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ADVANCING MICROGRAVITY RESEARCH: SCIENTIFIC AND INDUSTRIAL APPLICATIONS IN SPACE

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ABSTRACT

The Microgravity Sciences and Processes Symposium, organized under the International Astronautical Federation (IAF), focuses on advancing scientific research and practical applications in microgravity environments. Microgravity provides unique conditions for studying physical, biological, and material processes without the dominant influence of gravity, enabling new insights into human physiology, biotechnology, pharmacology, and materials science. Research in this field contributes to understanding bone and muscle loss in astronauts, supporting investigations related to osteoporosis, muscular dystrophy, and long-duration space missions. Microgravity also facilitates innovations in tissue engineering, 3D bioprinting, crystal growth, nanomaterials, and advanced manufacturing. Furthermore, it supports the development of novel technologies relevant to future lunar and Martian exploration. The interdisciplinary nature of microgravity research integrates physics, chemistry, biology, and engineering while generating valuable scientific knowledge with industrial and commercial applications. The symposium serves as a platform for scientists, engineers, and industry representatives to exchange ideas, develop collaborative projects, and address challenges associated with space exploration. Overall, microgravity studies play a crucial role in technological innovation, medical advancements, and the development of sustainable space activities, while also producing benefits for industries and society on Earth.

Keywords: *microgravity, space research, protein crystallization, materials science, biotechnology, commercial space applications*

JEL classification codes: ***O32, I12, L63***

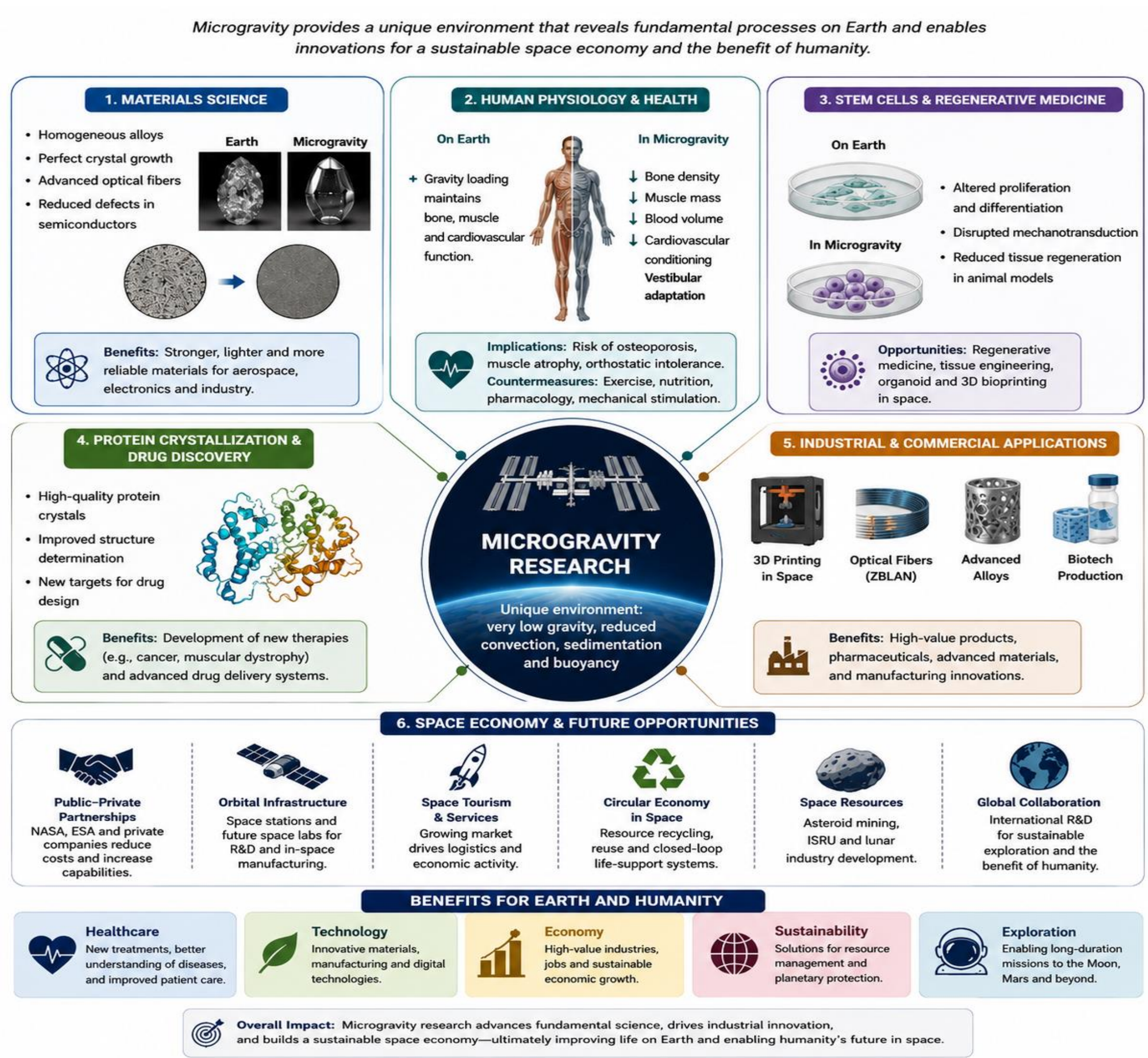
INTRODUCTION

Long-duration space missions and future habitat deployment in space induced the requirement for the investigation of the impact of microgravity to the physical chemical and biological organisms. The unique environment of space, are void of microgravity, cosmic radiation, and absence of atmospheric pressure, provide a unique opportunity to study Process in Space And Time unlike their terrestrial conditions (National Research Council, 2011). Science in microgravity has contributed remarkably to the advance of science and technology. In microgravity, gravity related forces, such as convection, sedimentation and hydrostatic pressure differences, are virtually eliminated, and this leads to the more simplified isolation of variables and the clearer observation of the mechanisms involved (Hamilton, 2025). This has not only facilitated new research frontiers in the range of fluid dynamics, combustion, material science, and most importantly biomedics, but it has also paved the way for numerous studies in areas including stem cell functionality, tissue regeneration, and drug design. In the life sciences, microgravity has revealed the pivotal role of mechanical loading in preservation of cell morphology, gene expression, and the pathways of differentiation that underlie cell and tissue homeostasis. Microgravity is reported to be a negative factor for stem cell differentiation and proliferation, which could possibly impact Human survival in long duration space journey. It also expands our understanding for regenerative medicine (https://pmc.ncbi.nlm.nih.gov/articles/PMC4235978/).

Meanwhile, the applications of space-unique research into the industrial field have been on the rise; the example of drug-maker developing the protein isomer with the microgravity resource and the example of material scientist improving the corresponding property by introducing new alloys Brothers would be given (Almeida, et al., 2014). That way, aside from the fact they are good for space applications, they make good earth industry items. Key facts and clarifications: biological and materials sciences and funding opportunities on board the ISS and for potential space labs to come as part of an international R&D (Blaber, et al., 2015; Grimm, et al., 2020). Microgravity is a special condition in space, it gives scientists the opportunity to observe the properties and principles of matter and physics from an angle that is impossible from Earth. On Earth, gravity dominates so nearly all processes are influenced by it (convection, settling of sediment, buoyancy (which is opposite of hydrostatic pressure), and hydrostatic pressure). In microgravity, you don't have or have very weak buoyancy effect like convection thingy, which makes you able to see things you couldn't (or twisted) because of the gravity (NASA, 2009).

An important advantage it provides is the ability to study heat and mass transfer in the absence of free convection. To pass through with scientific and technological verification of models of computational processes, thermodynamic and fluid mechanics etc. (NASA, 2019). As an example, Marangoni convection, a surface-tension-driven flow under microgravity, has been studied by experiments on board the ISS, which has proved useful in the developing of understanding of interface physics (Eckert et al., 2000). Microgravity research has emerged as one of the most important directions of modern space science, offering unique opportunities to investigate physical, biological, and material processes under conditions that cannot be replicated on Earth. The absence of gravity-driven effects enables scientists to gain deeper insights into human physiology, advanced materials, stem cell behavior, and pharmaceutical development. Figure 1 summarizes the major scientific, industrial, and socio-economic dimensions of microgravity research and highlights its contribution to future space exploration and sustainable development. As illustrated in Figure 1, microgravity research creates a bridge between fundamental scientific discoveries and practical applications in medicine, manufacturing, and the emerging space economy. The findings obtained under microgravity conditions contribute to the development of advanced materials, innovative healthcare solutions, and commercial space technologies. Consequently, microgravity studies not only support long-duration space missions but also generate significant technological and economic benefits for society on Earth.

Figure 1. Microgravity research: from scientific discovery to industrial and societal impact



Why Do You Do Science In Space?

In Materials science Microgravity provides the opportunity to form more homogeneous alloys, semiconductors and composite materials. On the earth, resutlant is gravity driven segregation and density driven stratification during the solidification, which affects material homogeneity. On the other hand, it is worth mentioning that space-based studies, like for example those carried out in the Materials Science Research Rack (MSRR) on the ISS, have allowed the growth of near perfect crystals and more homogeneous metallic samples (https://www1.grc.nasa.gov/space/iss-research/tpfse/). The results could pave the way to new materials that are stronger, lighter, and better suited for aerospace and other manufacturing applications.

Another line of research is based on the investigation of colloidal systems and glass transition. In microgravity, scientists can study long-range particle interactions without concerns of particle sedimentation, contributing to fundamental questions about phase transitions and disordered states of matter. The research could have applications that range from consumer electronics to biomedical devices.

Microgravity-induced changes in stem cell behaviour and regeneration

Novel findings suggest the concept of stem cell regenerative health in space as a new area within the field that explores how quiescence, self-renewal, proliferation, and differentiation are employed by adult stem cells to support and maintain tissue health. The mechanisms are clearly sensitive to internal (e.g., aging and oxidative stress) and external (e.g., mechanical due to moving under Earth’s gravity) factors. In space, microgravity and radiation have a profound impact on these cues leading to a decreased ability of tissues to remodel and regenerate. The bone marrow is a primary model in this regard, given that it is home to both mesenchymal and hematopoietic stem cells which give rise to major organs and tissues such as bone, blood and immune cells. On Earth, cyclical pressure and mechanical deformation caused by physical activity help induce regrowth, but such signals are absent in microgravity. It has been demonstrated that mechanical stimulation can induce stem cell differentiation in vitro, without interaction with biochemical factors (Almeida, et al. 2014). Exercise-enhanced Mechan regulation on the Earth promotes regeneration of muscle, heart, and bone tissues. ADCA increases bone healing and is associated with muscle loss, bone weakening, immune frailty, and anemia (loading unloading principle: i.e., loading is good for bones, e.g., after bone fractures, while unloading is bad) 5-8. Unfortunately, earth-bound experiments are always influenced by gravity.

There is no other environment that will allow us to see true loading effects compared to space flight. Studies of newt regeneration in space demonstrated decreased tissue growth and a disruption in the dynamic between cell proliferation and cell differentiation. These results imply that microgravity affects normal stem cell dynamics, particularly the essential transition from proliferation to differentiation (Ghani & Zubair, 2024). The development of pharmacological medication in space, however, is affected by microgravity, radiation, and changes in human physiology that could influence drug stability, metabolism, and delivery.

Yet, space research also offers great promise for the development of innovative therapeutics and advanced drug delivery systems, for the benefit of astronauts, as well as terrestrial patients (Aksoyalp, Temel & Karpuz, 2024).

Effect of spaceflight on human physiology and health

Human physiology is drastically affected by the microgravity environment of space. The lack of the mechanical force exerted by gravity results in a composite effect on several organ systems prompting a cascade of structural and functional changes. It is important to understand these alterations to maintain astronaut health during extended space missions (Iwase, Nishimura, Tanaka & Mano, 2020). The musculoskeletal system is the most apparent system to be altered in microgravity. In the absence of gravitational loading there is an increased resorption of bones. Osteoclast-activity whose work entails dissolving bone may stay the same or increase, as does osteoblast-activity, which is the builder of bone. This disbalance leads to a decrease of bone mineral density of 1-2% month on a load-bearing bone, such as the spine, femur, and pelvis (Smith, et al., 2015). At the same time, there is a marked atrophy of skeletal muscles, particularly in the lower extremities and trunk, which is attributed to nonuse. Equipment onboard the ISS such as the Advanced Resistive Exercise Device (ARED) is employed to counteract these effects (Iwase, Nishimura, Tanaka & Mano, 2020).

In space, gravity is lost, and fluids in the body move to the upper part of the body, thereby decreasing blood volume, including plasma and red blood cell mass. This in turn results in a temporary rise in both stroke volume and cardiac output. However, long-term spaceflight leads to cardiovascular deconditioning degradation of heart muscle effectiveness and orthostatic intolerance after return to earth (Krittanawong, et al., 2022; Hughson, 2012). Countermeasures, such as aerobic and resistive exercise, to mimic the Earth-like cardiovascular stress.

Microgravity results in disruption in the vestibular system, and in the otolith organs, which in the presence of gravity register acceleration and head position. This causes loss of sense of direction and coordination. Eventually, the brain compensates, adjusting sensorimotor inputs- a phenomenon that astronauts even have a term for: “space legs” (Manna, et al., 2024). However, such adjustment could, in turn, interfere with recovery of balance and orientation on an astronaut's return to his native planet or on landing on another planet.

Mechan transduction - the translation of mechanical forces into biochemical signals is largely altered in microgravity. Bone and muscle cells no longer sense and react to mechanical loading, thereby aggravating damage to tissues. Pharmacological agents and mechanical stimulation to simulate the loading effects of the Earth in space are currently being investigated (Blaber, et al., 2014).

Industrial and commercial uses of microgravity studies

Micro gravity also allows for higher quality protein crystals, which facilitate the design of more potent drugs. Research on the ISS has contributed to development of therapies for diseases including cancer and Duchenne muscular dystrophy. The crystallization of human manganese superoxide dismutase (MnSOD) using microgravity-based capillary counterdiffusion has enabled the growth of near-perfect crystals suitable for neutron crystallography. In Earth-based laboratories, gravitational forces introduce convection and sedimentation, which can disrupt the uniform growth of large, well-ordered crystals. In contrast, the microgravity environment aboard the International Space Station (ISS) eliminates these forces, allowing for a more controlled crystallization process. The capillary counterdiffusion method facilitates gradual mixing of protein and precipitant solutions, leading to optimal supersaturation conditions for crystal growth (Lutz, et. al., 2023). In space, without the influence of convection and sedimentation, one can make more advanced alloys, optical fibers (as in ZBLAN) or semiconductors with fewer defects compared to the ones produced here on Earth (Overton, 2018). In microgravity, cellular characteristics are affected, where stem cells and connective tissue structures grow better. These discoveries are now being employed toward regenerative medicine and organoid formation. Private organizations like Axiom Space, Blue Origin and SpacePharma are deploying microgravity as an R&D platform, which has resulted in commercial health, biotech, and materials applications (Comstock, 2020; Graham & Lucier, 2023).

Challenges and opportunities: creating self-sustaining space economy

Private firms are playing more of a role in space missions, with NASA and ESA increasingly partnering with them to bring costs down and capabilities up (Comstock, 2020). The Commercial Low Earth Orbit Development Program (CLDP) is illustrative of this shift. Orbital infrastructure, things like factories in space, will allow the manufacture of high value things in-space at a rate that is not limited by terrestrial production constraints (https://www.spacepharma.health/). Corporations like SpaceX and Blue Origin are promoting growth in space tourism, which, in addition to logistics, will form the basis of a buoyant space economy (Waddell, 2023). Creating a circular space economy (one in which resources are used, recycled and regenerated in orbit) is a key goal. It includes asteroid mining, ISRU and the development of the lunar industry (Comstock,2020).

CONCLUSION

Research in microgravity is said to be where science, medicine and industry meet and offers unparalleled chances to innovate on Earth and in space. Understanding biology, materials and the forces and processes governing the physical world will help develop new healthcare, manufacturing and technology solutions already being chased by those creating new products and services for those who dare to push humanity beyond its gravitational barrier on this planet. With deeper exploration throughout the solar system, exploiting unique characteristics of microgravity is essential to sustaining life in space and knowledge discovery across different fields. Given the high potential for microgravity research for the next decades, it is necessary to invest now into setting up a competitive and sustainable infrastructure, with international competition and collaboration.

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XÜLASƏ

Beynəlxalq Astronavtika Federasiyasının (IAF) tərkibində fəaliyyət göstərən Mikroqravitasiya Elmləri və Prosesləri Simpoziumu mikroqravitasiya mühitində elmi tədqiqatların və praktik tətbiqlərin inkişafına həsr olunmuşdur. Mikroqravitasiya fiziki, bioloji və material proseslərinin cazibə qüvvəsinin dominant təsiri olmadan öyrənilməsi üçün unikal şərait yaradır və insan fiziologiyası, biotexnologiya, farmakologiya və materialşünaslıq sahələrində yeni elmi biliklərin əldə edilməsinə imkan verir. Bu sahədə aparılan tədqiqatlar astronavtlarda sümük və əzələ kütləsinin azalmasının mexanizmlərinin daha dərindən anlaşılmasına töhfə verir, həmçinin osteoporoz, əzələ distrofiyası və uzunmüddətli kosmik missiyalarla bağlı araşdırmaları dəstəkləyir.

Mikroqravitasiya mühiti toxuma mühəndisliyi, 3D bioprintinq, zülal kristallaşdırılması, kristal böyüməsi, nanomaterialların hazırlanması və qabaqcıl istehsal texnologiyalarında innovasiyaların inkişafına şərait yaradır. Bundan əlavə, Ay və Mars missiyalarının gələcək inkişafı üçün əhəmiyyətli olan yeni texnologiyaların yaradılmasını təşviq edir. Mikroqravitasiya tədqiqatlarının multidissiplinar xarakteri fizika, kimya, biologiya və mühəndislik elmlərini birləşdirərək həm fundamental elmi biliklərin zənginləşdirilməsinə, həm də sənaye və kommersiya yönümlü tətbiqlərin formalaşdırılmasına xidmət edir. Simpozium alimlər, mühəndislər və sənaye nümayəndələri üçün ideya mübadiləsi aparmaq, birgə layihələr hazırlamaq və kosmik tədqiqatlarla bağlı aktual problemləri müzakirə etmək baxımından mühüm platforma rolunu oynayır. Ümumilikdə, mikroqravitasiya tədqiqatları texnoloji innovasiyaların, tibbi nailiyyətlərin və davamlı kosmik fəaliyyətlərin inkişafında mühüm əhəmiyyət kəsb edir, eyni zamanda Yer üzərində müxtəlif sənaye sahələri və cəmiyyət üçün faydalı nəticələr yaradır.

Açar sözlər: *mikroqravitasiya, kosmik tədqiqatlar, zülal kristallaşdırılması, materialşünaslıq, biotexnologiya, kommersiya kosmik tətbiqləri*

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