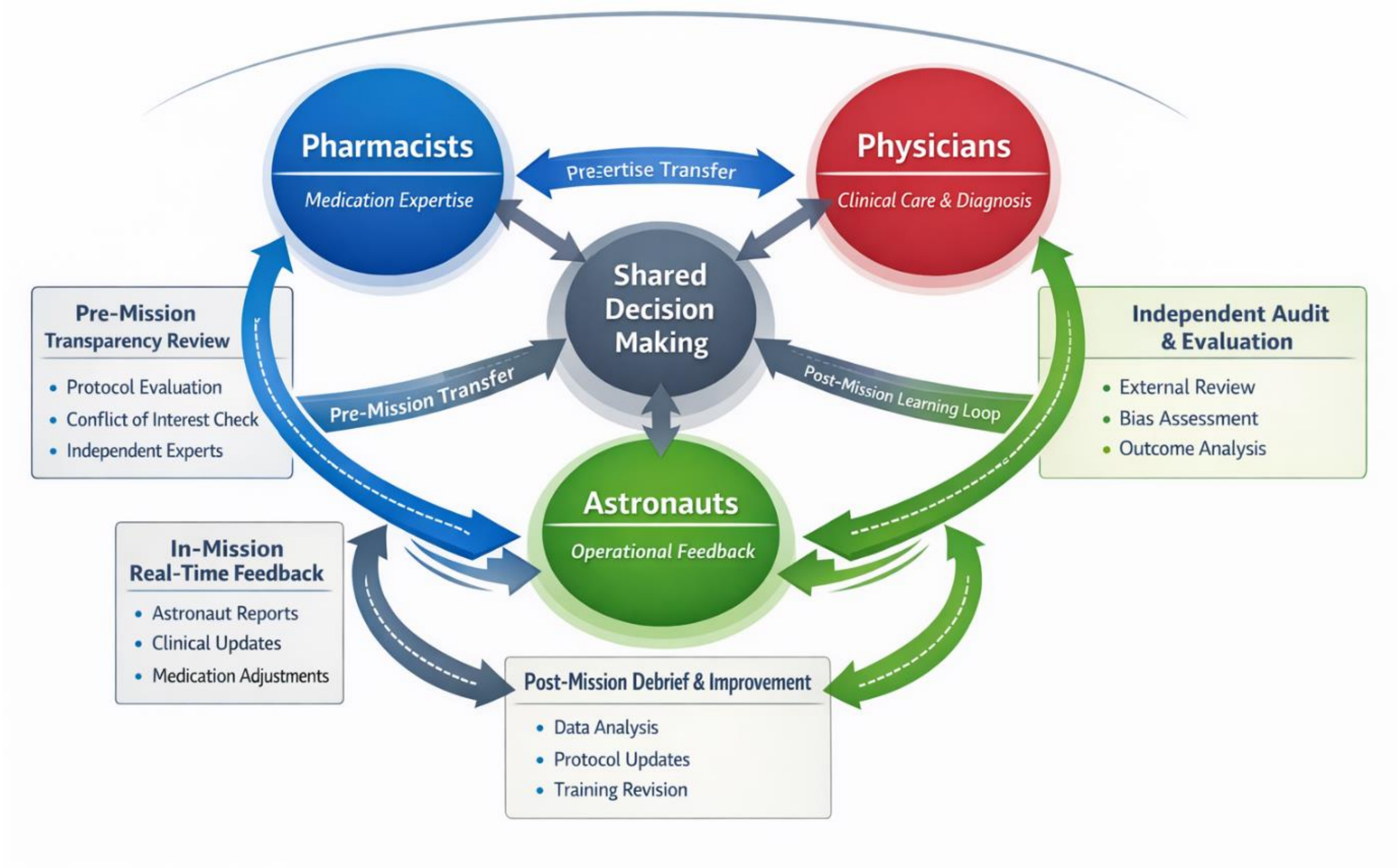

Table 1. Potential action plans at transforming astropharmacy from an emerging concept into a functional and sustainable pillar of space healthcare

Priority	Action plan	Description	Responsible / Follow-Up parties
High	Educational programs	Develop structured curricula, simulation-based workshops, and training for pharmacists and space medicine practitioners focusing on medication safety, stability, pharmacokinetics, pharmacodynamics, emergency pharmacotherapy, and personalized medicine in space.	Pharmacists, Space Medicine Educators, NASA Training Division
High	Policy and governance	Establish Space Pharmacy Council and guidelines regulating drug storage, transport, administration, contingency planning, and ethical/legal considerations for space pharmacotherapy; ensure international collaboration.	NASA, ESA, Space Pharmacy Council, Policy Makers, Legal Experts
Medium	Interdisciplinary collaboration	Facilitate coordination between pharmacists, physicians, engineers, mission planners, and AI specialists to integrate pharmaceutical expertise into mission planning, logistics, and predictive modeling.	Pharmacists, Physicians, Engineers, Mission Planners, AI/Data Scientists
Medium	Knowledge evaluation	Implement assessment systems using the Trickle-Down Model to monitor knowledge transfer, retention, and application; refine curricula and protocols iteratively.	Pharmacists, Educators, Research Teams, Space Agencies
Medium	Pharmaceutical research & development	Conduct research on drug stability under microgravity and radiation; develop space-stable formulations; optimize personalized pharmacotherapy using predictive models; support clinical simulation studies.	Pharmacists, Pharmaceutical Scientists, Research Institutes, Space Agencies
Low	Data infrastructure & monitoring	Develop digital platforms for medication inventory tracking, adherence monitoring, pharmacovigilance, telemedicine integration, and predictive analytics for mission planning.	IT Specialists, Pharmacists, Mission Medical Officers, Data Analysts
Low	Public awareness and advocacy	Promote astropharmacy research and awareness through publications, conferences, media campaigns, and academic curricula integration; attract talent and global collaboration.	Pharmacists, Academic Institutions, Space Agencies, Media / Outreach Teams