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Microbes Beyond Limits: A Review Onlife In Space, Ice And Other Extreme Ecosystems

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ABSTRACT:Outer space is a harsh environment harboring multiple forms of stress like cosmic radiation, space vacuum, extreme temperature and pressure, UV radiations, and altered gravity. Earth's atmosphere has several layers that expose microbial and terrestrial life to harsh external environments. In order to study the limits of survival of microbial life in extremes, it is imperative to study the response of microorganisms to space-related stress. The present chapter summarizes the various balloon and flight experiments performed to investigate the presence and response of microbial life in space. Studying microbial life in space also helps predict the plausible survival and endurance of microbial travel between planets, crucial to lithopanspermia theories and planetary protection.

Microbes over the past six decades have become closely linked to key aspects of space research such as manned and unmanned missions, interplanetary travel (related to panspermia), search for extra-terrestrial life as well as pharmaceutical applications. Various studies in the field of space microbiology delve into altered microbial responses in response to microgravity. These include changes in colony formation, alterations in secondary metabolite synthesis such as enhanced production of antibiotics, and increased virulence. The progress of vaccine development is being enhanced by leveraging the microgravity conditions present on the International Space Station (www.esa.int). Yet another exciting aspect, Astro microbiology offers prospects for investigating the feasibility of 'terraforming', the process of transforming inhospitable planets like Mars into habitable ones, capable of sustaining lifeThus, space exploration not only deepens our cosmic knowledge but also drives technological advancements, with microbes playing a crucial role in overcoming challenges in advanced space exploration by being 'tiny bioengineers'.[1]

Over view on extremophiles:Astrobiology's primary goal is to search for life on planetary bodies beyond Earth. Mars, Venus, and the icy moons Europa, Enceladus, and Titan offer numerous opportunities for investigating life's chemical evolution and origin. In addition, their similar biochemistry features to those that support life on Earth make them targets for extensive research. To ascertain extraterrestrial life, we must first define boundary conditions where life can thrive. Outer space presents severely harsh and inhabitable environmental conditions deleterious for life growth, including high radiation doses, extreme temperatures, different gravity, pressure, pH, salinity, energy source, and nutrient scarcity.[2]

Molecular & Genetic Adaptations:The International Space Station (ISS) is a closed environment that houses a diverse range of microorganisms, including potential pathogens

Whole-genome sequencing (WGS) and phenotypic characterization of any novel microbial species discovered on the ISS can help identify potential pathogens and comprehend their impact on the closed habitat and crew health[3]

Research conducted in space or using ground-based simulators has shown that microgravity conditions can alter various biological processes, including growth, morphology, gene expression, virulence, drug resistance, biofilm formation, and secondary metabolism.This study focused on the genomic peculiarities of novel species isolated from the ISS and compared WGS of the closest relatives found in Earth environments. A thorough analysis was conducted on genes associated with DNA repair, radiation resistance, microgravity adaptation, stress responses, and metabolic changes

Simulated Space / Mars Conditions:Recently, the simultaneous use of culture-dependent and culture-independent techniques (e.g., *Limulus* amoebocyte lysate assay [LAL], ATP bioluminescence assay, lipopolysaccharide-based microbial detection, and DNA-based PCR) have identified many nonculturable species [4]Research has also probed the feasibility of cultivating bacteria on Mars, provided they are shielded from UV radiation. Notably, it is recognized that a mere few millimeters of Martian soil would suffice for UV protection [5]numerous studies have meticulously documented diverse microbial responses potentially linked to space-like conditions. Noteworthy findings include a decrease in colony forming units (CFUs) in *B. subtilis* spores [6]

Long-term Exposure Studies:A recent study examined the influence of outer space on this unique microbe on a molecular level. After 1 year of exposure to low Earth orbit (LEO) outside the International Space Station during the Tanpopo space Mission, researchesfound that D. radiodurans escaped morphological damage and produced numerous outer membrane vesicles. A multifaceted protein and genomic responses were initiated to alleviate cell stress, helping the bacteria to repair DNA damage and defend against reactive oxygen species. Processes underlying transport and energy status were altered in response to space exposure. D. radiodurans used a primordial stress molecule polyamine putrescine as a reactive oxygen species scavenger during regeneration from space exposure.[7]

Editorial and Future Perspectives:The space environment, with its unique stressors like microgravity and radiation, significantly impacts microbial growth and behavior, altering their physiology, increasing virulence, and enhancing antibiotic resistance. These changes pose risks to spacecraft integrity and astronaut health by promoting biofilm formation and increasing the potential for infection, necessitating new strategies for monitoring and mitigation in long-duration missions. The altered environment of space can impact the composition and functionality of the gut microbiome, which may result in comparable health challenges for astronauts[8]Alterations in secondary metabolite synthesis have also been observed [9]

Microbes in Glacial / Cryosphere Environments

General Ecology of Cryosphere Microbes:Cold ecosystems are highly diverse and range from high mountains to deep oceans, polar region, and subterranean caves. They include aquatic and terrestrial ecosystems such as the deep sea (90% of the ocean volume is at a temperature below 5 °C), sea ice, lake ice, snow and glacial environments, cold water lakes, permafrost, cold soils and cold deserts, and even the atmosphere and clouds.In recent years, studies on microorganisms in cold habitats has been mainly focused on the Earth's cryosphere, i.e., frozen ecosystems, which include glaciers, ice sheets, sea ice, lake ice, and frozen ground (permafrost) (e.g., Anesio et al. 2017; Boetius et al. 2015; Hotaling et al. 2017a; Jansson and Tas 2014; Martin and McMinn 2018) and a recognition of the cryosphere as one of the biomes on Earth has even been proposed (Anesio and Laybourn-Parry 2012). Indeed, since ecosystems in the cryosphere are especially sensitive to climate changes (Beniston et al. 2018; Bibi et al. 2018; Huss et al. 2017), as indicated by the worldwide retreat of glaciers and ice sheets as well as permafrost thawing, an understanding of the role and potential of microbial life in these habitats has become crucial.

Glacier Ice as an Analog for Extraterrestrial Icy Worlds:

The icy worlds of the solar system and beyond meet these conditions of habitability, but their magnitudes are different. It is necessary to know what the intervals of these values are to make them habitable. To know the limits of life, we must first establish what these limits are on Earth, since it is the only case we know. One of the most life limiting features on Earth is low temperature. Actually, the Earth can be considered a cold place. For instance, 90% of the Earth's oceans have a temperature of 5°C or less (Russell, 1990).

Cryoconite Holes – Microbial Hotspots:Cryoconite holes, small meltwater pools on the surface of glaciers and ice sheets, represent extremely cold ecosystems teeming with diverse microbial life. Cryoconite holes exhibit greater susceptibility to the impacts of climate change, underlining the imperative nature of investigating microbial communities as an essential module of polar and alpine ecosystem monitoring efforts. Microbes in cryoconite holes play a critical role in nutrient cycling and can produce bioactive compounds, holding promise for industrial and pharmaceutical innovation. Understanding microbial diversity in these delicate ecosystems is essential for effective conservation strategies. Therefore, this review discusses the microbial diversity in these extreme environments, aiming to unveil the complexity of their microbial communities. [10]

Sea Ice Microorganisms: Sea ice is a characteristic and extremely important entity in Polar Regions, from both physical, chemical, biological, climatological, and geopolitical perspectives (Dieckmann and Hellmer 2010). Sea ice in the Arctic and Antarctic together cover about 10% of the world's oceans at its average winter maximum extent of 34 million km^2, an area larger than Africa (30.4 million km^2) (Lund-Hansen et al. 2020a, b). The Arctic sea ice extent varies from a minimum of 4.7 to 7.7 million km^2 and a maximum of 14.3 to 16.3 million km^2 (median values 1981–2010) (Cavalieri and Parkinson 2012).

Ancient Microbes in Ice:The first reports of microbes in glacier ice appeared early in the twentieth century[11]The microbes identified in glacier cores potentially represent the microbes in the atmosphere at the time of their deposition[12]

Implications & Applications:

Astrobiology :Astro microbiology offers prospects for investigating the feasibility of 'terraforming', the process of transforming inhospitable planets like Mars into habitable ones, capable of sustaining life. Microbes residing beneath the surface could be potential candidates for terraforming. [13]

Space Missions: space biology research has seen a surge in development, with ISS facilities incorporating fully automated technologies to conduct biological experiments. This advancement is exemplified by the use of Biological CubeSats equipped with biosensors, offering a cost-effective alternative to complex manned spaceflight missions, as highlighted by Kanapskyte et al. (2021) [14]

Gaps & Future Directions

- More long-term in situ studies of ISS-derived microbes to track evolution under space stressors.
- Deep sampling of subglacial lakes and ice cores to understand the metabolic potential of ancient and isolated microbial communities.
- Engineering of beneficial microbes for space travel (bio-regenerative life support) — while ensuring biosafety.

- Exploring the genomic and proteomic basis of cold adaptation for possible industrial enzyme exploitation.

Conclusion

Microbes in both **space** and **glacial** extremes demonstrate a remarkable capacity to survive, adapt, and even thrive under conditions that are lethal to most life. Their resilience is not just of academic interest — it has profound implications for *astrobiology*, *climate science*, and *biotechnology*. Studying them deepens our understanding of life's boundaries and offers insights for future explorations (both terrestrial and extraterrestrial).

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