Plasma Effects on Microorganisms in Space: Implications for Astrobiology and Space Missions

Punit Kumar

Department of Physics, University of Lucknow, Lucknow – 226007, India

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ABSTRACT

The survival and adaptability of microorganisms in space have profound implications for astrobiology, planetary protection, and the success of long-duration space missions. Among various extraterrestrial stressors, plasma, comprising ionized gases found in solar wind, cosmic radiation, and magnetospheric environments represents a significant yet underexplored factor influencing microbial behavior. This paper investigates the effects of both natural and artificial plasma environments on microorganisms in space, focusing on physiological, genetic, and biochemical responses. The research highlights plasma-induced oxidative stress, DNA damage, and membrane disruption, which can impair microbial viability or induce adaptive mechanisms. Special attention is given to extremophiles such as *Deinococcus radiodurans* and *Bacillus subtilis*, which exhibit remarkable resistance to plasma and radiation, making them valuable models for astrobiological studies. Further, the paper explores the role of plasma in prebiotic chemistry and the hypothesis of panspermia, where plasma-driven mechanisms could facilitate interplanetary microbial transfer. From a technological perspective, plasma applications in spacecraft sterilization, waste treatment, and bioreactor design are discussed as essential tools for maintaining microbial control and supporting life support systems. The study concludes by addressing the ethical and scientific challenges of studying plasma–microbe interactions and calls for interdisciplinary efforts to deepen our understanding. Ultimately, this research contributes to the broader quest of uncovering life's potential beyond Earth while enhancing the safety and sustainability of human space exploration.

Keywords: Plasma–Microbe Interactions, Space Microbiology, Astrobiology, Microbial Survival in Space, Plasma Sterilization, Panspermia Theory

INTRODUCTION

The environment of outer space presents a unique combination of extreme physical and chemical conditions that significantly differ from those on Earth. These include vacuum, intense cosmic radiation, microgravity, and plasma-rich regions shaped by the interaction of solar wind and magnetic fields. Together, these factors pose significant challenges to biological systems, especially microorganisms, which are among the simplest yet most resilient forms of life (Horneck et al., 2010). Among these space-specific stressors, the effects of plasma, ionized gas composed of free electrons and ions, on microorganisms remain relatively underexplored compared to radiation and microgravity.

The space environment, particularly in low Earth orbit (LEO), is characterized by a near-total vacuum, where atmospheric pressure is extremely low, leading to rapid desiccation of unprotected cells. Further, ionizing radiation from galactic cosmic rays (GCRs) and solar particle events (SPEs) poses constant oxidative and mutagenic stress on DNA and cellular components (Nicholson et al., 2000). Microgravity, another key feature of the space environment, influences cellular processes such as gene expression, cell signaling, and biofilm formation (Taylor, 2015). In addition, charged particle-rich plasma generated naturally by solar activity or artificially through spacecraft systems represents a fourth and significant space factor, capable of interacting with biological surfaces and altering cellular integrity (Shimizu et al., 2011).

Understanding how microorganisms respond to these stressors is essential not only for ensuring the health and safety of astronauts, but also for addressing key questions in astrobiology. Microorganisms can colonize spacecraft surfaces, form resistant biofilms, and pose risks to closed-loop life support systems. Simultaneously, they are indispensable to space missions for their roles in nutrient recycling, oxygen generation, and waste decomposition functions critical to long-duration missions (Yamaguchi et al., 2014). Moreover, microbial behaviour in space offers insights into the boundaries of life and informs the search for extraterrestrial biosignatures.

Microorganisms also play a central role in planetary protection protocols. Forward contamination, the transport of Earth-based microbes to other celestial bodies can compromise the integrity of life-detection missions. Similarly, backward contamination, the unintentional return of extraterrestrial microbes to Earth raises concerns about biosafety concerns (Rummel et al., 2014). Therefore, studying microbial responses to plasma is vital to developing effective sterilization methods for spacecraft and payloads.

The interaction between plasma and microbial cells involves complex physical and biochemical mechanisms. Plasma generates reactive oxygen and nitrogen species (ROS/RNS), ultraviolet photons, and charged particles that can cause oxidative damage to DNA, proteins, and membranes (Laroussi, 2005). Cold atmospheric plasmas (CAPs), a non-thermal form of plasma, have already shown efficacy in microbial inactivation in laboratory settings. However, how these mechanisms operate in space plasma conditions, often under vacuum, low temperatures, and microgravity requires further investigation.

Despite increasing interest in plasma medicine and plasma biosystem interactions on Earth, few studies have focused on how microorganisms behave under the combined conditions of plasma and space (Mendis et al., 2000). Extremophiles like *D. radiodurans* and *B. subtilis*, which demonstrate resistance to radiation and desiccation, have been used in simulated plasma experiments, suggesting that plasma may influence microbial survivability and mutagenesis in ways that are both destructive and adaptive (Horneck et al., 2001). This is especially relevant to the theory of panspermia, the hypothesis that life can be transported across space via meteoroids or dust grains. Plasma environments might either shield, or degrade microbial hitchhikers, influencing the plausibility of interplanetary life transfer.

This paper aims to critically examine the effects of plasma on microorganisms in space, exploring both naturally occurring and artificial plasma sources. It integrates data from space missions, laboratory simulations, and theoretical models to assess how plasma affects microbial survival, mutation, and functionality. Further, the study discusses the broader implications of these interactions in astrobiology, planetary protection, and the design of sustainable space habitats. By identifying both the threats and utilities posed by plasma to microbial life, the research contributes to the dual goals of ensuring human safety in space and enhancing our understanding of life's resilience in the cosmos.

Space Plasma Environment

Plasma, often referred to as the fourth state of matter, is a ubiquitous component of the space environment. Comprising ionized gases with freely moving electrons and ions, plasma is present throughout the cosmos from the solar corona and interstellar medium to planetary magnetospheres and the interplanetary space between celestial bodies (Bagenal, 2013). Understanding the various forms and behaviors of plasma in space is essential for assessing its potential effects on biological systems, especially microorganisms exposed during space missions. This section outlines the key characteristics of space plasma, its sources near and within spacecraft environments, and its interactions with spacecraft materials and microbial colonies.

Characteristics of Space Plasma

The plasma encountered in space can be broadly categorized based on its origin. One of the most prominent sources is the solar wind, a continuous stream of charged particles, primarily protons and electrons, ejected from the Sun’s outer atmosphere. Traveling at speeds ranging from 300 to 800 km/s, solar wind plasma carries with it magnetic fields, giving rise to a complex and dynamic interplanetary magnetic field (Zurbuchen, 2007). When this stream encounters a planetary magnetic field, it forms a magnetosphere, a region dominated by the planet's magnetic field where plasma dynamics are influenced by magnetic reconnection, charged particle trapping, and field-aligned currents (Kivelson & Russell, 1995).

Another major contributor to the space plasma environment is cosmic rays, which are high-energy protons and atomic nuclei originating from outside the solar system. Although cosmic rays are not strictly plasma, they interact with and modulate plasma populations in space, particularly in the heliosphere, where they contribute to the overall radiation environment (Spillantini et al., 2007). Within magnetospheres, magnetospheric plasma can exhibit high degrees of anisotropy and energy variation. This plasma is often shaped by interactions between solar wind and the planetary magnetic field, giving rise to features such as the Van Allen radiation belts, plasma sheets, and auroral zones.

Natural Plasma Sources in Space Missions

In the context of human spaceflight, natural plasma sources are encountered in a variety of locations. On the International Space Station (ISS), the orbital path traverses through regions influenced by both solar and geomagnetic activity. The ISS often passes through the South Atlantic Anomaly, a zone of high radiation and plasma density that can affect both hardware and biological experiments onboard (Reitz, 2008). Plasma environments also exist around the Moon, where the lack of a global magnetic field allows the solar wind to interact directly with the lunar surface, producing secondary plasmas from regolith–particle interactions (Farrell et al., 2007).

On planetary surfaces, particularly those with weak or absent magnetic fields like Mars, plasma can directly impinge on the atmosphere and surface, stripping away volatiles and creating conditions of high radiation and low pressure (Dubinin et al., 2006). In interplanetary space, spacecraft are constantly immersed in plasma from the solar wind and may also encounter plasma shocks, turbulence, and reconnection regions that vary based on solar activity and location within the heliosphere (Schwenn, 2006).

Types of Plasma

Space plasmas can be broadly categorized into thermal (equilibrium) and non-thermal (non-equilibrium) plasmas. Thermal plasmas, typically found in stars or very hot regions, consist of particles in local thermodynamic equilibrium, with ion and electron temperatures nearly equal. These are not commonly encountered by spacecraft. In contrast, non-thermal plasmas such as those in the solar wind, or artificial spacecraft-generated plasmas feature electrons with significantly higher energy than ions, and often exhibit anisotropic velocity distributions (Chen, 2016).

A critical feature of many space plasmas is their magnetization, i.e., their interaction with magnetic fields. Magnetized plasmas exhibit behaviours such as cyclotron motion, magnetic mirroring, and field-aligned transport, which influence how particles are distributed and move in space. These effects can modulate the exposure and shielding that microorganisms experience on spacecraft surfaces, especially in polar or equatorial orbital regimes (Kivelson & Russell, 1995).

Interaction of Plasma with Spacecraft and Microbial Biofilms

When plasma interacts with spacecraft, it can induce surface charging, erosion, and changes in material properties. More importantly for bio-experiments, these interactions can affect microbial colonies, especially biofilms that form on spacecraft surfaces and instruments. Plasma-induced surface charging can generate localized electric fields that influence microbial adhesion and ion exchange processes (Hoffman et al., 2017). Furthermore, exposure to reactive species in plasma, such as oxygen radicals, UV photons, and ion bombardment can lead to oxidative damage of microbial membranes, proteins, and nucleic acids, affecting their viability (Laroussi, 2005).

Experiments conducted on Earth with CAP have demonstrated its effectiveness in sterilizing surfaces by damaging bacterial cell walls and DNA without significant thermal effects (Graves, 2014). In space, plasma conditions vary greatly, but similar principles apply. For instance, biofilms exposed on the ISS or on external

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spacecraft platforms (e.g., EXPOSE-E on ESA missions) have shown varying survival rates depending on shielding, exposure duration, and microbial species (Horneck et al., 2010). Understanding plasma biofilm interactions in these contexts is critical for both life support systems and planetary protection protocols.

Additionally, plasma can affect electrochemical gradients and nutrient diffusion within microbial communities, potentially altering their metabolic activity. This is especially relevant for bioreactors and bioregenerative life support systems where microorganisms are employed for air purification, or waste recycling (Yamaguchi et al., 2014). Long-term exposure to plasma in microgravity may result in unforeseen genetic adaptations or biofilm fortification, complicating sterilization strategies.

Microorganisms in Space: Known Effects

Microorganisms are remarkably resilient life forms, capable of surviving and thriving in extreme environments. Space represents one of the most challenging environments for life, combining microgravity, vacuum, radiation, desiccation, and temperature fluctuations. Studying microbial behaviour in such conditions is essential not only for ensuring crew health and mission success, but also for understanding the potential for life beyond Earth. This section reviews the known effects of space travel on microbial physiology and genetics, insights from key spaceflight experiments, microbial resistance to space-induced stressors, and the significance of biofilm formation in space habitats.

Effects of Space Travel on Microbial Physiology and Genetics

Exposure to the space environment has been shown to induce profound changes in microbial physiology and genetics. Spaceflight conditions, particularly microgravity and ionizing radiation, influence microbial growth, morphology, metabolism, and gene expression. Studies have demonstrated altered growth rates, increased virulence, and changes in antibiotic resistance in several bacterial strains exposed to microgravity (Taylor, 2015). For example, *Salmonella enterica* exhibited increased virulence after spaceflight, with changes in gene regulation related to stress responses and pathogenesis (Nickerson et al., 2004). Similarly, *Escherichia coli* and *Pseudomonas aeruginosa* have displayed modifications in biofilm structure, enhanced growth kinetics, and shifts in metabolic pathways under microgravity conditions (Kim et al., 2013).

At the genetic level, space exposure can result in DNA damage, increased mutation rates, and activation of stress response genes. The radiation environment, especially outside Earth's magnetosphere, can cause single and double-strand breaks in microbial DNA, prompting cellular repair mechanisms or adaptive mutations (Horneck et al., 2010). Moreover, transcriptomic studies have revealed significant shifts in gene expression related to oxidative stress, membrane transport, and DNA repair in bacteria exposed to long-duration space missions (Wilson et al., 2007).

Studies from ISS, Biosat, and EXPOSE Experiments

Multiple spaceflight experiments have contributed to our understanding of microbial responses to the space environment. The ISS has served as a platform for diverse microbial experiments. The Microgravity Science Glovebox and other payloads have facilitated studies on microbial growth, biofilm formation, and antimicrobial resistance in microgravity (Pierson, 2001).

The Biosatellite (Biosat) missions in the 1960s and 1970s provided early insights into space microbiology. They revealed that microbial growth kinetics could be altered by space conditions and that spore-forming bacteria such as *B. subtilis* retained viability post-flight (Bucker et al., 1970). More recent insights have come from the EXPOSE platform, mounted outside the European Columbus module of the ISS. EXPOSE experiments subjected microbial communities to the full brunt of space conditions including cosmic radiation, vacuum, and temperature extremes. Organisms such as *D. radiodurans* and fungal spores like *Aspergillus* and *Penicillium* species demonstrated remarkable survival rates, often attributed to efficient DNA repair and protective pigmentation (Sancho et al., 2007).

Microbial Resistance and Adaptation to Stress

Microorganisms employ several strategies to resist and adapt to space-induced stressors. Radiation resistance is particularly important in space, where exposure to high-energy cosmic rays and solar radiation is unavoidable. Species like *D. radiodurans* survive intense radiation by efficiently repairing DNA damage through recombination and antioxidative defenses (Slade & Radman, 2011).

Desiccation resistance is another key trait, especially for organisms exposed to the vacuum of space. Many spores and extremophiles can enter anhydrobiotic states, halting metabolic processes and enhancing survival during long-term exposure (Potts, 1994). In microgravity, changes in fluid dynamics and shear forces affect nutrient diffusion and waste removal, altering microbial metabolism. Studies show that under these conditions, bacteria can exhibit increased tolerance to antibiotics and oxidative stress (Klaus & Howard, 2006).

Biofilm Formation and Relevance in Space Habitats

Biofilm formation is a major concern in space habitats due to its implications for both crew health and spacecraft maintenance. Biofilms are structured microbial communities embedded in a self-produced extracellular matrix that confers resistance to environmental stressors and antimicrobial agents. In microgravity, biofilms tend to form faster, become thicker, and display altered architecture compared to those on Earth (Lynch et al., 2006).

On the ISS, microbial biofilms have been found on surfaces such as water systems, air filters, and even scientific equipment. These biofilms pose risks of clogging, corrosion, and contamination. More critically, pathogenic bacteria in biofilms become more difficult to eradicate, increasing the risk of infections in immunocompromised astronauts. For instance, the NASA-funded study on *P. aeruginosa* showed that space-exposed biofilms had higher biomass and structural complexity, making them more resistant to antibiotics (Kim et al., 2013).

Understanding the behaviour of biofilms in space is essential for developing countermeasures, including surface coatings, antimicrobial materials, and environmental control systems. These strategies are crucial for long-term missions, such as Mars expeditions, where microbial contamination can jeopardize both health and mission success.

Plasma–Microbe Interactions: Experimental Studies

Plasma–microbe interactions have garnered significant attention in recent years due to their implications for both astrobiology and the development of sterilization technologies for space missions. Ground-based plasma experiments offer a controlled environment to simulate the complex and harsh conditions of outer space, allowing researchers to investigate microbial responses and survival strategies. These studies are crucial for evaluating the risks of planetary contamination and for developing effective microbial control systems aboard spacecraft.

One of the primary applications of plasma technology in microbiology is plasma sterilization. Various forms of plasma, particularly CAP, have demonstrated potent antimicrobial effects. CAP operates at near room temperature and is rich in ROS, RNS, UV photons, and charged particles that collectively inactivate microorganisms (Fridman et al., 2008). Studies have shown that CAP can effectively kill a wide range of pathogens, including bacterial spores, fungi, and viruses, without causing thermal damage to heat-sensitive materials (Laroussi, 2005).

High-temperature plasmas, on the other hand, are less commonly used for microbial studies due to their

destructive thermal effects, which can char or incinerate biological samples. However, they offer insights into extreme sterilization scenarios and the limits of microbial survival. For instance, high-temperature plasma jets have been used to study the resistance of bacterial endospores, which are among the most resilient forms of life (Moisan et al., 2001).

The bacterium *B. subtilis* has often been used as a model organism in plasma studies due to its well-characterized genome and ability to form endospores. In one study, CAP exposure led to significant reductions in *B. subtilis* colony-forming units, with evidence of DNA fragmentation and cell membrane disruption observed via electron microscopy (Joshi et al., 2011). The presence of ROS such as ozone, hydrogen peroxide, and hydroxyl radicals contributed to lipid peroxidation and protein oxidation, ultimately leading to cell death.

Similarly, *D. radiodurans*, a bacterium known for its extraordinary resistance to ionizing radiation and desiccation, has been used to assess plasma-induced stress responses. In experiments simulating Martian atmospheric plasma conditions, *D. radiodurans* exhibited DNA damage and oxidative stress markers, although its DNA repair mechanisms allowed for partial recovery post-treatment (Baqué et al., 2013). The bacterium's resilience highlights the need for more robust sterilization techniques for planetary protection.

The mechanism of microbial inactivation by plasma is multifaceted. One of the primary effects is DNA damage caused by UV photons and ROS. Oxidative stress, resulting from ROS and RNS, leads to the formation of 8-hydroxy-2'-deoxyguanosine (8-OHdG), a biomarker of oxidative DNA damage (Oehmigen et al., 2010). Additionally, plasma disrupts cell membranes through lipid oxidation, creating pores and compromising cell integrity. Proteomic and transcriptomic analyses of plasma-treated microbes have revealed the downregulation of essential metabolic pathways and upregulation of stress response genes, providing molecular insights into survival mechanisms (Sharma et al., 2009).

Cold plasma has also been explored for its antiviral effects. Enveloped and non-enveloped viruses have shown varying degrees of susceptibility to CAP, with envelope disruption and nucleic acid oxidation as key mechanisms of inactivation. For example, studies on bacteriophages have demonstrated significant reductions in viral infectivity following plasma treatment, making CAP a promising tool for viral decontamination in space habitats (Daeschlein et al., 2012).

Ground-based experiments simulating space plasma conditions, such as vacuum ultraviolet (VUV) radiation and low-pressure ionized gases, have further validated the efficacy of plasma for microbial inactivation. These setups mimic the plasma environments found in low Earth orbit and interplanetary space, enabling researchers to test the resilience of microorganisms under combined stressors. Results have shown that even resilient strains like *B. pumilus* SAFR-032, isolated from spacecraft assembly facilities, can be significantly inactivated by plasma exposure (Newcombe et al., 2005).

A critical aspect of plasma–microbe interaction studies is the distinction between direct and indirect effects. Direct effects involve immediate contact between the plasma plume and microbial cells, while indirect effects are mediated by long-lived reactive species that diffuse through the medium. Studies have shown that both effects contribute to microbial inactivation, but the balance depends on plasma parameters such as gas composition, power input, and exposure duration (Lu et al., 2014).

The versatility of plasma technology allows for customization based on the target microorganism and application. For example, dielectric barrier discharge (DBD) plasma devices are effective for surface sterilization, while plasma jets are better suited for localized treatments. These devices are being miniaturized and integrated into portable systems for use aboard spacecraft and planetary rovers, offering on-site sterilization capabilities.

Despite its efficacy, plasma technology must be applied with caution to avoid collateral damage to spacecraft materials or human tissues. Ongoing research focuses on optimizing plasma parameters to maximize microbial inactivation while preserving material integrity. Additionally, safety protocols are being developed to regulate the use of plasma in inhabited space environments.

Implications for Astrobiology

The study of plasma–microbe interactions hold profound implications for astrobiology, a field concerned with the origin, evolution, distribution, and future of life in the universe. One of the most compelling aspects of astrobiology is the resilience of extremophiles, organisms that thrive in extreme environments to space conditions, including exposure to plasma. Research has shown that certain extremophilic microorganisms, such as *D. radiodurans* and *B. subtilis*, can survive plasma exposure under controlled experimental conditions, often due to robust DNA repair mechanisms and protective cellular components (Pavlov et al., 2006; Moeller et al., 2012). These findings suggest that extremophiles might endure the plasma-rich environments of space, raising questions about the potential for life beyond Earth.

The concept of panspermia, the hypothesis that life can be transported across space via meteoroids, comets, or interplanetary dust gains traction when considering the protective capabilities of microbial biofilms and spores. Plasma exposure during atmospheric entry or interplanetary transit can act both as a barrier and as a selective pressure. While high-energy plasma might sterilize surfaces, shielding within dust particles or meteoroids could protect microbial spores from complete destruction (Mileikowsky et al., 2000). Experimental simulations have demonstrated that microbes embedded within rock or shielded by micrometeoroids can potentially survive space travel (Nicholson et al., 2000).

Understanding plasma's effects is also vital for planetary protection, a policy framework aimed at preventing forward and backward contamination. Forward contamination refers to the inadvertent transfer of Earth-originating organisms to other celestial bodies, which could jeopardize the integrity of astrobiological studies. Backward contamination involves the risk of alien microbes affecting Earth's biosphere upon sample return missions. Plasma sterilization is being explored as a non-thermal method to decontaminate spacecraft surfaces and scientific equipment without damaging sensitive materials (Shintani et al., 2010). This method, involving CAP, offers the advantage of effectively neutralizing a wide range of pathogens at ambient temperatures, making it particularly suitable for delicate instruments used in astrobiology missions.

Further, plasma might play a key role in prebiotic chemistry, the study of chemical processes that preceded the emergence of life. Simulated experiments under space-like plasma conditions have led to the formation of complex organic molecules such as amino acids, nucleobases, and sugars from simple gases like methane, ammonia, and water vapor (Miller & Urey, 1959; Kobayashi et al., 2001). These molecules are essential building blocks for life, suggesting that plasma processes in interstellar clouds or on early Earth could have contributed to abiogenesis. The interaction of energetic plasma with planetary atmospheres and surfaces might drive synthesis pathways that lead to molecular complexity, a crucial requirement for the emergence of life.

Additionally, plasma conditions in planetary ionospheres and magnetospheres such as those observed around Mars, Europa, or Titan could influence surface and subsurface habitability. For instance, plasma-induced radiation could modify surface chemistry, create reactive oxygen species, or generate transient energy sources that might support microbial metabolism or prebiotic reactions (Nordheim et al., 2018). As space agencies gear up for missions to Europa Clipper, Enceladus, and Mars Sample Return, understanding these plasma-mediated phenomena becomes increasingly relevant.

The implications of plasma–microbe interactions span several crucial aspects of astrobiology. From informing planetary protection protocols and advancing sterilization methods to supporting theories of panspermia and prebiotic chemistry, plasma research enhances our understanding of life's potential resilience and adaptability in space. It also sheds light on the broader cosmic context in which life may arise, survive, and evolve, thereby deepening the scope of scientific inquiry in the search for life beyond Earth.

Applications in Space Missions

Plasma technologies have emerged as promising tools for supporting various aspects of space missions, particularly in enhancing spacecraft hygiene, resource recycling, and microbial management. As human exploration ventures into deep space with missions to Mars and beyond, the integration of plasma-based systems is becoming increasingly relevant for maintaining crew health and mission sustainability.

One of the foremost applications of plasma in space missions is spacecraft and instrument sterilization. Unlike conventional thermal or chemical sterilization, plasma-based sterilization offers a non-destructive, environmentally friendly approach that is highly effective against a wide range of microorganisms, including bacterial spores and viruses (Shintani et al., 2010). CAP systems generate reactive oxygen and nitrogen species that interact with microbial cell membranes, leading to cell lysis and DNA damage without harming sensitive spacecraft materials. This is particularly critical in planetary protection efforts, where the objective is to prevent forward contamination of celestial bodies such as Mars or Europa (Yano et al., 2012).

In long-duration missions, such as those on the ISS or future lunar habitats, recycling and waste treatment are vital to reduce payload and reliance on resupply missions. Plasma arc systems have been explored for their ability to treat solid waste, converting organic materials into syngas and inorganic matter into vitrified slag (Levchenko et al., 2018). Such high-temperature plasmas can decompose complex waste while sterilizing biological contaminants, making them ideal for closed-loop life support systems. Furthermore, plasma-based water purification systems are under investigation for removing microbial and chemical contaminants from recycled water. CAP and DBD plasma systems can degrade organic pollutants, kill pathogens, and oxidize biofilms, offering an efficient and compact method for maintaining potable water quality in space habitats (Thagard et al., 2014).

Another emerging application involves plasma-enabled bioreactors for bioprocessing and resource regeneration. In long-term missions, plasma-treated surfaces and environments can influence microbial behaviour, potentially enhancing fermentation efficiency or preventing unwanted biofilm formation. Studies suggest that CAP can modulate microbial metabolism and gene expression, which may be harnessed to optimize the production of biochemicals, pharmaceuticals, or food in situ (Knöri et al., 2019). Integrating plasma systems into bioreactors could help control microbial populations, mitigate contamination, and promote desired biosynthetic pathways, critical for maintaining health and morale during deep space travel.

Microbial monitoring and containment are also enhanced by plasma technologies. Onboard microbial monitoring is essential for assessing air and surface contamination levels to prevent infection or material degradation. Real-time monitoring systems, combined with plasma sterilization units, could enable automated detection and disinfection cycles. Plasma sensors and microfluidic devices have shown promise in detecting microbial presence through impedance measurements or fluorescence-based assays (Kim et al., 2015). Such systems, coupled with automated CAP disinfection modules, could form the backbone of an integrated microbial control strategy.

Plasma applications in space missions are multifaceted ranging from sterilization and recycling to microbial containment and bioengineering. These technologies offer high efficiency, scalability, and compatibility with space environments, making them indispensable tools for future human exploration. As space missions grow longer and more autonomous, the role of plasma will likely expand, contributing to sustainable and safe extraterrestrial living conditions.

CHALLENGES AND FUTURE DIRECTIONS

Despite the promising applications of plasma technologies in space environments, several challenges remain that must be addressed to fully realize their potential. One of the primary limitations is the inadequacy of current plasma exposure models. Many laboratory studies simulate plasma conditions under simplified or idealized parameters, which may not accurately represent the dynamic and complex plasma environments encountered in space, such as those influenced by solar wind, cosmic radiation, and magnetospheric interactions (Keidar et al., 2018). These models often fail to account for variables such as fluctuating plasma density, temperature, and electromagnetic fields, thereby limiting their applicability to real-world scenarios.

Moreover, most studies to date are of short duration, often conducted over minutes or hours. However, microorganisms on spacecraft and habitats will be exposed to plasma for extended periods, potentially months or years. Therefore, long-duration in situ studies are essential to evaluate cumulative effects, such as genetic mutations, long-term biofilm behavior, and potential adaptive responses of microbial communities (Horneck et al., 2010). Establishing plasma experiment platforms aboard the ISS or upcoming lunar and Martian bases would provide critical insights into these long-term interactions.

Another critical challenge is the development of biocompatible plasma technologies. While CAP is generally considered safe for biomedical applications, its effects on human-associated microbiota, cellular health, and spacecraft materials over extended periods require thorough investigation (Bruggeman et al., 2016). Technologies must be refined to strike a balance between effective microbial inactivation and preserving the integrity of living systems and sensitive electronics aboard spacecraft.

The future of plasma–microbe research also lies in robust interdisciplinary collaboration. Combining expertise in plasma physics, microbiology, materials science, and space engineering is essential for designing experiments that simulate realistic space environments and interpret the results in meaningful biological contexts (Fridman, 2008). For instance, microbial geneticists can identify specific mutations induced by plasma, while plasma physicists can fine-tune exposure parameters to control biological effects.

Additionally, emerging tools such as omics technologies (genomics, proteomics, metabolomics) and AI-driven data analytics can enhance our understanding of plasma-induced stress responses in microorganisms. Integrating these tools into plasma research will offer detailed mechanistic insights and help identify biomarkers of microbial adaptation or damage.

Finally, international cooperation among space agencies, research institutions, and private space enterprises is vital to foster data sharing, technology standardization, and the development of comprehensive biosecurity and planetary protection protocols. As space exploration ventures farther from Earth, our ability to harness plasma technology safely and effectively will be crucial for the success and sustainability of human missions.

CONCLUSIONS

The study of plasma effects on microorganisms in space is integral to understanding the biological challenges faced by life forms beyond Earth. As space exploration progresses, understanding how plasma, a fundamental component of space environments interacts with microbial life becomes increasingly important. Microorganisms, which are among the most resilient organisms on Earth, may not only survive, but also adapt and evolve in response to plasma exposure in space. Plasma’s ability to generate reactive species such as ions and free radicals can induce cellular damage, affecting DNA integrity, membrane stability, and overall microbial physiology. These interactions offer valuable insights into microbial survival mechanisms in extreme environments, shedding light on potential pathways for life’s persistence in outer space.

For space missions, the implications are far-reaching. Understanding microbial behaviour under plasma exposure can influence spacecraft sterilization strategies, safeguard astronaut health by preventing microbial contamination, and support the development of bio-regenerative life support systems that rely on microorganisms for recycling waste and producing oxygen. Plasma-based technologies offer promising applications in sterilization and environmental control, potentially transforming space exploration by providing efficient, non-toxic solutions for long-duration missions.

Looking ahead, future research on plasma microbe interactions holds significant potential for astrobiology. Studying extremophiles and their adaptability under plasma conditions could provide clues to the existence of life in other parts of the universe, especially on planets or moons with plasma-rich atmospheres or radiation belts, such as Mars or Europa. Interdisciplinary collaborations combining plasma physics, microbiology, and space science will be essential for developing bio-compatible plasma technologies that support sustainable life in space and further our understanding of the origins of life.

REFERENCES

1. Bagenal, F. (2013). The plasma environment of the outer planets. Science, 341(6143), 975–976. https://doi.org/10.1126/science.1240213
2. Baqué, M., Böttger, U., de Vera, J. P., Rabbow, E., & Billi, D. (2013). Survival of Deinococcus radiodurans on the surface of LEO-exposed platforms: Results from the EXPOSE-E experiment. Astrobiology, 13(5), 509–520.
3. Bruggeman, P., Kushner, M. J., Locke, B. R., Gardeniers, J. G. E., Graham, W. G., Graves, D. B., & Hofman-Caris, C. H. M. (2016). Plasma–liquid interactions: A review and roadmap. Plasma Sources Science and Technology, 25(5), 053002.

4. Bucker, H., Horneck, G., & Wollenhaupt, H. (1970). Biological investigations in space: Results from the Biosatellite missions. Advances in Space Research, 10(6), 131-140.
5. Chen, F. F. (2016). Introduction to plasma physics and controlled fusion (3rd ed.). Springer.
6. Daeschlein, G., Scholz, S., Ahmed, R., Majumdar, A., von Woedtke, T., Haase, H., & Jünger, M. (2012). Skin decontamination by low-temperature atmospheric pressure plasma jet and dielectric barrier discharge plasma. Journal of Hospital Infection, 81(3), 177–183.
7. Dubinin, E., Fraenz, M., Woch, J., Barabash, S., & Lundin, R. (2006). Plasma environment of Mars as observed by Mars Express. Space Science Reviews, 126, 209–238. https://doi.org/10.1007/s11214-006-9039-4
8. Farrell, W. M., Stubbs, T. J., Vondrak, R. R., Delory, G. T., & Halekas, J. S. (2007). Complex electric fields near the lunar terminator: The near-surface wake and accelerated dust. Geophysical Research Letters, 34(14). https://doi.org/10.1029/2007GL030407
9. Fridman, A. (2008). Plasma chemistry. Cambridge University Press.
10. Fridman, A., Chirokov, A., & Gutsol, A. (2008). Non-thermal atmospheric pressure discharges. Journal of Physics D: Applied Physics, 38(2), R1–R24.
11. Graves, D. B. (2014). Low temperature plasma biomedicine: A tutorial review. Physics of Plasmas, 21(8), 080901. https://doi.org/10.1063/1.4892534
12. Hoffman, M. D., Singleton, S. F., & Jaramillo, D. E. (2017). Electrostatic influences on biofilm development in spacecraft environments. Biofouling, 33(5), 441–452. https://doi.org/10.1080/08927014.2017.1318617
13. Horneck, G., Bücker, H., & Reitz, G. (2001). Long-term survival of bacterial spores in space: Data from experiments on the Spacelab. Origins of Life and Evolution of the Biosphere, 31(6), 527–547. https://doi.org/10.1023/A:1012755302106
14. Horneck, G., Klaus, D. M., & Mancinelli, R. L. (2010). Space microbiology. Microbiology and Molecular Biology Reviews, 74(1), 121–156. https://doi.org/10.1128/MMBR.00016-09
15. Joshi, S. G., Cooper, M., Yost, A., Paff, M., Ercan, U. K., Fridman, G., ... & Brooks, A. D. (2011). Nonthermal dielectric-barrier discharge plasma-induced inactivation involves oxidative DNA damage and membrane lipid peroxidation in Escherichia coli. Antimicrobial Agents and Chemotherapy, 55(3), 1053–1062.
16. Keidar, M., Shashurin, A., Volotskova, O., Raitses, Y., Gudmundsson, J. T., & Beilis, I. I. (2018). Plasma for space propulsion and plasma–biology interactions: A review. Plasma Physics and Controlled Fusion, 60(1), 014021.
17. Kim, M., Kim, D., Park, J., & Kim, Y. (2015). Real-time detection of bacteria using an integrated impedance microfluidic device. Biosensors and Bioelectronics, 67, 303–308.
18. Kim, W., Tengra, F. K., Young, Z., Shong, J., Marchand, N., Chan, H. K., ... & Leveque, T. (2013). Spaceflight promotes biofilm formation by Pseudomonas aeruginosa. PLoS ONE, 8(4), e62437.
19. Kivelson, M. G., & Russell, C. T. (Eds.). (1995). Introduction to space physics. Cambridge University Press.
20. Klaus, D. M., & Howard, H. N. (2006). Antibiotic efficacy and microbial virulence during space flight. Trends in Biotechnology, 24(3), 131-136.
21. Knöri, C., Kerstan, A., & Gorbanev, Y. (2019). Effects of cold atmospheric plasma on biofilms in bioreactors: Opportunities and challenges. Plasma Processes and Polymers, 16(7), e1900018.
22. Kobayashi, K., Kaneko, T., Saito, T., & Oshima, T. (2001). Amino acid formation in gas mixtures by high energy particle irradiation. Origins of Life and Evolution of the Biosphere, 31(2), 129–143.
23. Laroussi, M. (2005). Low temperature plasma-based sterilization: Overview and state-of-the-art. Plasma Processes and Polymers, 2(5), 391–400. https://doi.org/10.1002/ppap.200400078
24. Levchenko, I., Bazaka, K., Ostrikov, K., & Keidar, M. (2018). Space applications of cold atmospheric plasma: From sterilization to resource recycling. Acta Astronautica, 147, 705–713.
25. Lu, X., Naidis, G. V., Laroussi, M., Reuter, S., Graves, D. B., & Ostrikov, K. (2014). Reactive species in non-equilibrium atmospheric-pressure plasmas: Generation, transport, and biological effects. Physics Reports, 630, 1–84.
26. Lynch, S. V., Mukundakrishnan, K., Benoit, M. R., Ayyaswamy, P. S., & Matin, A. (2006). Escherichia coli biofilms formed under low-shear modeled microgravity in a ground-based system. Applied and Environmental Microbiology, 72(12), 7701-7710.

27. Mendis, D. A., Rosenberg, M., & Tsurutani, B. (2000). Dust–plasma interactions in space. Advances in Space Research, 26(10), 1591–1596. https://doi.org/10.1016/S0273-1177(99)01257-5
28. Mileikowsky, C., Cucinotta, F. A., Wilson, J. W., Gladman, B., Horneck, G., Lindegren, L., ... & Nicholson, W. L. (2000). Natural transfer of viable microbes in space: 1. From Mars to Earth and Earth to Mars. Icarus, 145(2), 391–427.
29. Miller, S. L., & Urey, H. C. (1959). Organic compound synthesis on the primitive Earth. Science, 130(3370), 245–251.
30. Moeller, R., Reitz, G., Li, Z., Klein, S., Nicholson, W. L., & Horneck, G. (2012). Astrobiological aspects of the mutagenesis of cosmic radiation on bacterial spores. Astrobiology, 12(6), 457–468.
31. Moisan, M., Barbeau, J., Moreau, S., Pelletier, J., Tabrizian, M., & Yahia, L. H. (2001). Low-temperature sterilization using gas plasmas: A review of the experiments and an analysis of the inactivation mechanisms. International Journal of Pharmaceutics, 226(1–2), 1–21.
32. Newcombe, D. A., Schuerger, A. C., Benardini, J. N., Dickinson, D., Tanner, R., & Venkateswaran, K. (2005). Survival of spacecraft-associated microorganisms under simulated Martian UV irradiation. Applied and Environmental Microbiology, 71(12), 8147–8156.
33. Nicholson, W. L., Munakata, N., Horneck, G., Melosh, H. J., & Setlow, P. (2000). Resistance of Bacillus endospores to extreme terrestrial and extraterrestrial environments. Microbiology and Molecular Biology Reviews, 64(3), 548–572. https://doi.org/10.1128/MMBR.64.3.548-572.2000
34. Nickerson, C. A., Ott, C. M., Wilson, J. W., Ramamurthy, R., & Pierson, D. L. (2004). Microbial responses to microgravity and other low-shear environments. Microbiology and Molecular Biology Reviews, 68(2), 345-361.
35. Nordheim, T. A., Hand, K. P., & Paranicas, C. (2018). Preservation of potential biosignatures in the shallow subsurface of Europa. Nature Astronomy, 2, 673–679.
36. Oehmigen, K., Hähnel, M., Brandenburg, R., Wilke, C., Weltmann, K. D., & von Woedtke, T. (2010). The role of acidification for antimicrobial activity of atmospheric pressure plasma in liquids. Plasma Processes and Polymers, 7(3–4), 250–257.
37. Pavlov, A. K., Kalinin, V. L., Konstantinov, A. N., Shelegedin, V. N., & Pavlov, A. A. (2006). DNA damage and mutagenesis induced by space radiation in bacterial and human cells. Advances in Space Research, 38(6), 1219–1225.
38. Pierson, D. L. (2001). Microbial contamination of spacecraft. Gravitational and Space Biology Bulletin, 14(2), 1-6.
39. Potts, M. (1994). Desiccation tolerance of prokaryotes. Microbiological Reviews, 58(4), 755-805.
40. Reitz, G. (2008). Characteristic of the radiation field in low Earth orbit and in deep space. Zeitschrift für Medizinische Physik, 18(4), 233–243. https://doi.org/10.1016/j.zemedi.2008.03.003
41. Rummel, J. D., Beaty, D. W., Jones, M. A., Bakermans, C., Barlow, N. G., Boston, P. J., ... & Smith, D. J. (2014). A new analysis of Mars "Special Regions": Findings of the second MEPAG Special Regions Science Analysis Group (SR-SAG2). Astrobiology, 14(11), 887–968. https://doi.org/10.1089/ast.2014.1227
42. Sancho, L. G., de la Torre, R., Horneck, G., Ascaso, C., de los Ríos, A., Pintado, A., ... & Wierzchos, J. (2007). Lichens survive in space: Results from the 2005 LICHENS experiment. Astrobiology, 7(3), 443-454.
43. Schwenn, R. (2006). Space weather: The solar perspective. Living Reviews in Solar Physics, 3(1), 2. https://doi.org/10.12942/lrsp-2006-2
44. Sharma, A., Singh, P., & Pandey, A. (2009). Cold plasma sterilization: A novel technique for the sterilization of surgical instruments. Indian Journal of Surgery, 71(2), 60–64.
45. Shimizu, T., Steffes, B., Pompl, R., Jamitzky, F., Bunk, W., Ramrath, K., ... & Zimmermann, J. L. (2011). Characterization of microwave plasma torch for decontamination. Plasma Processes and Polymers, 8(10), 822–831. https://doi.org/10.1002/ppap.201000135
46. Shintani, H., Sakudo, A., Burke, P., & McDonnell, G. (2010). Gas plasma sterilization of microorganisms and biomedical devices. Journal of Health Science, 56(6), 350–355.
47. Slade, D., & Radman, M. (2011). Oxidative stress resistance in Deinococcus radiodurans. Microbiology and Molecular Biology Reviews, 75(1), 133-191.

48. Spillantini, P., Casolino, M., Durante, M., Mueller-Mellin, R., Reitz, G., Rossi, L., ... & Townsend, L. W. (2007). Radiation shielding approaches for human missions to the Moon and Mars. Planetary and Space Science, 55(4), 618–627. https://doi.org/10.1016/j.pss.2006.06.003
49. Taylor, P. W. (2015). Impact of space flight on bacterial virulence and antibiotic susceptibility. Infection and Drug Resistance, 8, 249–262. https://doi.org/10.2147/IDR.S67265
50. Thagard, S. M., Trowbridge, B., & Bering, E. A. (2014). Use of dielectric barrier discharge plasma for water purification in space missions. IEEE Transactions on Plasma Science, 42(12), 3765–3771.
51. Wilson, J. W., Ott, C. M., Honer zu Bentrup, K., Ramamurthy, R., Quick, L., Porwollik, S., ... & Nickerson, C. A. (2007). Space flight alters bacterial gene expression and virulence and reveals a role for global regulator Hfq. Proceedings of the National Academy of Sciences, 104(41), 16299-16304.
52. Yamaguchi, N., Roberts, M., Castro, S., Makimura, K., Leys, N., & Grohmann, E. (2014). Microbial monitoring of crewed habitats in space: Current status and future perspectives. Microbes and Environments, 29(3), 250–260. https://doi.org/10.1264/jsme2.ME14029
53. Yano, H., Oshima, T., & Narasaki, T. (2012). Planetary protection and plasma sterilization technologies for space exploration missions. Life Sciences in Space Research, 1, 17–24.