Microbiology and space exploration

Teacher - I heard that an astronaut got an infection while in space! How can that happen?

Rosa Santomartino

UK Centre for Astrobiology, School of Physics and Astronomy, University of Edinburgh, Edinburgh, UK.

Microbiology and space exploration

Storyline

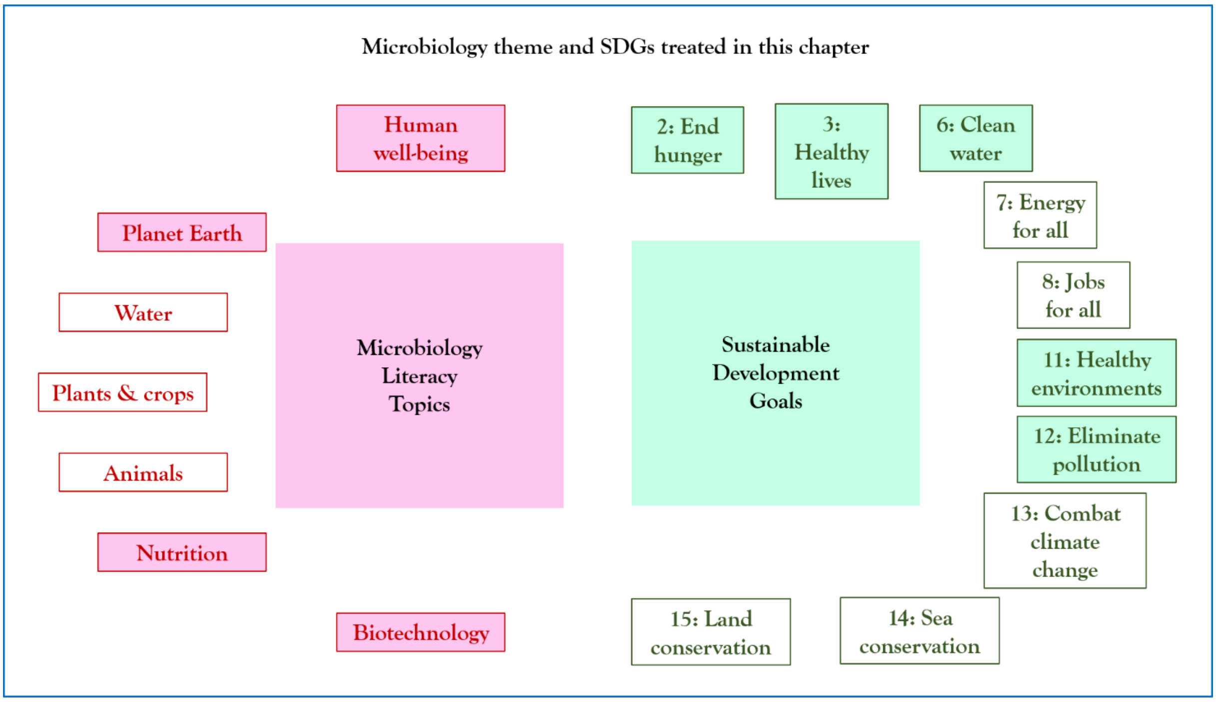
Microbes are ubiquitous and critical for our life on Earth. The human body contains billions of bacteria, fungi and other microorganisms, constituting the human microbiome, and they are essential for our health and survival. Modules of space stations and spacecrafts are assembled in clean rooms on Earth to maintain their sterility. However, when astronauts go in space, they take their microbes with them which eventually colonise spacecraft surfaces. Conditions that are present in space are quite different than those on Earth. In open space:

- *temperatures* reach extremes that can go from very high to very low (close to absolute zero, which is the lowest temperature matter can reach),
- *the absence of atmosphere* creates a vacuum, meaning that pressure is close to zero and oxygen is absent,
- *a higher dose of radiations*, coming from the Sun and the universe, is experienced. This is again due to the absence of atmosphere, which protects us from some of these radiations on Earth,
- the further we move away from Earth, or other objects in space, the lower the gravity we experience. It can become so close to zero – but never really zero - that it looks like being absent. The scientific name for this is microgravity, sometimes referred to as weightlessness.

All these conditions change if we are on the Moon, Mars, or on a spacecraft. For instance, inside the International Space Station (ISS) temperature and pressure are controlled. This is why astronauts wear spacesuits outside the space station, but not inside. On Mars, these conditions are different from Earth, but also from open space. The conditions in space are therefore uniquely extreme, and have big effects on all living beings. Understanding if and how simple organisms such as microbes resist, or even thrive, under these conditions can provide insights on the origin of life, as well as on the possibility of extraterrestrial life. Discovering microbial responses to space conditions has also big implications on human health, especially considering that the immune system of astronauts does not work as well in space as it does on Earth. Research has shown that some pathogenic or opportunistic microbes can increase their virulence when they are in space. Microbes can also become dangerous for spacecrafts, causing corrosion and deterioration. Because microorganisms perform countless tasks for us on Earth, acquiring knowledge on their behaviour in space provides direct insights on possible uses in space exploration. They may for instance be used for food production, for soil formation from extraterrestrial regolith, to produce oxygen, for the extraction of useful elements in biomining, and in other processes aimed to support self-sustaining settlements. This is particularly important considering that future space missions aim to extend the current length of spaceflights. For instance, travelling to Mars is estimated to take a minimum of 6 months. This knowledge can also be applied to terrestrial biotechnological applications.

The Microbiology and Societal Context

The microbiology: astrobiology; microbiome; sterility; extremotolerance; biofilms; infections; opportunistic pathogens; antimicrobial resistance; biocorrosion; biotechnology; bioremediation; biorecycling. *Sustainability issues:* end hunger; healthy lives; clean water; healthy environments; eliminate pollution.



Microbiology and space exploration: the Microbiology

1. ***What is microgravity?*** Gravity is the universal force of attraction acting between objects with mass or energy. It controls the trajectories of bodies in the solar system and in the cosmos, for instance planets orbiting around a star. Gravity is measured by the acceleration that it gives to freely falling objects, and it is about 9.8 m/s^2 on Earth, or 1 x *g*. The gravity acceleration is lower on the Moon and Mars: 1.6 m/s^2 (0.16 x *g*) and 3.8 m/s^2 (or 0.38 x *g*), respectively.

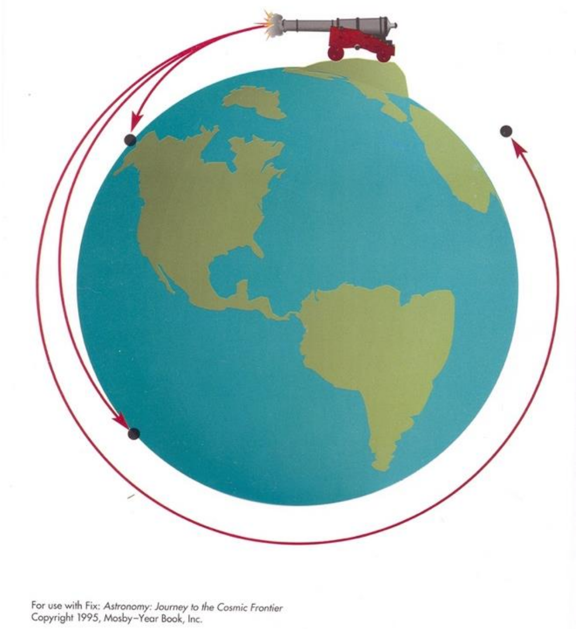
It is commonly believed that gravity is absent in space, but this is not true and the term “zero gravity” is scientifically inaccurate. In fact, gravity is present everywhere in space, but it can become so weak that it appears to be absent. Microgravity (micro = very small. This is why it is also the prefix in microorganisms or microbes), a synonym of “weightlessness”, is the correct term to indicate the conditions in which gravity is indeed very small, but never zero.

You may be familiar with images of astronauts and objects orbiting in space, for instance on the International Space Stations (ISS). The ISS is at an altitude of around 400 km above the sea level. At this altitude, gravity acceleration is still 90 % of that on Earth surface.

2. ***Microbiomes of astronauts.*** The human microbiome is the group of microbes (bacteria, fungi, archaea and viruses) that are living in and on our body. They are present on our skin, inside our gut, stomach, mouth, nose, ears, and genitals. The human microbiome has a protective and beneficial role for our health, for instance by producing vitamins, digesting nutrients from food that would not be assimilated otherwise, and limiting the proliferation of pathogenic microbes. The microbiome is highly susceptible to variations, depending on a large range of stimuli and lifestyles. For instance, a vegetarian person develops a microbiome that is widely different from that of an omnivorous person, in term of microbial species.

So, why do people and objects float on the ISS?

On the ISS, microgravity is indeed experienced, but is actually a consequence of its orbit around Earth. Orbiting objects (including the Moon, but also the Earth orbiting the Sun, and so on) are in a state of constant free fall: in a vacuum, gravity makes all objects fall towards Earth with the same acceleration, regardless of their mass. A person dropping something at the beginning of a free fall would see the object falling with them with the same acceleration, and therefore the object would appear to be floating in front of that person. The ISS is constantly free falling toward Earth. However, it is also moving at such a high speed (7.7 km/s) that its falling curve matches the curve of Earth As a result, the spacecraft keeps falling toward but around Earth. Because the ISS and any crew or object abroad are free falling together around Earth, they all appear as though they are floating.



When launching an object at the right speed (plus other conditions, of course), its falling curve will match Earth's curve, allowing the object to start orbiting around Earth (Astronomy: Journey to the Cosmic Frontier Copyright 1995, Mosby-Year Book, Inc.).

Is it possible to experience microgravity on Earth?

Yes, it is. For instance, airplanes can create a short period of microgravity by flying in up-and-down parabolas: at the top of the parabola, people and objects inside the airplane experience few seconds of free fall. It can be fun, but is not always pleasurable, and this is why these airplanes are often referred to as "vomit comets". Other facilities are drop towers, very high towers in which a vacuum is created by pumping air out, and fall experiments can be performed by dropping a variety of objects or samples. Both these principles are also used in amusement parks (roller coasters and drop towers).

The astronaut Jessica Meir observes a floating sphere of water (NASA).

So, next time you enjoy one of these rides you can feel like an astronaut for few instants! Another way scientists can study microgravity is by simulating it. They can use special devices (e.g.; clinostats) in which constant rotations are applied to samples in such a manner that gravity, although always present, is counterbalanced and neutralised.

Stress can also modify the microbiome. Astronauts are subjected to unique stressors related to spaceflight and space conditions (e.g.; microgravity, radiations, etc.), but also caused by the social isolation and the pressure of a high-responsibility job. As a consequence, astronauts' microbiome undergoes variations. Research have shown that the general diversity of astronauts' gut microbiome remains similar or increases during spaceflight, and this is due to a shift in relative abundances, acquisition or loss of bacterial species. Some species associated with gut diseases and inflammation have been found, but a clear correspondence between these variations and astronauts health requires further study.

Interestingly, the gut microbiomes of different astronauts tend to become similar, even between people inhabiting the ISS in different periods of time. This is probably due to the fact that they eat similar food onboard the ISS.

Skin infections, rashes and congestion symptoms are sometimes experienced by astronauts. However, skin and nose microbiomes did not vary much in space, apart from a few microbial species whose presence varied. Some of these, in particular *Staphylococcus*, have been associated with respiratory diseases and may partially explain the symptoms experienced by space crew. The changes observed appeared shortly after the start of the spaceflight and remained constant for a prolonged period of time. Interestingly, the microbiome of ISS surfaces resembles that of the crew's skin, with some of these microbes being considered opportunistic pathogens.

Modules of space stations and spacecrafts are assembled in clean rooms on Earth to maintain their sterility. When astronauts go in space, the microbes of their microbiome eventually colonise spacecraft surfaces, explaining the resemblance. The similarities observed are temporary and change quickly when new crew members arrive to the ISS, although some long-term microbial species remain stably present onboard.

3. ***Infectious diseases in space.*** Research has shown that astronauts experience a large variety of changes in their body during spaceflight. Microgravity affects bone and muscles, which naturally deteriorate because they do not have to sustain the body weight in space as they do under terrestrial gravity. This is why it is very important for astronauts to exercise every day when in space. Microgravity also affects the circulation of blood and other body fluids. Radiation can penetrate tissues and cells, and cause long-term damage to brain, the immune system and other organs.

Moreover, it is important to consider the psychological stress caused by social isolation, fears, impaired day/night rhythms, being away from family and friends, and indeed from the Earth itself. Astronauts often show a weakened immune system, and they could be more susceptible to illness or allergic reactions during spaceflights.

Some infectious diseases experienced in the past by astronauts while in space are colds, upper respiratory infections, urinary tract infections and skin infections. Despite often being mild illnesses on Earth, they can become more serious and disruptive when experienced in space. For instance, cold infections spread among astronauts of the Apollo missions 7, 8 and 9, in the 60s. The impact on the crew was so disruptive that NASA subsequently decided for future missions to implement a pre-spaceflight quarantine for all crew members, to be sure that no infectious disease is introduced into the spacecraft.

4. ***Space conditions have an impact on microorganisms as well.*** Scientists have found that latent (non-active) viruses, such as herpes simplex (which causes the cold sores that appear on our lips and around our mouths, etc., when we get stressed), can reactivate during spaceflight. Some microorganisms show an increased virulence during spaceflight. This was first demonstrated in 2007, when a group of researchers discovered that the pathogenic bacterium *Salmonella*

typhimurium, which causes gastroenteritis, responded to space condition by inducing molecular changes and altering its virulence.

Microbes are single-cell organisms, but they can create communities and build complex micro-structures, often attached to surfaces, called biofilms. Living in biofilms provides some advantages to microbes, such as the exchange of nutrients and molecules and protection from external stresses, including drugs and antibiotics. Because the conditions experienced during spaceflights are considered stressing also for microorganisms, some of them react by producing a thicker biofilm. Consequently, they become more resistant to antibiotic treatment, and infections may become more difficult to treat.

5. ***Life in extreme conditions.*** As mentioned above, environmental conditions present in open space are quite unique and extreme. They include extremes of temperatures and pressures (vacuum), high doses of radiations, and different gravity conditions, for instance microgravity. On planetary bodies, additional stresses can exist, such as the presence toxic compounds, and extremely acidic or basic pH conditions. The presence of water should be also considered.

Astrobiologists are primarily, though not exclusively interested in the question "is there life anywhere else in the Universe?" One of the ways to answer this is to look in places on Earth in which the conditions are quite harsh, and search for life there. These places, sometimes referred to as "extraterrestrial analogues", can provide useful indications of the possibility to actually find life on planets that have similar conditions. For instance, if we want to know if life could exist under extreme hot or cold temperatures, we can try and search for any form on life near volcanoes and hydrothermal vents, or in Antarctica and Greenland. This is how scientists discovered that many environments on Earth, previously believed to be dead, actually host many forms of life, which are often microorganisms (this is why, when astrobiologists imagine a possible alien form of life, they will usually think about a microbe, not some scary green humanoid with a huge head). We refer to them as extremotolerant, if they can resist in extreme conditions but would rather live in milder environments, or extremophiles (philia = love) if they thrive under extreme conditions and would consider "extreme" what we would describe as quite a pleasurable environment.

Why are they often microorganisms? This is because microbes are quite simple, when compared to complex multi-cellular organisms (such as plants, animals and us, for instance), and this allows them to be very plastic and adaptable. They have also existed on Earth for about 4 billion years, which is a long time for evolution, and during this time have explored all manner of ways of living and of exploiting all available planetary resources that can serve as sources of food and energy. Collectively, microbes have evolved an amazing diversity of metabolic capacities that allow them to inhabit environments far too hostile for complex organisms.

Extremotolerants and extremophiles can adopt different strategies to survive or thrive under a specific condition, and these may be specific for the single species. For instance, the microbe *Pyrococcus furiosus* (an Archaea) grows very happily around 100 °C because its enzymes are more rigid and do not break easily when heated. It also has proteins whose structures reduce water evaporation. On the contrary, microbes growing at cold temperatures (less than 15 °C, but the lowest limit is around -80 °C), for instance *Chryseobacterium greenlandense*, adapted by keeping their membranes and enzymes more flexible, but also producing specific antifreeze agents and slowing their metabolism. Very salty (e.g., the Dead Sea) and very dry (e.g., deserts) environments require similar strategies, because the main issue in both case is the lack of liquid water. The strategies usually involve the reduction of water loss.

Another interesting strategy is to enter into a dormant state called spore, a condition in which a cell simply stops being active to avoid damage caused by an adverse environment, and just wait for more favorable conditions to occur and "wake up" again. Not all microbial species can form spores, but those that can are of great interest from an astrobiological point of view, because they can survive under conditions such as space vacuum.

Some fascinating microbes are also able to survive extremely high doses of radiation. *Deinococcus radiodurans*, for instance, can survive radiation doses 2000 times higher than those that would kill a human being. Their protection strategy involves the rapid repair of molecules damaged by radiation, and also the production of specific molecules that absorb radiation and screens them, similar to the sun creams we use. Another strategy is to reduce exposure to radiation, for example by living under the surface of Earth, within rocks for instance, in which radiation is usually reduced.

It must be said, though, that natural environments often exhibit more than one extreme conditions, the so-called polyextreme environments. This is also true for other planets, for instance Mars presents a lack of water, low pressure, extremes of temperatures, high salt concentrations and high radiation on its surface. However, some of the microbial defence strategies contribute to tolerance of multiple extremes.

Learning about life in extreme environments on Earth does not directly tell us if there is life on other planets, but it helps us understand which are the boundaries of life, at least for microbes on Earth. Many microbiology experiments that have been performed on spacecrafts, for instance on the Shuttle, the Mir and the ISS, studied extremophiles or extremotolerant microbes. In these cases, the experiments could be performed either inside or outside the spacecraft. When experiments are performed inside the spacecraft, the microbial cells are usually inserted into hardware specifically designed for the experiment. Because they are inside, they are not subjected to the whole spectrum of space conditions described above, but only to higher dose of radiation and microgravity, while temperature and pressure are mild and controlled (otherwise astronauts won't be very comfortable!). On the other hand, when the experiment is performed outside the spacecraft, the microbes are also exposed to vacuum, extreme temperature variations and stronger radiation. This requires hardware specifically designed and dedicated facilities, as is the case for the European Space Agency (ESA) facility EXPOSE present onboard the ISS.

6. ***Corrosive microbes.*** Spacecrafts are strictly enclosed environments. This is necessary for the maintenance of the right pressure, temperature and air composition inside the spacecraft, to protect the crew from deadly space conditions incompatible with human life. Nevertheless, corrosion of spacecrafts and space stations have been documented on several occasions. Spacecraft structures and surfaces are subjected to physical damages due to high dose of radiation and vacuum encountered in space. In addition to physical stresses, microbial action can also enhance deterioration of spacecraft surfaces.

We discussed above (section 2) how microbes often produce thicker biofilms as a response to space conditions, and how this can make infectious diseases in space more dangerous. Biofilms also have a role on the corrosion and deterioration of surfaces on which they are attached. The Mir space station suffered from microbial colonization and corrosion of the rubber gaskets around windows, on space suits, cables, insulation tubes and communications devices. They also corroded metal structures. The most dangerous species were fungi rather than bacteria. Studies on similar biological corrosions happening on the ISS are ongoing.

Some microbes that have been found on the ISS surfaces are capable of deterioration and corrosion on Earth, but their possible role on corrosion in space needs more investigation. Research on this field is important, because we aim to prolong the duration of spaceflights in the future. Therefore, it is necessary to understand how to limit microbial colonization of structure surfaces, but also how to produce more resistant materials.

7. ***Space biotechnologies and manufacturing.*** So far, we mainly discussed how dangerous microbes could be for astronauts. However, they also perform countless tasks for us on Earth, and it would be unfair to only mention the negative aspects of microorganisms, without mentioning how beneficial they could be for our survival in space.

The ISS is a very efficient system, which recycles water from air and astronauts' urine by chemical reactions, and constantly cleans its air by using dedicated depuration filtering. However, this is not sufficient, and the ISS still relies on a constant resupply of resources from Earth, which is necessary but also very expensive and not fully sustainable. The aim for the future decades of space exploration is to go further and further, reaching the Moon and then Mars. The further we will go, the more expensive and the less sustainable it will be to rely on a constant resupply of materials from Earth.

Biotechnologies involving microbes and plants could be the solution. Microbes could, for instance, be useful for food, drink and food supplement production. One example is the use of *Spirulina*, which is a particular type of bacterium (cyanobacterium) which requires very little space to grow and is considered a superfood because it is full of nutrients. Microorganisms could also help producing oxygen, as some of them can perform photosynthesis like plants. With their biofilms, they could help in decontaminating water, atmosphere, and planet surfaces (bioremediation).

They can also help extracting useful materials from the extraterrestrial rocks, a process widely used on Earth and called biomining, and producing biofuel that will be necessary for the use of rockets and machines.

Research is ongoing to understand if we can harness radiation-resistant microbes to create buildings with shielding and self-healing properties in space. Finally, when humans will be fully settled on an extraterrestrial environment, microbes will be necessary for the establishment of advanced biotechnologies, for instance pharmaceutical industries to produce drugs, in order to make the settlement completely self-sufficient.

A project from the ESA called MELiSSA, has been studying for 30 years how to recycle waste products to produce oxygen, water, and food in space missions using microbes and plants. The concept is based on terrestrial ecosystems: each component, or compartment, of MELiSSA uses waste material from the previous one (including human waste) as a form of nutrient or a source of energy, eventually producing waste material that can be used by the following compartment. Applying this concept to extraterrestrial settlements, waste production can be reduced, and recycling will naturally be enhanced. This would make the settlement not only very efficient, but also green. The project still requires research, but it is a good example of how microbes will be important for us in space.

8. ***Terrestrial applications.*** Most space agencies (ESA, NASA, UK Space Agency etc.) currently support the United Nations' Sustainable Development Goals (SDGs), and are committed to use space research to improve life on Earth. Did you know that some of the most exciting technologies that we use in our everyday life were first invented for space application? This is because space is quite a challenging environment, requiring the best innovations that science can offer. Once the technologies are produced for space exploration, they are also available for terrestrial applications.

One example is satellites, originally developed for space exploration, but now necessary for our telecommunications as well as for monitoring weather, natural disasters, pollution and deforestation.

Research on how to reduce the astronauts' muscle and bone loss during spaceflight has helped treating serious muscle-skeletal diseases. According to the same principle, understanding how some microbes adapt to and thrive in harsh space conditions is relevant for space applications, of course, but also informs us about how to harness the power of microorganisms for applications on Earth. For instance, the most successful cleaning and sterilizing procedures performed for spacecraft assembly can be applied to clean rooms of pharmaceutical industries. Filtering systems using biofilms to depurate air and water could be used on polluted terrestrial environment. Microorganisms naturally or artificially (i.e., by biological engineering) capable of degrading toxic molecules from nasty extraterrestrial regolith (dust and rock fragments) may be used for soil decontamination and fertilization on Earth. Moreover, by learning how to use microorganisms to optimize waste recycling in space and create self-sustaining extraterrestrial settlements, we are also learning how to improve sustainability on Earth, and how to solve environmental issues.

By studying the changes in human microbiome in space we might predict what happens to our gut and skin microbes when people are confined in a closed environment, or when they are subjected to extreme physical and psychological stresses on Earth (e.g., during a pandemic, in hospitals or in prisons), and how this affects their health. We can learn more on infectious diseases by observing what happens to astronauts and microbial virulence in space.

It is important to know that a large part of research conducted on the ISS has the primary aim to benefit Earth and terrestrial applications, rather than space exploration. Plus, we do not need to go to space to find space microbiology research useful for applications on Earth. Studying microbes that thrive under extreme conditions already brought us several technological advances. For instance, the PCR technique, widely used in biology laboratories and particularly important for COVID-19 diagnostics, is possible because of the discovery of enzymes found inside high temperature-loving microorganisms. Other enzymes found in similar microbes are used in liquid washing detergents.

9. ***Planetary protection.*** The scientific advancement in space science made space exploration quite a routine adventure, and we now send several spacecrafts to explore other planets. For instance, only in July 2020 three different space missions were sent to Mars, despite the pandemic! Space agencies must ensure that they do not introduce any terrestrial biological contamination to other planets or planetary bodies that scientists think may have potential for past or present life (forward contamination). This is necessary not only to prevent harming indigenous lifeforms, but also not to jeopardize studies on extraterrestrial life.

One way to prevent this is by assembling modules of space stations and spacecrafts in clean rooms on Earth to maintain their sterility. It is also important that we do not bring back to Earth any potential harmful form of extraterrestrial life (back contamination), if they exist, that may pose danger to terrestrial life. However, not all planets or moons requires the same level of protection: it depends on the probability of them hosting or having hosted extraterrestrial life, according to scientists. For instance, while Mars is currently highly protected because it is of big interest from an astrobiological point of view, the Moon has a very low probability of hosting indigenous lifeforms, and therefore scientists reckon less protection is needed.

These concepts are described by the planetary protection policy, formulated by the Committee on Space Research (COSPAR) to guide compliance with the United Nations Outer Space Treaty. Planetary protection policy needs to be constantly updated, following the advances and aspiration of space exploration, and therefore COSPAR and scientists meets every two years.

Relevance for Sustainable Development Goals and Grand Challenges

As mentioned above, most space agencies support the United Nations' Sustainable Development Goals (SDGs), and committed to use space research to improve life on Earth. This includes space microbiology:

- **Goal 2. End hunger.** One of the main issues for long-term space exploration is how to produce food with limited resources and in a hostile environment. Strategies that aim to use microorganisms as superfood, as producers of nutraceutical compounds, or as agents that can enrich extraterrestrial regolith to produce fertile soil can be applied to terrestrial environments with limited resources, to implement food production and enhance the efficacy of human waste recycling.
- **Goal 3. Healthy lives.** The space environment is quite unique and hostile, and has effects not only on the space crew, but also on its microbiome and on the microbes that colonise the spacecraft. Research aimed to study the changes on these aspects and their consequences on human health can teach us how to improve our life on Earth.
- **Goal 6. Clean water.** Spacecrafts are strictly enclosed environments, in which recycling of water is of essential importance. It is constantly depurated from the air and from crew urine by sophisticated filtering systems that are under constant development. The use of biofilms to biofiltrate and decontaminate water is under investigation, and such technologies could be also used for terrestrial applications.
- **Goal 11. Healthy environments.** Similar to goal 2, we know how microorganisms, humans and the environments are strictly correlated and influence each other in a closed environment such as a spacecraft. We are also studying how to create future extraterrestrial space settlements in the most sustainable and efficient way, and microorganisms will be essential components of this future. This knowledge will be of high impact not only to improve space missions, but also to enhance the quality of our lives on Earth and of the environments that surround us. This research is precious to learn how to enhance sustainability, recycling of resources and support circular economy.
- **Goal 12. Eliminate pollution.** Air depuration is essential on a spacecraft, and filtering strategies used can be applied to terrestrial application. Moreover, settling on a planet such as Mars would likely require the decontamination of Martian regolith from toxic molecules and nasty compounds. Microbes could perform this for us, thanks to a strategy called bioremediation. Bioremediation is already used on Earth to decontaminate polluted environment. Learning how to make the mechanisms work under the harsh space conditions may unlock possibilities to enhance and improve them for terrestrial applications, and allow the microbial decomposition of recalcitrant pollutants. Furthermore, extraterrestrial settlements will require a highly efficient level of waste recycling. In conditions in which resources are limited, it is mandatory to recycle as much as possible and to limit waste production. This means that by studying how to make space exploration possible, we are learning that sustainability is mandatory and that microorganisms will be key to the success of a settlement. This raises awareness on the importance of investing in sustainability and circular economy, and particularly on microbial biotechnologies that could make this a reality, to reduce pollution on Earth.

Potential Implications for Decisions

1. ***Individual***
   a. Keep being updated on the newest advances in space microbiology, space science and space exploration, and their applications.
   b. Reduce waste production and promote recycling, taking as example what it is done on spacecrafts and extraterrestrial settlements.
   c. Be aware of how different environments could have different microbial communities, how these could impact our health, and how we impact them in return.
   d. Attend events on the topic, go to exhibitions and museums that teach you about space exploration.

2. ***Community policies***
   a. Similarly, it is useful and interesting to keep being updated on the advances in the field of space microbiology and space exploration in general.
   b. Raise awareness on how space microbiology can impact and support terrestrial applications.
   c. Societies and communities could support events with scientists and science communicators to teach the community about the topic.
   d. Establishment of exhibitions, dedicated areas in museums, etc.
   e. Promote sustainability, waste management and recycling in community, using as example the strategies of self-sustainment and sustainability used for space explorations.
   f. Promote improvement of sustainability of space explorations.

3. ***National policies relating microbes, space exploration and behaviour of microbes in space***
   a. Promote knowledge on space microbiology and its impact on space exploration and terrestrial applications.
   b. Harness the catching topic of space microbiology to teach about science to the public, and to raise awareness on sustainability, health, technology and the importance of research.
   c. Involve the public as stakeholders on choices on the next objective to pursue in space microbiology and space exploration, particularly promoting campaigns that support their sustainability.
   d. Promote investment and funding for research on this topic.
   e. Promote terrestrial application of research, knowledge and technologies developed for space exploration.
   f. Facilitate the development of a circular economy and biotechnologies by observing the strategies adopted for spacecrafts and extraterrestrial settlements.
   g. Most space agencies currently support the United Nations' Sustainable Development Goals (SDGs), and committed to use space research to improve life on Earth. It is important to keep on promoting this commitment for the future of human space exploration.

Pupil Participation

1. *Class discussion of the issues associated with microbes, space exploration and behaviour of microbes in space*

a. Do you know any movies, TV series or videogames that treat any of the themes encountered here (related to microorganisms)? Can you spot which of these have a solid scientific base and which are based on pure fantasy?

b. Imagine living on the ISS for 6 months. Discuss what resources (of any kind) and tasks will be essential for your survival in space. How will they change if you need to stay onboard for more time? And if you are travelling to Mars?

c. Do you know which of these resources and tasks are or could be produced/performed by microbes on Earth?

d. Could microbes produce/perform them in space? If so, which parameters and changes should be taken into consideration?

2. *Pupil stakeholder awareness*

a. How will space exploration affect your life? Where do you think humans will travel to in your lifetime?

b. What will change in our society if we discover that life existed in the past on Mars or on another planet?

c. How can space microbiology help us comply with Sustainable Development Goals (SDGs)?

3. *Exercises and class experiments*

a. Make a study of one planet or planetary body in our Solar System: which physical conditions are experienced there? Then, discuss if these are compatible with life. If they are, try to draw and describe an extraterrestrial microbe that could live on that planet, according to the conditions that it will encounter. Note to teachers: the planetary bodies with the highest interest from an astrobiological point of view are Mars, Europa, Enceladus and Titan.

b. Great ideas can be found here: https://www.nasa.gov/pdf/145916main_Astrobiology.Guide.pdf.

c. Further ideas for engaging exercises and class experiments to understand space conditions can be found at

- www.destinationspace.uk, although they are not strictly related to microorganisms. For instance:
- http://www.destinationspace.uk/mission-modules/get-grips-space-disorientation/
- http://www.destinationspace.uk/mission-modules/learn-about-pressure-space/

The Evidence Base, Further Reading and Teaching Aids

https://kids.frontiersin.org/article/10.3389/frym.2017.00035#:~:text=The%20human%20body%20is%20inhabited,with%20us%20throughout%20our%20lives.
http://www.destinationspace.uk/
https://spaceplace.nasa.gov/
https://www.nasa.gov/pdf/145916main_Astrobiology.Guide.pdf
https://www.nasa.gov/mission_pages/station/research/news/microbiology-101-space-station-microbes-research-iss
https://www.nasa.gov/audience/forstudents/5-8/features/nasa-knows/what-is-microgravity-58.html
https://spacemicrobes.com/
https://www.news-medical.net/life-sciences/What-is-Astro-Microbiology.aspx
https://www.youtube.com/watch?v=eJTfcV1ZceE&t=6s
https://www.bbc.com/future/article/20200311-how-do-you-keep-a-space-station-clean
https://www.youtube.com/watch?time_continue=72&v=lEyCq2KRZik&feature=emb_title
Cleaning a spacecraft: http://www.destinationspace.uk/resources/cleaning-spacecraft/
https://science.nasa.gov/science-news/science-at-nasa/2007/11may_locad3
https://gameon.nasa.gov/2020/01/30/how-is-biotechnology-preparing-us-to-live-on-the-moon-and-mars/
Planetary Protection by ESA:
https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Exploration/ExoMars/Planetary_protection
http://www.esa.int/Enabling_Support/Preparing_for_the_Future/Space_for_Earth/ESA_and_the_Sustainable_Development_Goals
Horneck G, Klaus DM, Mancinelli RL. Space microbiology. Microbiol Mol Biol Rev. 2010;74(1):121-156. doi:10.1128/MMBR.00016-09
Voorhies AA, Mark Ott C, Mehta S, Pierson DL, Crucian BE, Feiveson A, Oubre CM, Torralba M, Moncera K, Zhang Y, Zurek E, Lorenzi HA. Study of the impact of long-duration space missions at the International Space Station on the astronaut microbiome. Sci Rep. 2019 Jul 9;9(1):9911. doi: 10.1038/s41598-019-46303-8. PMID: 31289321; PMCID: PMC6616552.
Mora M, Wink L, Kögler I, Mahnert A, Rettberg P, Schwendner P, et al. Space Station conditions are selective but do not alter microbial characteristics relevant to human health. Nat Commun [Internet]. 2019;10(1):3990. Available from: http://dx.doi.org/10.1038/s41467-019-11682-z
Wilson JW, Ott CM, Höner Zu Bentrup K, Ramamurthy R, Quick L, Porwollik S, et al. Space flight alters bacterial gene expression and virulence and reveals a role for global regulator Hfq. Proc Natl Acad Sci U S A. 2007;104(41):16299–304.
Moissl-Eichinger C, Cockell C, Rettberg P. Venturing into new realms? Microorganisms in space. FEMS Microbiol Rev. 2016;40(5):722–37.
Checinska Sielaff A, Urbaniak C, Mohan GBM, Stepanov VG, Tran Q, Wood JM, et al. Characterization of the total and viable bacterial and fungal communities associated with the International Space Station surfaces. Microbiome. 2019;7(50):1–21.

Glossary

Antibiotic: a type of antimicrobial substance active against bacteria.
Archaea: single-celled microorganisms with structure similar to bacteria, but evolutionarily distinct from bacteria and eukaryotes. They form the third domain of life.
Astrobiology: sometimes referred to as exobiology, it is the discipline that studies the origins, early evolution, distribution, and future of life in the universe (including Earth).
Atmosphere: layer of gases (nitrogen, oxygen, carbon dioxide etc.) that surround a planet or a planetary body.
Bacteria: single-celled microorganisms with a simple cell structure. They constitute a large domain of prokaryotic microorganisms which, in contrast to eukaryotic cell, do not possess nucleus or organelles.
Biodiversity: variability of living organisms.
Biofilm: complex micro-structures composed of one or more types of microorganisms that can grow attached on surfaces. One common example of a biofilm is dental plaque.
Biomining: process of using microorganisms to extract metals of economic interest from rock ores or mine waste.
Biotechnology: the harnessing of biological (cellular and biomolecular) processes in technology, to produce strategies and products with higher efficiency and sustainability.
Clean rooms: facilities used in manufacture or research designed to maintain the level of particulates and microorganisms extremely low.
Ecosystem: "a geographic area where plants, animals, and other organisms, as well as weather and landscape, work together to form a bubble of life. Ecosystems contain biotic or living, parts, as well as abiotic factors, or nonliving parts. Biotic factors include plants, animals, and other organisms. Abiotic factors include rocks, temperature, and humidity. Every factor in an ecosystem depends on every other factor, either directly or indirectly" (from National Geographic).
Enzyme: particular type of protein that can speed up biochemical reactions in an organism.
Extraterrestrial life: hypothetical life that may occur outside Earth.
Free fall: an object is in free fall when the only force acting upon it is gravity. Objects or planetary bodies (e.g.; a spacecrafts, or the Moon) orbiting around a planet are also in free fall, but they do not actually fall on the planet because of their orbital speed (Box I).
Fungi: kingdom of eukaryotic organisms that includes microorganisms such as yeasts and molds, as well as mushrooms.
Gravity: the universal force of attraction acting between all matter. It controls the trajectories of bodies in the solar system and in the cosmos. Gravity is measured by the acceleration that it gives to freely falling objects, and it is about 9.8 m/s^2 on Earth, or 1 x *g*. It is lower on Moon and Mars, being smaller objects: 1.6 m/s^2 (0.16 x *g*) and 3.8 m/s^2 (or 0.38 x *g*), respectively.
Human Microbiome: collection of all microbial communities (microbiota) that reside on or within human tissues. Types of human microbiota include bacteria, archaea, fungi, protists and viruses.
Immune system: A complex network of cells, tissues, organs, and the substances they make that helps the body fight infections and other diseases. The immune system includes antibodies, white blood cells and organs and tissues of the lymph system, such as the thymus, spleen, tonsils, lymph nodes, lymph vessels, and bone marrow (NCI's Dictionary).
International Space Station (ISS): a modular space station orbiting around Earth since 2000. It has been continuously occupied by astronauts since then, allowing a constant human presence in space. The ISS serves as a unique facility for scientific research in space and microgravity, and it is a multinational collaborative project.

Microorganisms or microbes: microscopic single-cells organisms that are not visible by naked eye. They belong to the domains of Archaea, Bacteria and Eukarya (for instance yeasts and molds).
Microgravity: condition in which gravity is so low that it is almost zero, but never really absent. See Box I.
Mir: the Russian modular space station that was active in space before the ISS (1986-2001).
Opportunistic: an opportunistic microorganism that is a microbe that is commonly present in or on our body without causing harm, but can produce disease when the host's immune system is compromised or when the host is weak.
Pathogenic: something that can cause a disease. When referring to a bacterium, it indicates a microbe that can cause infection or other disease.
Planetary body: any secondary body that is geologically differentiated or in hydrostatic equilibrium and thus has a planet-like geology. It can describe a planet, dwarf planet, or the larger moons and asteroids. Usually, the term planets refers to the main 8 celestial bodies of the Solar System (Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune), while "planetary bodies" is used in a broader way to define all of these, but also the Moon, other planets' moons, and sometimes large asteroids.
Pressure: a measure of the force is applied on a surface area.
Radiation: emission or transmission of energy in the form of waves or particles.
Regolith: dust and rock fragments, generally loose and heterogeneous, covering solid rocks. It is present on Earth, the Moon, Mars, some asteroids, and other terrestrial planets and moons.
Space microbiology: the study of microorganisms (microbiology) under space conditions or applied to space science.
Spacecraft: vehicle or machine designed to fly in space. Artificial satellites, space stations, the Shuttles and space probes are all examples of spacecrafts.
Spaceflight: generally referred to any travels of flight beyond the terrestrial atmosphere.
Spore: a bacterial spore is a structure which some bacterial species produce when exposed to some stressors, for instance an adverse environment, high or low temperatures, lack of liquid water, vacuum etc. When in a spore state, the cell is dormant and does not eat nor reproduce. It can reverse its state to vegetative When the conditions are more favourable, the spore can germinate to form a vegetative cell that can metabolise and grow. Spores can survive for years: some studies claimed to have revived spores 10,000 years old and more! This term should not be confused with fungal spore, which is a specific reproductive form of fungi.
Sterility: in microbiology, the condition of absence of viable microorganisms in a certain environment.
Vacuum: absence of all matter, including air (credits: NASA).
Virulence: pathogen's or microorganism's ability to cause damage to a host.
Virus: biological entity that replicates as a parasite inside a host, such as a living cell or an organism. It is debated if they are considered alive or not, but nevertheless they are commonly included in the definition of microorganisms, or microbes.