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Space Pharmacy for Human Space Exploration: Overcoming Drug Stability, Packaging Challenges, Pharmacokinetic Variations, and Developing Innovative On-Demand Therapeutic Solutions for Long-Duration Missions Beyond Earth

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Abstract

As humankind prepares for prolonged space exploration and the establishment of lunar and Martian habitats, ensuring reliable access to safe and effective medicines has emerged as a critical challenge. The evolving discipline of space pharmacy addresses the unique pharmaceutical needs of astronauts in microgravity and radiation-rich environments, where drug stability, packaging, and pharmacokinetics are markedly different from conditions on Earth. Traditional dosage forms often undergo accelerated degradation, while altered fluid distribution and metabolism in microgravity may impact therapeutic outcomes. Furthermore, the logistical limitations of resupply missions necessitate innovative approaches to extend shelf life, minimize storage requirements, and ensure timely access to essential therapies. Recent research has focused on advanced protective packaging, real-time monitoring of drug potency, and the development of on-demand pharmaceutical manufacturing technologies such as 3D printing and bioreactors for protein and nucleic acid therapies. Telepharmacy and AI- assisted monitoring are also being explored to support in-flight medication management. Despite these advances, significant knowledge gaps remain regarding long-term stability under cosmic radiation, the pharmacogenomic adaptation of astronauts, and scalable production models for deep-space missions. This review critically examines current challenges, highlights recent innovations, and outlines future directions in space pharmacy. By integrating drug stability studies, novel delivery platforms, and personalized therapeutic strategies, the field is poised to become an indispensable component of human space exploration. Ultimately, space pharmacy will play a central role in safeguarding astronaut health and enabling sustainable missions beyond Earth.

Keywords: Space pharmacy, drug stability, microgravity, pharmacokinetics, packaging, on-demand manufacturing, astronaut healthcare, space exploration

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INTRODUCTION

The dream of extending human presence beyond Earth has shifted from the realm of science fiction to tangible reality. With the International Space Station (ISS) serving as a continuous orbital laboratory for more than two decades, humanity has acquired valuable insights into the physiological, psychological, and technological challenges of spaceflight [1, 2]. As agencies such as NASA and ESA, along with private companies like SpaceX and Blue Origin, advance toward long-duration missions and interplanetary colonization, the provision of safe and effective medical care in space emerges as one of the most critical determinants of mission success [3–5]. At the center of this effort lies the evolving discipline of space pharmacy, which investigates how medicines behave under extraterrestrial conditions and how best to ensure their stability, efficacy, and availability during human exploration of deep space. Unlike terrestrial environments, space presents a unique array of stressors that simultaneously affect both the human body and pharmaceutical products. Microgravity alters pharmacokinetics by influencing drug absorption, distribution, metabolism, and excretion, which means standard dosing regimens developed on Earth may not always produce predictable outcomes during spaceflight [6, 7]. Physiological adaptations such as fluid shifts toward the upper body, reductions in renal clearance, and changes in hepatic enzyme activity all contribute to altered drug handling, creating significant uncertainty in therapeutic outcomes [8, 9]. At the same time, long-term storage of medicines in orbit or on planetary surfaces exposes them to cosmic radiation and temperature fluctuations that accelerate chemical degradation, reduce shelf life, and compromise therapeutic efficacy [10, 11].

On Earth, the availability of resupply and pharmaceutical monitoring provides a safety net when medicines degrade or prove ineffective. In contrast, the extreme logistical challenges of space travel make regular replenishment impractical. For example, a mission to Mars involves transit times of six to nine months and communication delays of up to 20 minutes one way, which severely restricts the feasibility of resupply or real-time medical guidance [12, 13]. This reality makes it imperative that medicines be capable of remaining stable for extended durations and that astronauts be empowered with systems for on-demand production and adaptive therapeutic monitoring [14–16].

The spectrum of health risks faced by astronauts underscores the importance of robust pharmaceutical support. Acute conditions such as infections, trauma, and space motion sickness coexist with chronic risks including radiation-induced carcinogenesis, bone demineralization, immune dysregulation, and neuro-ocular changes [17–19]. Mental health concerns, sleep disorders, and stress-related conditions add further layers of complexity that necessitate reliable and diverse therapeutic options [20]. A failure to maintain drug stability or deliver effective dosing could jeopardize not only individual health but also the safety of entire missions. This risk becomes especially acute in scenarios involving planetary colonization, where immediate return to Earth is impossible and medical autonomy becomes essential [21, 22].

To address these issues, researchers are exploring packaging systems designed to shield medications from radiation, optimize storage conditions, and mitigate degradation in microgravity [23]. Biotechnological advances have also highlighted the possibility of using engineered microbes for in situ synthesis of protein-based or nucleic acid-based therapies, reducing the dependence on stored pharmaceuticals [24]. Additive manufacturing technologies, particularly 3D printing of dosage forms, are increasingly seen as transformative tools that enable astronauts to produce customized medicines on demand, reducing payload mass and increasing therapeutic flexibility [25, 26]. Complementing these approaches, digital health innovations such as telepharmacy and artificial intelligence-driven decision support systems are being developed to provide remote monitoring, drug interaction checks, and individualized dosing strategies in environments where Earth-based medical expertise is not immediately accessible [27, 28].

The integration of these solutions is central to the long-term vision of establishing sustainable settlements on the Moon and Mars. Colonization efforts will require closed-loop pharmaceutical systems capable of independent manufacturing, monitoring, and distribution of medicines without reliance on Earth-based supply chains [29, 30]. Such innovations not only enable self-sufficiency for spacefarers but also mirror the broader challenge of developing regenerative life-support systems for food, oxygen, and water. Without effective pharmaceutical provision, untreated medical conditions could compromise not only astronaut health but also the long-term viability of extraterrestrial colonies [31, 32]. It is equally important to recognize that advances in space pharmacy generate knowledge with terrestrial relevance. Research into radiation-induced degradation, stability under extreme conditions, and bioreactor-based production of biologics has potential applications for improving medicine access in remote, resource-limited, or disaster-affected regions on Earth [33, 34]. Thus, the field serves as both a necessity for human survival beyond Earth and an innovation driver for global health resilience.

Given these imperatives, this review aims to critically examine the current state of space pharmacy, including the impact of microgravity and radiation on drug stability, advances in pharmaceutical packaging, alterations in human pharmacokinetics, and the role of emerging technologies such as on-demand manufacturing and digital health support. By mapping existing research, highlighting solutions under development, and identifying knowledge gaps, the article positions space pharmacy as an indispensable component for ensuring astronaut health during long-duration missions and for supporting humanity's aspiration of colonizing Mars [35–60] (Figure 1).

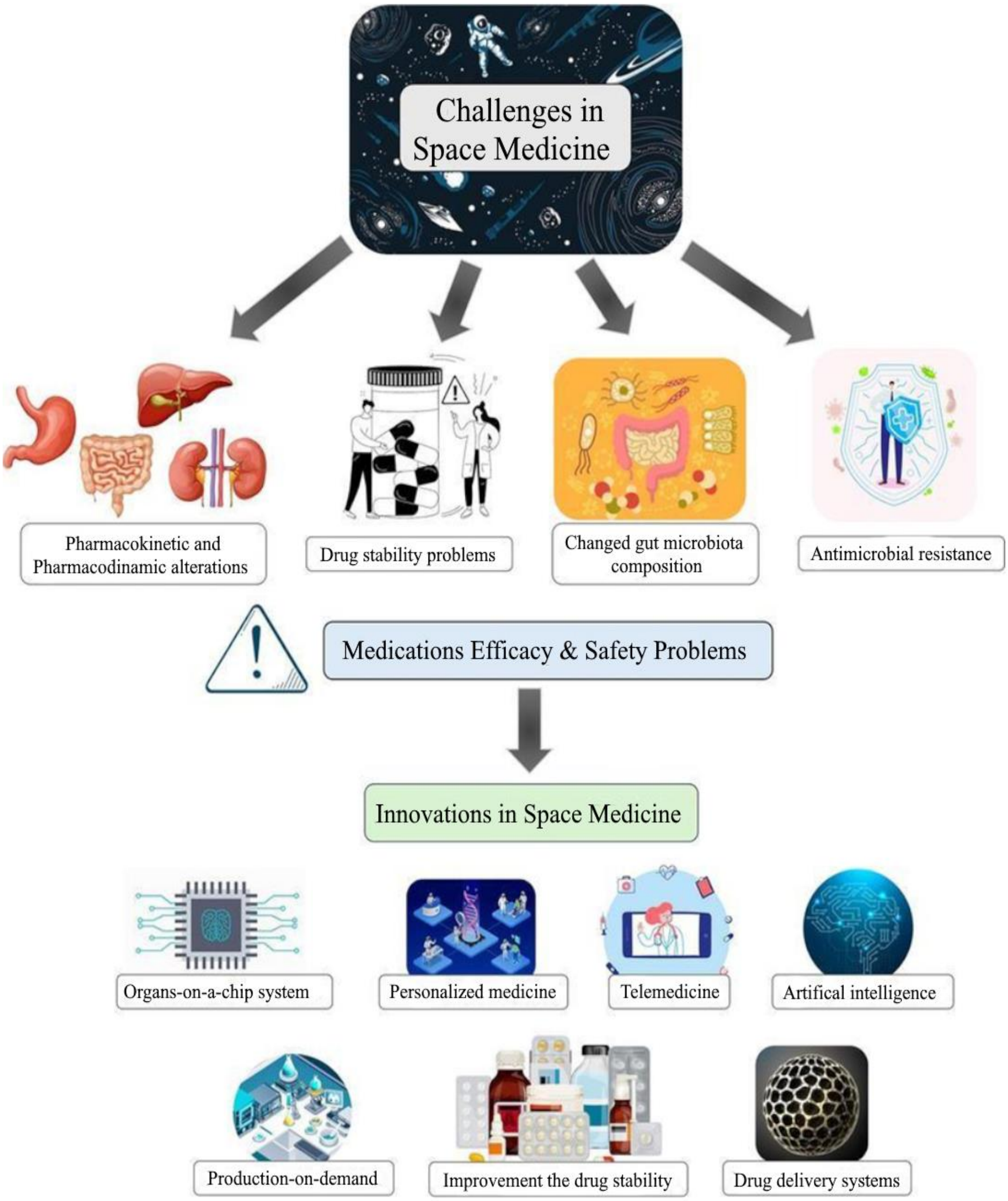

Figure 1. Challenges in space medicine [61].

PHARMACEUTICAL CHALLENGES IN SPACE

Drug Stability Under Space Conditions

One of the most pressing issues in space pharmacy is maintaining the stability of pharmaceutical compounds during long-duration missions. On Earth, drugs are typically designed with controlled storage conditions in mind, including stable temperatures, humidity regulation, and protection from radiation. In space, however, these parameters cannot always be guaranteed. Radiation is a particularly concerning factor, as high-energy cosmic rays and solar particle events can accelerate the degradation of active pharmaceutical ingredients (APIs). Studies conducted aboard the International Space Station (ISS) have revealed that several medications degrade faster in orbit than on Earth, showing reduced potency before their expected expiration dates [10, 11]. This degradation is thought to be driven by radiation- induced oxidation, molecular rearrangements, and interactions between APIs and excipients [12].

Microgravity adds another layer of complexity to drug stability. Suspensions, emulsions, and other liquid formulations may behave differently in low gravity, leading to precipitation of active ingredients or uneven drug distribution [13]. For example, sedimentation-driven separation on Earth is replaced by surface tension-driven aggregation in microgravity, resulting in unpredictable formulation behavior. These stability concerns become particularly critical during missions to Mars or deep-space outposts, where resupply is impossible and drugs must remain viable for months or years (Table 1) [14].

Table 1. Comparison of key differences in drug stability, handling, and medical logistics between Earth-based conditions and space environments.

Category	On Earth	In Space
Drug Stability	Stable under standard storage conditions with controlled temperature, humidity, and shielding from radiation.	Stable under standard storage conditions with controlled temperature, humidity, and shielding from radiation.
Packaging & Storage	Conventional packaging materials maintain sterility and integrity under gravity.	Packaging must resist radiation, microgravity effects, and vibration during launch while ensuring sterility.
Pharmacokinetics	Well-studied ADME (Absorption, Distribution, Metabolism, Excretion) with predictable outcomes.	Altered fluid shifts, microgravity, and immune changes affect absorption and distribution; metabolism and excretion uncertain.
Pharmacodynamics	Drug effects consistent with known physiology.	Altered cardiovascular, immune, and musculoskeletal systems may modify drug responses.
Logistics & Resupply	Reliable resupply chains and access to pharmacies, hospitals, and cold storage.	Extremely limited resupply opportunities; strict payload limits; must rely on pre-stocked or in-situ manufacturing.
Emergency Care	Advanced medical infrastructure, specialists, and emergency interventions available.	Astronauts rely on limited onboard kits, telemedicine, and non-specialist crew training in emergencies.

Packaging and Storage Issues

The effectiveness of pharmaceuticals in space is tightly linked to how they are packaged and stored. Traditional packaging systems, such as blister packs, glass vials, and plastic containers were never designed to withstand the unique environmental stresses of spaceflight. Packaging must protect drugs from radiation exposure, prevent microbial contamination, and maintain sterility, while also being lightweight to minimize payload mass [23]. In microgravity, vibration and mechanical stress during launch and in-flight operations can compromise seals, potentially leading to leakage or contamination [14].

Researchers are exploring advanced materials for pharmaceutical packaging, including multilayer polymers with radiation-absorbing properties, nanocoatings that block microbial penetration, and vacuum-sealed containers that maintain sterility [15, 16]. Another emerging strategy is the use of 3D-printed or in situ-fabricated packaging, which would allow astronauts to generate sterile containers as needed, reducing the reliance on pre-launched storage systems. Ultimately, packaging innovation is as critical as drug formulation itself, since poorly protected medicines may degrade or become unsafe before use.

Pharmacokinetics and Pharmacodynamics in Altered Gravity

Even when drugs remain chemically stable, their behavior inside the human body can change under spaceflight conditions. Pharmacokinetics (absorption, distribution, metabolism, and excretion) and pharmacodynamics (drug-receptor interactions and physiological effects) are strongly influenced by gravity-dependent processes. In microgravity, astronauts experience fluid redistribution toward the upper body, gastrointestinal motility changes, reduced bone density, and altered cardiovascular dynamics [6–9]. These physiological shifts can impact drug absorption through the gut, plasma protein binding, hepatic metabolism, and renal clearance (Figure 2).

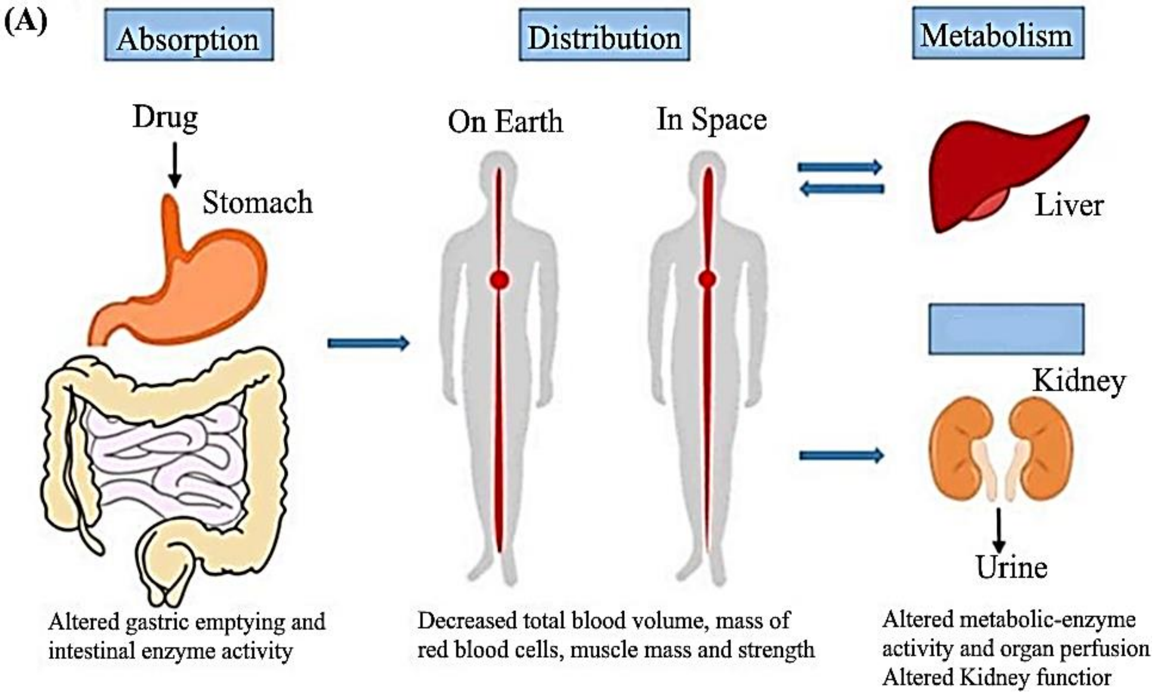

Figure 2. Effect of gravity on drug ADME [62] For example, oral medications may be absorbed at different rates due to slowed gastric emptying and altered intestinal blood flow [17]. Sedatives or antihistamines may produce exaggerated central nervous system effects, while common analgesics may be less effective [18]. Without robust data from space-specific pharmacological trials, dosing regimens remain uncertain, increasing the risk of under-treatment or adverse drug reactions. This variability underscores the urgent need for more in-flight pharmacology studies, as Earth-based clinical assumptions cannot reliably be applied to astronauts in microgravity.

Logistical and Supply Limitations

Logistics are another formidable challenge in space pharmacy. On Earth, pharmacies rely on frequent resupply and replenishment, but spacecraft cannot depend on such flexibility. Even on the ISS, occasional launch delays have led to shortages of critical supplies [19]. For deep- space missions, such as Mars expeditions, resupply is not an option; astronauts must rely entirely on the medicines they carry at launch or are able to manufacture during mission [12, 20].

This restriction requires careful planning of compact, multifunctional pharmaceutical inventories that cover a wide range of potential medical needs. Redundancy in drug selection is often impossible due to mass and volume constraints. A single degraded antibiotic, anesthetic, or cardiovascular drug could significantly compromise mission safety. To mitigate this, researchers are investigating in situ drug manufacturing technologies, including bioreactors and 3D printing of pharmaceuticals, as potential solutions for autonomous medical support [20].

Emergency Medical Scenarios in Space

Emergency medicine represents perhaps the greatest uncertainty in space pharmacy. Astronauts remain at risk for trauma, burns, infections, cardiac events, and unexpected illnesses that may require immediate pharmaceutical intervention [17, 21]. The unpredictability of such events makes it impossible to stock every conceivable treatment, especially for rare but potentially catastrophic conditions.

Communication delays with Earth-based medical teams complicate the situation further. While astronauts aboard the ISS can typically consult with physicians in real time, those on Mars would face communication lags of up to 20 minutes each way [13]. In such scenarios, astronauts must make autonomous medical decisions using limited pharmaceutical resources. If critical drugs are degraded, absent, or ineffective due to altered pharmacokinetics, the outcome of emergencies could threaten not only individual health but also crew survival and mission success [22].

Additional Pharmaceutical Challenges in Space Psychological and Behavioral Health Needs

Beyond physical illness, astronauts are at high risk of psychological issues such as anxiety, insomnia, and depression due to isolation, circadian rhythm disruption, and prolonged confinement in spacecraft [25, 27]. These conditions require reliable supplies of psychotropicdrugs like anxiolytics, antidepressants, and sleep aids. However, many of these compounds are chemically unstable in radiation environments [11], and their altered pharmacodynamics in microgravity raise concerns about efficacy and side effects [17]. The lack of precise dosing data complicates their safe use, making mental health support a major pharmaceutical challenge during long-duration missions.

Drug–Nutrient and Food Interactions in Space

Space diets are rich in processed, shelf-stable foods supplemented with vitamins and minerals to prevent deficiencies. However, these nutrient profiles can influence drug metabolism. For example, altered calcium and vitamin D intake affects bone-health drugs, while high iron intake can interfere with antibiotic absorption [26]. Furthermore, microgravity alters gastrointestinal function, which may amplify or reduce food–drug interactions. This creates uncertainty in designing safe medication protocols for astronauts [18].

Sterility and Risk of Microbial Contamination

In closed spacecraft environments, microbial growth is a persistent risk. Pathogens adapt to microgravity with enhanced virulence and antibiotic resistance [22]. Drugs and medical devices must remain sterile for extended durations, but breaches in packaging or in-flight handling could compromise sterility [23]. Even minor contamination events could lead to infections that are more difficult to treat in space due to both altered pathogen behavior and limited antibiotic efficacy [21].

Personalized Medicine and Genetic Variability

Astronauts come from diverse genetic backgrounds, and spaceflight stressors further modify gene expression. Studies show that space travel induces epigenetic changes that may alter how individuals respond to drugs [24]. Standardized dosing may therefore be inadequate, as some astronauts might metabolize drugs too quickly or too slowly. Personalized medicine approaches – potentially using AI-driven monitoring – are being considered to optimize treatments but remain logistically complex in space [20].

Ethical and Regulatory Challenges

Developing pharmaceuticals for space use is not only a scientific challenge but also an ethical and regulatory one. Current clinical trial regulations are Earth-centric and do not account for microgravity-specific pharmacology [28]. Testing drugs on astronauts raises ethical concerns, as crew members are both patients and mission-critical personnel. Moreover, liability for failed treatments or degraded drugs in space remains legally undefined [29]. These uncertainties complicate the approval and deployment of space-specific pharmaceuticals.

TECHNOLOGICAL SOLUTIONS

Smart Packaging and Protective Materials

One of the earliest and most practical solutions to overcome drug instability in space is the use of advanced packaging systems. Radiation-resistant polymer films, multilayer laminates, and vacuum-sealed pouches are now being investigated to protect drug formulations from degradation [11, 14]. Smart packaging equipped with embedded sensors can monitor temperature, humidity, and radiation exposure, giving astronauts real-time data on medicine quality [30]. This innovation is especially valuable during missions to Mars or lunar outposts, where resupply is impossible.

On-Demand Medicine Manufacturing (3D Printing)

Since carrying every possible drug on board is impractical, additive manufacturing (3D printing) offers a transformative solution. Researchers are developing printable drug formulations that allow astronauts to manufacture tablets, capsules, or films on demand [31, 33]. NASA and ESA have already explored this technology to create customized oral dosage forms during long-duration missions [34]. Beyond solid drugs, bioprinting methods may also enable the production of tissue scaffolds and emergency biomaterials in space (Figure 3) [35].

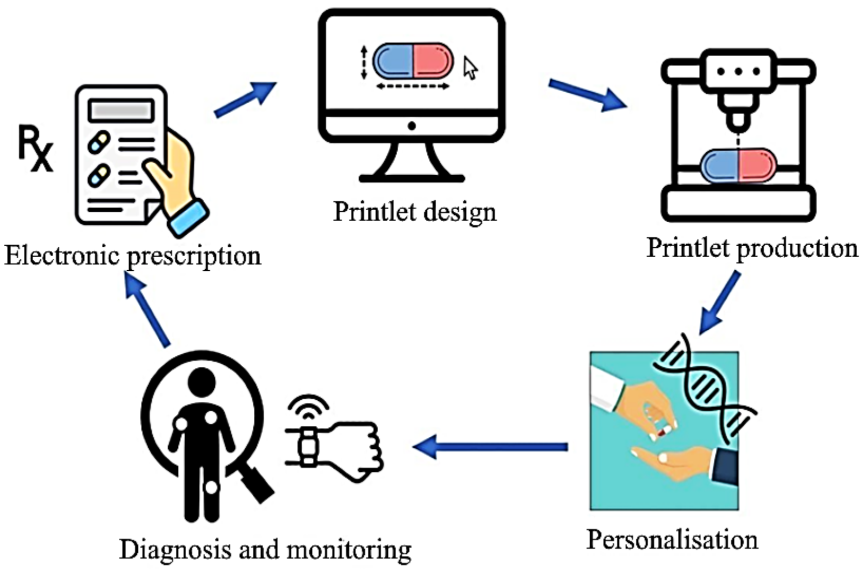

Figure 3. Workflow of Personalized Medicine [63].

Biopharmaceutical Production in Space

Another emerging approach is the in situ production of medicines using living systems such as yeast, bacteria, or plants. Synthetic biology enables microbes to produce complex molecules like insulin, monoclonal antibodies, or vaccines directly on spacecraft [36].

Experiments on the International Space Station (ISS) have demonstrated the feasibility of cultivating genetically engineered yeast and algae in microgravity to yield therapeutic proteins [37]. Plant-based systems are also under investigation, as they offer the dual benefit of food and pharmaceutical production for future Martian colonies [38].

Telepharmacy for Astronauts

Given the small medical teams aboard spacecraft, telepharmacy services represent a vital tool to extend Earth-based expertise. Using encrypted communication systems, pharmacists on Earth can guide astronauts in drug preparation, dosage adjustments, and emergency management [39]. Although communication delays pose a challenge during interplanetary missions, AI-assisted telepharmacy platforms can provide decision support locally while still being supervised remotely (Figure 4) [40].

Role of Artificial Intelligence and Nanotechnology

AI is expected to be a central pillar of future space pharmacy. Algorithms can analyze astronauts' biomedical data in real time, predict adverse drug reactions, and optimize individualized dosing schedules [41]. Combined with nanotechnology-based drug delivery systems, AI can help design smart nanoparticles that protect drugs from radiation, release them in a controlled manner, and even target specific tissues [42]. These hybrid solutions may ultimately overcome the pharmacokinetic uncertainties caused by microgravity [43].

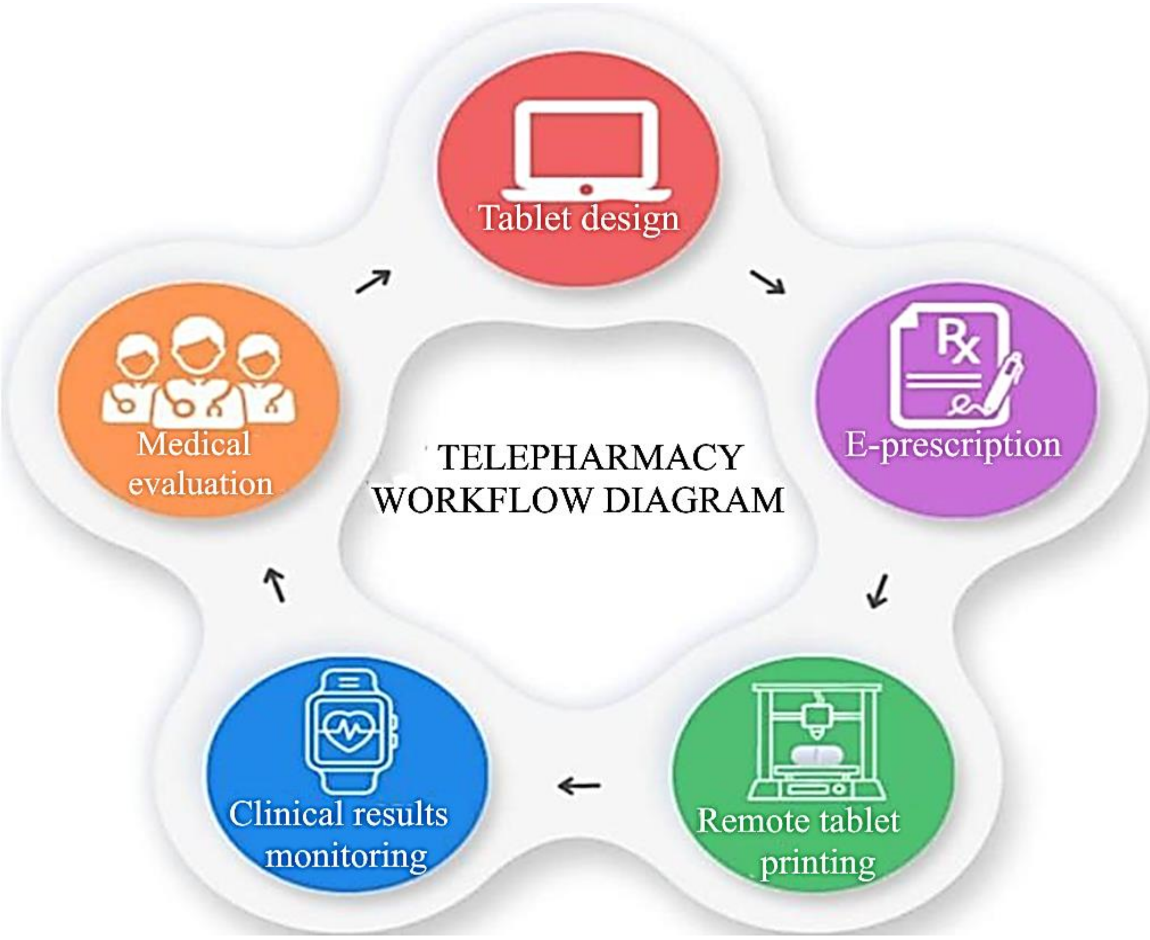

Figure 4. Telepharmacy workflow [64].

Additional Technological Solutions in Space Pharmacy

Cryogenic and Advanced Cold-Chain Storage

Some medicines, particularly biologics and vaccines, require strict temperature control. In space, conventional refrigeration is unreliable due to power limitations and vibration during launch. To address this, cryogenic freezers and phase-change material (PCM) systems are being tested for long-duration stability of sensitive pharmaceuticals [44]. These technologies maintain ultra-low temperatures while reducing energy consumption, which is vital for interplanetary travel.

Regenerative Medicine and Stem Cell Therapies

Microgravity has been shown to accelerate stem cell proliferation and differentiation, opening pathways for regenerative medicine in space [45]. Astronauts may benefit from on-board stem-cellderived therapies for tissue repair, bone loss, or radiation injury.

Experiments have already shown the feasibility of culturing stem cells in orbital platforms [46], making this an exciting future avenue for deep-space healthcare.

Wearable Biosensors and Closed-Loop Drug Delivery

Continuous health monitoring through wearable biosensors allows real-time tracking of vital signs and biochemical markers. These sensors can be integrated with closed-loop drug delivery devices, such as insulin pumps or smart inhalers, which automatically adjust dosages in response to physiological changes [47]. Such systems reduce the need for frequent manual interventions and minimize dosing errors in space missions.

Radioprotective Agents and Shielding Technologies

Radiation is a major cause of drug and tissue damage during spaceflight. Alongside smart packaging, radioprotective pharmacological agents such as amifostine, melatonin, and antioxidant nanoparticles are under investigation to safeguard both astronauts and stored drugs [48]. Additionally, electromagnetic and polymer-based shielding technologies are being designed to reduce radiation exposure inside spacecraft [49].

Digital Twins for Space Medicine

The concept of digital twins – a virtual replica of an astronaut's physiology – offers a futuristic approach to personalized medicine in space. By simulating drug pharmacokinetics and pharmacodynamics in a digital environment, mission doctors can predict how a specific drug will behave before actual administration [50]. This technology could be integrated with AI-based decision support for safe and optimized treatments during long-term missions.

CURRENT RESEARCH AND MISSIONS

The advancement of space pharmacy has been possible largely due to active global collaboration across major space agencies. Agencies such as NASA, ESA, JAXA, and ISRO are now making targeted efforts to understand drug stability, pharmacokinetics, and therapeutic delivery in microgravity, ensuring astronaut health for both short- and long-duration missions [12, 18, 25].

NASA: Pharmaceutical Stability and Human Research Program

NASA has been the leader in systematic studies of drug stability in space. Its Pharmaceutical Stability Program assessed over 35 medications stored aboard the ISS for up to 880 days [14]. Results revealed that several drugs, including amoxicillin, ciprofloxacin, and antihistamines, exhibited faster degradation rates compared to terrestrial storage [19]. The primary causes identified were ionizing radiation, vibration during launch, and storage conditions in microgravity [21].

Additionally, NASA's Human Research Program (HRP) maintains a comprehensive Human Research Roadmap, which catalogs findings related to astronaut physiology, immune dysregulation, altered pharmacokinetics, and countermeasure development [36]. HRP reports emphasize that pharmacological care for Mars missions will require not just improved packaging but also on-demand drug synthesis [22].

ESA: Protein Crystallization and Biologics Research

The European Space Agency (ESA) has pioneered research into biopharmaceutical stability, particularly monoclonal antibodies and protein formulations [28]. Studies aboard the ISS demonstrated that protein crystallization in microgravity can improve drug purity and stability, potentially leading to better therapeutic effectiveness [29]. ESA's MELiSSA (Micro-Ecological Life Support System Alternative) project has also explored bioregenerative life support systems that integrate pharmaceutical production with plant and microbial growth, laying the foundation for in-situ drug production on Mars [30].

JAXA: Pharmacokinetics and Astronaut Health

The Japan Aerospace Exploration Agency (JAXA) has concentrated on how altered gravity affects drug absorption, metabolism, and excretion. In its Pharma–ISS program, JAXA monitored astronaut pharmacokinetics using drugs such as acetaminophen and demonstrated slower gastric emptying and altered hepatic metabolism under microgravity [31]. These findings suggest that astronauts may require adjusted dosages or new formulations to achieve therapeutic efficacy [32]. JAXA also collaborates with NASA on multi-omics studies that assess how microgravity influences gene expression and drug-metabolizing enzymes [18].

ISRO: Gaganyaan and Emerging Biomedical Research

Although India's ISRO entered human spaceflight later, the Gaganyaan mission (expected in the late 2020s) has spurred research into space medicine and pharmacy [33]. ISRO has initiated projects in partnership with Indian universities and biotech firms to study:

- Drug stability under simulated microgravity and radiation conditions,
- Packaging materials suitable for long-duration storage, and
- Portable telemedicine and telepharmacy systems [34].

Given India's focus on low-cost, high-impact solutions, ISRO's space pharmacy research emphasizes affordable packaging, indigenous manufacturing, and AI-enabled monitoring systems for astronaut health.

International Space Station (ISS) as a Research Hub

The ISS serves as a global laboratory for space pharmacy. Numerous studies on drug degradation, microbial contamination, and packaging stability have been conducted across its modules [14, 27]. Findings from joint missions involving NASA, ESA, and JAXA have shown that standard shelf-life projections on Earth often fail in orbit, necessitating new models for expiry dating and packaging design [19]. The ISS has also tested miniaturized bioreactors for microbial drug production, marking the first steps toward pharmaceutical self-sufficiency in space (Figure 5) [30].

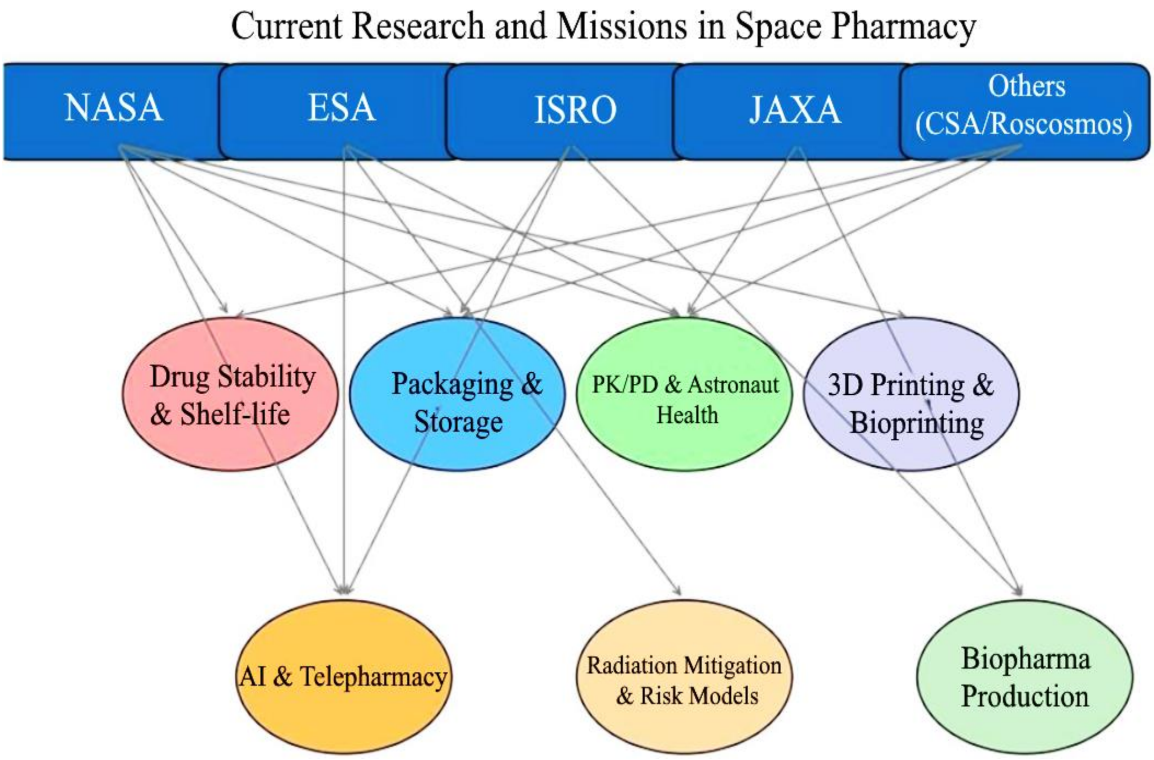

Figure 5. Global space agencies collaboration for space pharmacy

FUTURE PERSPECTIVES IN SPACE PHARMACY.

As human exploration expands beyond low Earth orbit to the Moon, Mars, and beyond, the demand for innovative pharmaceutical strategies becomes more urgent. Current research has laid the foundation, but future perspectives in space pharmacy must incorporate personalization, portability, nanotechnology, and planetary-scale models (Figure 6) [37, 41].

Personalized Astronaut Medicine

Future missions will require precision medicine tailored to each astronaut's genetic, physiological, and metabolic profile. Spaceflight alters gene expression, immune response, and drug metabolism in unpredictable ways [38]. Hence, pharmacogenomics and personalized dosing algorithms will be critical to ensure efficacy. NASA's Twin Study highlighted that long-term missions lead to altered expression of genes regulating immunity, oxidative stress, and DNA repair [39]. Such findings reinforce the need for real-time monitoring of biomarkers and AI-driven dose adjustments to achieve safe, individualized care in space [40].

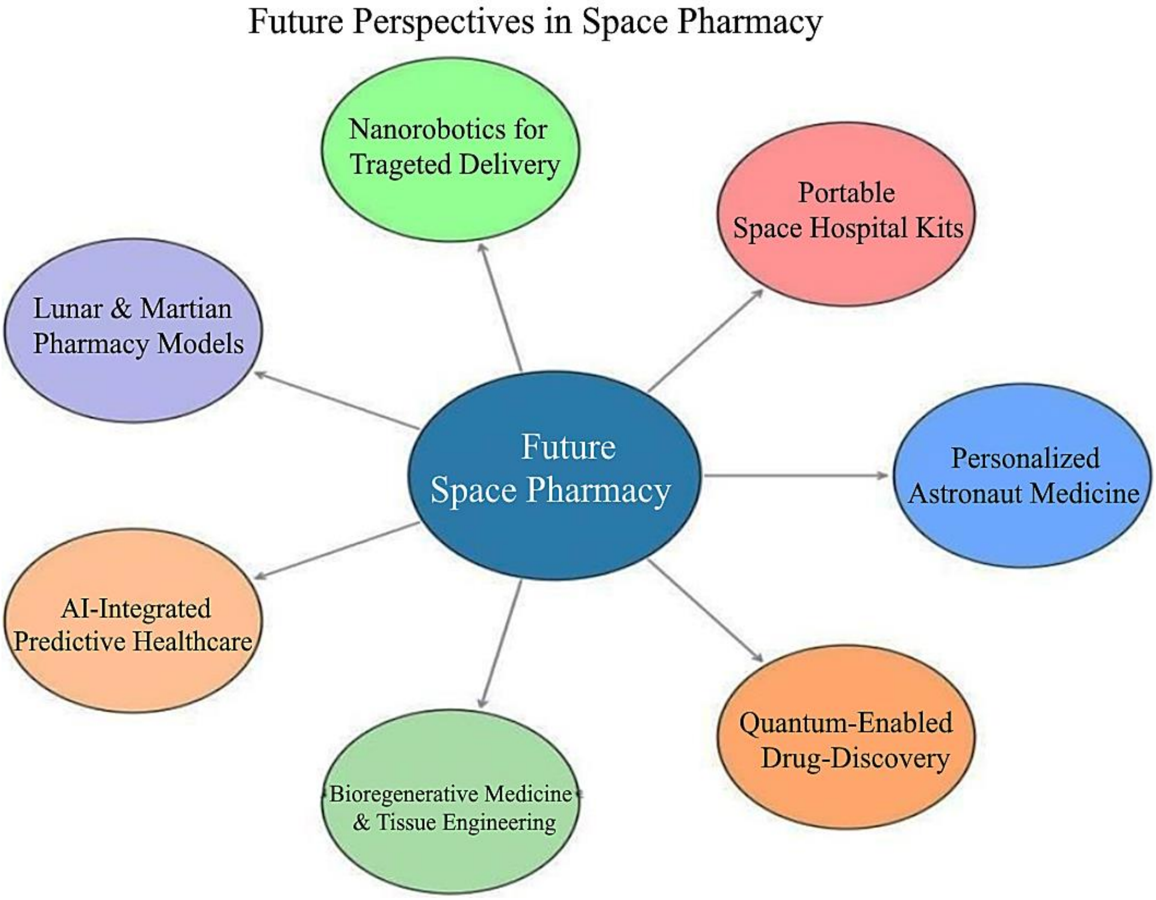

Figure 6. Innovative technologies for space pharmacy.

Portable "Space Hospital" Kits

Astronauts on lunar and Martian bases will be far from Earth-based emergency support. Thus, portable "space hospital kits" equipped with compact diagnostic devices, AI-enabled telemedicine platforms, and on-demand drug manufacturing tools will be essential [41].

These kits may integrate lab-on-a-chip technologies, wearable biosensors, and automated dispensing systems, allowing astronauts to manage acute and chronic conditions without waiting for resupply missions [42]. Current advancements in point-of-care testing devices and miniaturized bioreactors offer promising prototypes for these systems (Figure 7) [43].


Figure 7. Portable Space Hospital Kits [65].

Nanorobotics for Targeted Drug Delivery

Nanotechnology offers a transformative approach to overcome the unique pharmacokinetic challenges of spaceflight. Nanorobots and smart nanocarriers could provide controlled, site-specific delivery, bypassing issues such as altered gastric absorption or hepatic metabolism [44]. For example, stimuli-responsive nanoparticles activated by pH or temperature could deliver drugs more precisely in astronauts experiencing radiation-induced inflammation [45]. Research on AI-integrated nanorobotics suggests that such systems may eventually monitor tissue health, repair damage, and release drugs in a fully autonomous manner [46].

Lunar and Martian Base Pharmacy Models

Establishing permanent human settlements on the Moon and Mars will necessitate self-sustaining pharmacy ecosystems. Since resupply missions are expensive and infrequent, pharmaceutical systems on planetary bases must include:

- On-site production of essential drugs using plants, microbes, and cell-free biosynthesis [47].
- 3D printing of pills and patches, enabling rapid response to new medical needs [48].
- Closed-loop recycling of biomaterials to minimize waste and maximize sustainability [49].

The MELiSSA project (ESA) and NASA's BioNutrients program already serve as prototypes for such models [30, 47]. In the long term, a Martian base pharmacy might function as a hybrid of telepharmacy, on-demand synthesis, and biomanufacturing hubs, ensuring astronaut independence and resilience [50].

Integrating AI for Predictive Healthcare

Artificial Intelligence (AI) will likely become the backbone of future space healthcare. Beyond decision support, AI could integrate omics data, pharmacogenomic profiles, and wearable biosensor outputs to predict illnesses before symptoms arise [51]. Combined with nanotechnology and personalized medicine, AI could establish a proactive healthcare model, reducing the risks of medical emergencies during interplanetary missions [46].

Bioregenerative Medicine & Tissue Engineering

In long-duration missions, trauma, bone loss, or organ damage may not always be treatable with standard pharmaceuticals. Bioregenerative medicine, using stem cells, tissue engineering, and organ-on-chip platforms, could provide astronauts with tools to regenerate damaged tissues in space [52]. Research on 3D bioprinting of bone and cartilage under microgravity has shown encouraging results, suggesting that future "space hospitals" may include bioprinters for tissues and grafts [53]. This not only reduces reliance on stored drugs but also opens the possibility of on-site organ repair during interplanetary travel.

Quantum-Enabled Drug Discovery for Space

Another cutting-edge frontier is the use of quantum computing in drug discovery. Space exposes astronauts to unique health risks such as radiation-induced cancers, immune dysregulation, and neurocognitive decline [54]. Traditional Earth-based R&D cycles are too slow for evolving needs in space. With quantum algorithms, molecular simulations can be accelerated to design space-specific countermeasures (e.g., radioprotectors or anti-osteoporosis drugs) much faster [55]. In the future, astronauts may even carry portable quantum-assisted computing modules to model and optimize treatments in situ, ensuring adaptability for unforeseen health crises.

ETHICAL & LOGISTICAL CONSIDERATIONS

As space pharmacy transitions from experimental studies to practical applications for deep-space missions, several ethical and logistical questions emerge that must be addressed for safe and sustainable implementation.

One major challenge is drug regulation in space. On Earth, the FDA, EMA, and national health authorities provide oversight for drug approval, quality control, and post-marketing surveillance [56]. In space, however, there is no unified regulatory framework for how medicines are tested, validated, or approved for astronaut use. Questions remain about whether terrestrial standards are sufficient, or whether a dedicated "Space Medicine Regulatory Body" will eventually be required [57].

Another key issue is ownership and intellectual property (IP). If a pharmaceutical product is developed, synthesized, or modified aboard the ISS, Lunar Gateway, or future Martian colonies, who owns the patent – the astronaut who performed the experiment, the agency that funded it, or the nation where the technology originated? Space law, as outlined in the Outer Space Treaty of 1967, does not directly cover biopharmaceutical rights, leaving a legal vacuum [58]. This could become even more complex with the involvement of private companies such as SpaceX, Axiom, and Blue Origin, who may push for commercial exploitation of space-derived medicines.

Finally, the cost vs. benefit balance is a persistent concern. Developing specialized pharmaceutical storage systems, in-situ manufacturing platforms, or nanorobotics for drug delivery in space requires billions of dollars of investment [59]. Decision-makers must weigh whether these costs are justified against the expected benefits for relatively small astronaut populations, especially when Earth-based healthcare crises demand similar innovations. However, advocates argue that space pharmacy often leads to spin-off technologies – such as advanced packaging, AI-driven diagnostics, and cold-chainlogistics – that also benefit global health systems [60].

In summary, the future of space pharmacy depends not only on scientific breakthroughs but also on equitable, transparent, and globally accepted ethical frameworks that guide regulation, ownership, and funding. Without these, the translation of laboratory progress into real space missions may face significant barriers [61–65].

CONCLUSION

Space pharmacy is no longer a futuristic curiosity; it is becoming an essential pillar of human space exploration. As humanity pushes beyond low-Earth orbit toward long-duration missions on the Moon and Mars, the ability to store, manufacture, and deliver medicines safely in space will determine not only mission success but also astronaut survival. The challenges – ranging from radiation-induced drug degradation to altered pharmacokinetics in microgravity – demand bold, interdisciplinary solutions that combine pharmaceutical sciences, aerospace engineering, biotechnology, and artificial intelligence.

Encouragingly, ongoing efforts by NASA, ESA, JAXA, ISRO, and private industry have already transformed space into a living laboratory, producing valuable data on drug stability, packaging, and on-demand manufacturing. Emerging technologies such as 3D printing, biopharmaceutical cultivation, nanorobotics, and AI-driven telepharmacy hold the promise of transforming spacecraft and future habitats into self-sufficient healthcare ecosystems. What once required resupply from Earth may soon be generated aboard, shifting the paradigm of medical care from dependency to autonomy.

Looking ahead, the vision of a personalized space pharmacy tailored to each astronaut, supported by portable “space hospital” kits and integrated AI diagnostics, is within reach. Beyond supporting human exploration, the innovations born in space pharmacy will likely redefine medicine on Earth, improving drug stability, precision delivery, and healthcare access in extreme environments.

In essence, space pharmacy represents more than a scientific frontier – it is a commitment to safeguarding human life wherever we venture. Just as vaccines, antibiotics, and sterile packaging revolutionized medicine on Earth, the breakthroughs of space pharmacy may become the backbone of a new era in healthcare, ensuring that humanity’s journey into the cosmos is not just possible, but sustainable.

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