Microbes define the biosphere

Maisy: Teacher, are microbes important to our planet?

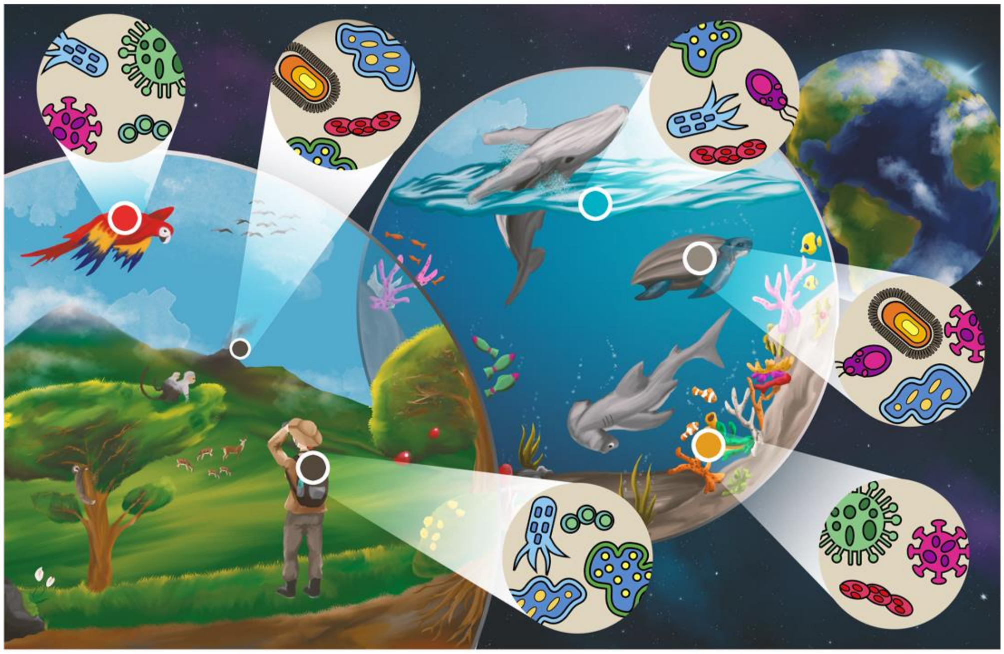


Figure 1. Microorganisms are ubiquitous on Earth and define our biosphere. Illustration by *Jose Arce Gómez.*

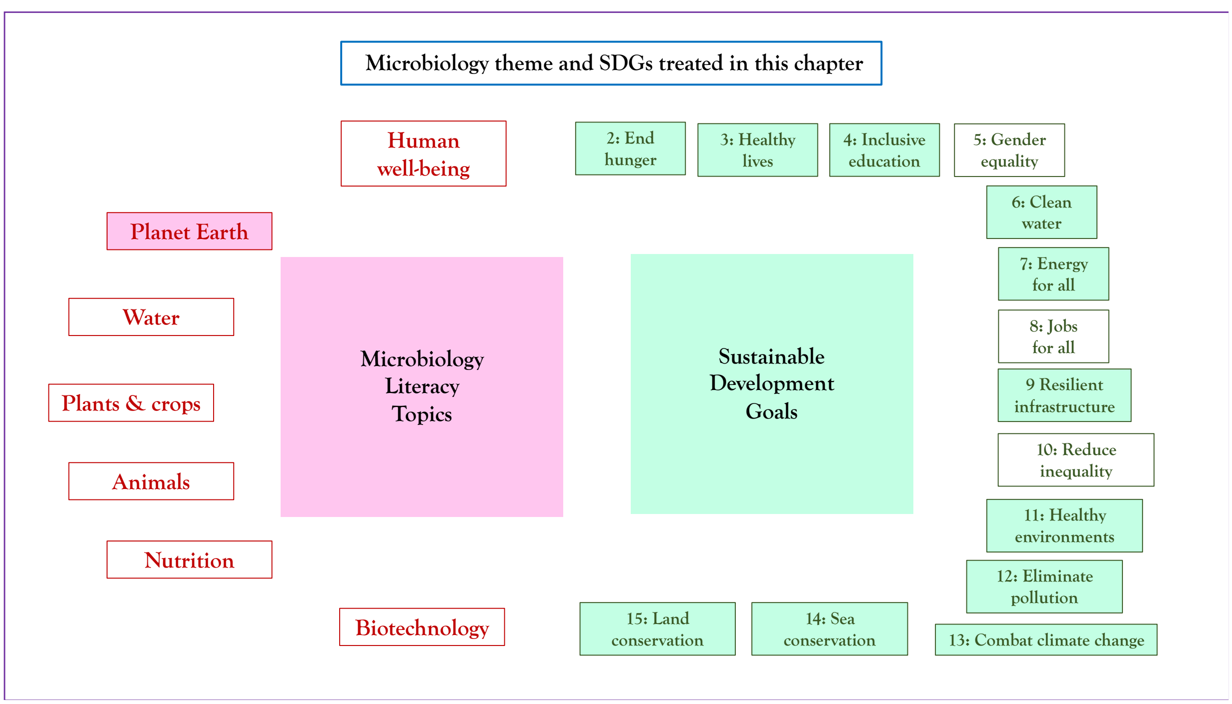
Sofía Vieto[1], Rafael Montenegro[1], Priscila Chaverri[2,3] & Max Chavarría[1,2,4]

[1]Centro Nacional de Innovaciones Biotecnológicas (CENIBiot), CeNAT-CONARE, 1174-1200 San José (Costa Rica). [2]Centro de Investigaciones en Productos Naturales (CIPRONA), Universidad de Costa Rica, 11501-2060 San José (Costa Rica). [3]Escuela de Biología, Universidad de Costa Rica, 11501-2060 San José (Costa Rica). [4]Escuela de Química, Universidad de Costa Rica, 11501-2060 San José (Costa Rica).

Microbes define the biosphere

Storyline

Microorganisms are ubiquitous. Although we are often unable to see them with our naked eyes, and therefore it is difficult for children to notice their existence, there are a large number of manifestations in nature and daily life that allow us to demonstrate their pervasiveness. The biosphere, by definition, is the sum of all of the Earth's ecosystems. It therefore includes every component of our planet that is alive, and the nonliving components that enable the development of this life (including soil, water, minerals and surfaces exposed to sunlight). If we think about the living organisms that make up the biosphere, it is easy to imagine mushrooms and other fungal fruiting bodies, animals, plants, and us, humans. But if one could look more closely through a microscope, we would see an immeasurable amount of living creatures of microscopic scale. These microorganisms, that include bacteria, archaea, viruses, microscopic fungi and protists, are omnipresent, and the first three have been on Earth for over 3.5 billion years. Their adaptability has let them evolve into master chemists that are capable of performing very diverse and complex chemical reactions. Because of their amazing biological diversity, they live in every ecosystem, from the most common sites to the most unimaginably harsh environments. Regardless of the ecosystem, these microscopic living beings are the greatest agents of change on the planet and, through their biochemistry and interaction with other components (living and non-living), define and modify the biosphere. To help understand why and how microorganisms define the biosphere, we describe here some habitats in which they can be found and the essential ecological roles they carry out that support life on Earth.



The societal context of microbiology

The Microbiology: microbial habitats; microbiomes; microbial diversity; microbes and health/disease; extremophiles. *Sustainability Issues:* biodiversity loss; climate change; circular economy; energy; food production and safety; energy; environmental pollution; human health; medicines; global pandemics.

Microbes define the biosphere: The Microbiology

1. *Microbes are the main inhabitants of the ocean.* Our planet is mostly covered by water, which is why oceans represent the largest contiguous habitat on Earth. If we weighed all the living organisms of the ocean, 65% of that weight would be microbial[1], which means that there is more microbial biomass in the sea than all other lifeforms combined. The composition of microbial communities changes throughout the ocean due to the existence of gradients of light and oxygen with depth. Phytoplankton, which includes microscopic photosynthetic algae and cyanobacteria, live in the upper ocean layer. Here, they perform three crucial functions: they harvest energy from the sun and produce food for the entire ocean's food web; they regulate the carbon cycle by removing billions of tons a year of carbon dioxide from the air; and they produce 50% of the oxygen we breathe. Accumulation of dead phytoplankton on the ocean floor over millions of years, and its burial and fossilization under the sediment, led to the formation of petroleum and natural gas, from which humans extract energy. Tectonic activity and re-shaping of the land masses of the planet has resulted in these fossil fuel deposits now being located under the surface of both land and seabed. Mining the fossil fuels used to provide humans with energy thus involves both offshore and onshore drilling.

We can also find viruses in the ocean. They are known to kill 20% of the oceanic biomass daily; which helps control microbial populations of phytoplankton and prevent harmful algal blooms. Viruses can also live within other marine microorganisms, such as bacteria and fungi, making their hosts change, for example, becoming more or less pathogenic. Furthermore, viruses play an important role in nutrient cycling because during cell lysis, amino acids and other carbon compounds are released and taken up by other microorganisms such as heterotrophic bacteria, who are the main producers of CO_2 in the ocean. Bacteria and archaea are found at different levels along the water column and sediments, performing all kinds of chemical processes involved in nitrogen, carbon, sulfur and phosphorous cycling, but also living in symbiosis with animals, algae and other organisms in the ocean. Lastly, marine fungi also play an important role in breaking down complex carbon molecules of dead plants and animal carcasses from habitats as diverse as mangroves and the deep sea, as well as forming mutually beneficial relationships with other marine organisms, such as animals or plants, or even causing them disease. Collectively, marine microbes are the living creatures that sustain life in the ocean.

2. ***Microbes fertilize soil and promote plant growth.*** Microorganisms in the soil carry out fundamental processes that sustain plant growth, crop production and, consequently, life on Earth[2]. Microbes are key players in nutrient cycling and soil fertilization. As an example, nitrogen-fixing bacteria convert atmospheric nitrogen, which is metabolically useless to plants and animals, into ammonia and other nitrogen-related compounds that can be absorbed by living organisms. In the

same way, bacteria are capable of making available sulfur and phosphorous nutrients, which are also needed for plant growth. On the other hand, many microorganisms such as fungi and actinobacteria, are excellent decomposers of organic matter. These microorganisms break down dead plants and animals, releasing nutrients to the soil and creating humus, an important carbon-rich soil component. Furthermore, soil microbes secrete molecules that glue soil particles together, contributing to soil architecture.

The root microbiome is the main determinant for plant growth and health[3]. Up to 10 billion bacterial cells inhabit each gram of soil around the plant root region,[4] and assist plants in crucial functions. Fungi form symbiotic associations with plant roots, called mycorrhiza, which extend the root system to obtain water and nutrients from deeper soil layers for the plant, and supporting plants' health and tolerance against drought and salinity. On the other hand, microorganisms can produce hormone-like molecules that stimulate plant growth; and toxins, antibiotic and antifungal compounds, that can help plants defend against pathogens. Microbes thereby promote healthy soils, which are the foundation of our planet's sustainable and productive agroecosystems[2].

3. ***Microbes inhabit animals and determine their lifestyles.*** Essentially, all animals on Earth are covered and inhabited by microorganisms. Although animal:microorganism relationships can sometimes result in disease in animals, they mostly are of vital mutual benefit. First, microbes can help animals digest their food. Ruminants for example, have a specialized compartment in their stomachs (rumen), where anaerobic bacteria and archaea, protozoa and fungi help break down plant fiber and ferment sugars, providing energy to the host[5]. A similar example can be found in termites, wood-eating insects, that are supported by their gut microorganisms which produce specialized enzymes that break down wood into fermentable sugars. In addition, woodpeckers carry fungi in their beaks to help in decomposition and softening of the hard wood, facilitating cavity excavation, and thus access to the buried insects that compose their diets. Furthermore, we can find other examples in the ocean, specifically inside coral reefs. Here, a type of protist called dinoflagellate, lives inside coral tissues and carries out photosynthesis, producing sugars for the coral. In return, corals emit waste products in the form of ammonium, which microbes consume as nutrients.

On the other hand, microorganisms have a vital role in protecting animals from pathogen attack and disease. Many insects are known to have protective associations with actinobacteria[6]. For example, wasps cultivate *Streptomyces* bacteria in their antenna and apply them to their larvae, where they produce a mixture of antimicrobial compounds that protect the larvae from fungal attack. Also, bacteria of the genus *Pseudonocardia*, who live on the cuticle of leafcutter ants, produce antifungal molecules that also protect them from pathogenic fungi[7]. Lastly, microorganisms can have other specialized functions in animals; such as making them shine in the dark! Squids have a specialized "light organ" that is colonized by *Vibrio fischeri*, a bacterial species that can produce light. This luminescence helps squids find mates, attract prey and repel or hide from predators. In summary, symbioses between animals and microorganisms are ubiquitous on Earth, from the ocean to the forest, and help shape our entire ecosystem[8].

Box 2. We did not invent agriculture, leaf-cutter ants did! *Photographs by Jeffrey Arguedas*

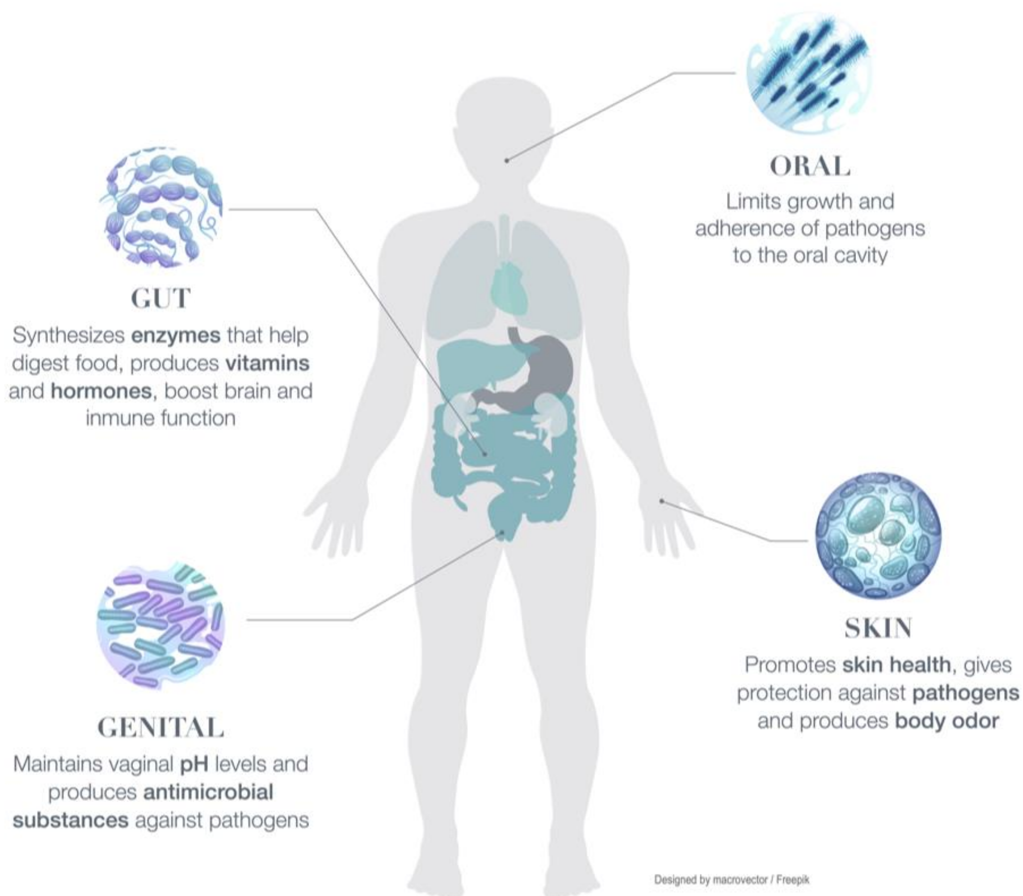
Leaf-cutter ants of the genus *Atta* (**A**) grow fungi of the Agaricaceae family as food. The cultivated fungus (also called fungal garden) serves as the primary food source for the colony and is preserved through a process that includes fertilizing with plant substrate, ant excrement, dead insects or seeds. (**B**) On the other hand, the benefit obtained by the fungus is that the ant keeps it free of microorganisms that can affect its growth. This mutualistic relationship seems to be even more complex, due to the apparently symbiotic participation of bacteria that are in charge of protecting the fungal garden. An example that has been demonstrated of this dependence is the mutualistic interaction between leaf-cutter ants and some filamentous bacteria of the genus *Pseudonocardia* (of the Actinobacteria class) for the control of the parasitic fungus *Escovopsis*, which may be able to devastate the fungal garden[11]. Interestingly, the presence of these bacteria was identified in the cuticle of ants in specific anatomical regions depending on the species. The presence of these bacteria can be seen as white patches on the body of the ants. At these sites, the bacteria develop and secrete antibiotics, which have been found to be potent inhibitors in the development of *Escovopsis*[11].

Photographs by Jeffrey Arguedas

4. Microbes live inside us and determine our health. It is important to remember that we live in a microbial world. That being said, it should not be a surprise that our bodies are not just ours, but they are a habitat for numerous microscopic creatures that correspond to half of our body's cell number[9]. From the moment we are born, microorganisms from the environment begin to colonize our skin, mouth, nose, genitalia and gut; and assemble into highly complex and dynamic microbial communities. This process is critical in our first six months of life, since the numerous bacteria, viruses and fungi that reside in our bodies, are fundamental for the development of our immune system. Besides, throughout life, these commensal microorganisms, that create *second skins* of our body surfaces, protect us from pathogens, help us digest food and boost our brain function. As an example, it was recently suggested that our gut microbiome may even influence our mood and prevent depression, since these microorganisms can produce or stimulate the production of neurotransmitters and neuroactive compounds[10].

Box 3. The human microbiota. *Illustration by Sofía Vieto based on Freepik resources*

Microorganisms are found in all parts of our body, fulfilling different functions. Multiple studies have revealed that the microbiota has a close relationship with human health and disease[12].



As you may think, since this colonization process is influenced by environmental exposure, the human microbiota is highly individual, and in early life, there are key factors that shape it, such as: delivery mode at birth, type of milk consumption and diet. Even though in adulthood our microbiome composition becomes more stable, it is never static, and the microbial ecosystem continually adapts to our lifestyles. However, since these commensal communities are carefully balanced, if they become perturbed they may no longer be able to provide key protective functions and a state of dysbiosis arises, which predisposes individuals to infections (e.g. antibiotic-induced perturbation of our gut microbiota may cause *Clostridium difficile* to 'bloom', increase its numbers to abnormal levels, and cause disease – colitis – of the colon), and diseases like obesity, diabetes, cancer and even Alzheimer's disease. Moreover, a lack of exposure to microorganisms in our early lives is linked to the development of asthma, allergies and other autoimmune diseases. In summary, together with their human host, microorganisms form a "superorganism"[13], with the microbiome playing a fundamental role in our physiology, metabolism and health in ways we are only beginning to understand.

5. Microorganisms are capable of adapting to and modifying extreme environments. When we say that microorganisms are everywhere, we are also referring to the most inhospitable places on Earth: where temperatures reach 100 ºC, in frozen sea waters, volcanic acidic environments, or in the depths of the oceans with high pressures and no light or oxygen. These harsh environmental conditions cannot support human life and yet, microorganisms have managed to adapt and thrive in these inhospitable environments. Microbes that live in these habitats are called extremophiles, and they are categorized according to the conditions in which they grow. Thermophiles (optimal growth 45°C - 80°C) and hyperthermophiles (>80 °C) proliferate at high temperatures and are mostly found in geothermally heated environments like hot springs and near hydrothermal vents and volcanoes, or just deep in the Earth. In contrast, psychrophiles (<15°C) live in cold environments such as the polar regions, permafrost and in the deep-sea. Acidophiles (<pH 5) are found in acid lakes or acid rock drainage (ARD) sites; in contrast, alkaliphiles (>pH 9) prefer higher pH sites like soda lakes. In the case of barophiles, they can tolerate – and even require – high pressures to live. These microorganisms can be found deep inside the oceans, where they survive 800 times the pressure humans experience at sea level. On the other hand, halophiles like habitats with high salt concentrations and are found in sea water, and even in the hypersaline Dead Sea. Xerophiles prosper in low water conditions such as desserts; and lastly, metallophiles inhabit sites with high heavy metal concentrations.

But how do extremophiles survive to these conditions? In addition to familiar metabolic pathways, such as photosynthesis, microbes can also have metabolisms based upon methane, sulfur or iron. This wide metabolic diversity is coupled with extraordinary genetic and metabolic adaptations, allowing them to colonize very diverse and extreme environments. Let's take hyperthermophiles as an example. These microorganisms, that include bacteria and archaea, live in hot environments that are rich in reduced chemicals from inside the Earth, such as sulfur compounds, which microbes oxidize as their energy source. In addition, they have adapted to synthetize stable and densely packed proteins and enzymes that are resistant to heat denaturation and possess cell membranes rich in saturated fatty acids and of different chemical compositions, that gives them stability and functionality at high temperatures.

Box 4. Microorganisms can inhabit environments that are uninhabitable for other life forms such as plants, animals and humans. *Photographs by Zhifei Zhou and Max Chavarría.*

(A). In hypersaline water of solar salterns, *Haloarchaea* have an exceptional capability to overcome the potential damaging effects in physiology (turgor loss) or toxicity (excess sodium), that are typical of environments with high salt concentrations[14]. (**B)** Poás Volcano in Costa Rica has extreme conditions of pH (average of 0.29) and temperatures that can reach 95ºC. Despite such unfavorable conditions for life, bacteria of the genera *Acidiphilium*, that have a sulfur-based metabolism, have been found thriving here[15]. **(C)** Borbollones in Tenorio Volcano National Park in Costa Rica is a CO_2-rich hydrothermal vent that has a temperature of 60ºC and a pH of 2.4. It is dominated by an archeon from the order Thermoplasmatales and one bacterium from the genus *Sulfurimonas*[16]. **(D)** In Antarctica, anaerobic methanogenic archae of the *Methanococcoides* genus have been found in extreme cold (1-2 ºC) bottom waters[17].

The discovery of extremophiles, such as the bacterium *Thermus aquaticus*, has had a great impact in the biotechnology industry, since the enzymes they produce, are stable under the extreme conditions used in industrial and laboratory processes. Because it is estimated that we have only discovered about 1% of the Earth's microorganisms[18], we still have many extreme habitats to explore with new microorganisms waiting to be found!

6. Microbes are part of our built environment and they constantly change it. Like any other ecosystem, microorganisms are found in every part of our built environment. By this, we refer to the man-made material space, that includes the buildings, houses and towns where we live, work, study and spend our leisure time. The Earth's ubiquitous microbes and their spores, travel to these materials mostly through the air and water, and their major sources are: humans, pets, plants, dust, plumbing and ventilation systems, and the outdoor environment. Because humans spend over 90% of their time indoors, the built environment's microbiome is of particular interest, since these microorganisms can positively or negatively influence our own microbiome and health[19]. For example, some molds in damp indoor environments are known to cause allergies, asthma, respiratory infections and even intoxication. In addition, built environments are unique meeting places for environmental and human-derived bacteria. Here, their interactions are favored, and the interchange of genetic material between species (horizontal gene transfer) may happen. Because the ability to resist chemicals and drugs is carried in genes, this type of interactions can play an important role in disseminating antibiotic resistance to other bacteria.

Although most of the materials used in built environments are designed to be inhospitable for microbial life, microorganisms have adapted to colonize new niches of both organic (plastic, leather, paper, wood) and inorganic (metal, stone, concrete) composition[19]. Microbes are so powerful that they can cause the biodeterioration of our built environment by destroying buildings, monuments, documents and artwork, some of which represent part of our cultural heritage. Fungi, lichens and bacteria are among the most common colonizers of human-built structures, and they act by penetrating in cracks and pores, expanding their growth through the formation of biofilms, and excreting enzymes and metabolites to degrade the different substrates – even steel. Scientists are interested in these enzymes, since they can be used for degrading plastic contaminants or for transforming lignocellulolytic residues into value-added products like biofuels. Fungi are excellent decomposers and metabolically more versatile than any other biodeteriogens in the microbial kingdom; and we are still discovering new species of them, thriving on every surface, from plastic to paint.

To conclude: anywhere there is life – the biosphere – there are microbes and there are many places in the biosphere where there are only microbes. Therefore, microbes define the biosphere.

Relevance for Sustainable Development Goals and Grand Challenges

What would our biosphere be like without microbes? In the absence of microorganisms, life on Earth would be hard to imagine. These microscopic creatures are ubiquitous and have a fundamental role in environmental health and thriving ecosystems[20]. For this reason, once we understand that microorganisms are responsible of defining the biosphere, many of our everyday decisions will become more informed and related to Earth's sustainability[21]:

- ***Goal 2.*** **Zero hunger.** Microorganisms are not only part of our diet, but also help us produce other foods, and develop better production practices. Understanding that microorganisms are the greatest agent of change on the planet, will favor the application of good agricultural practices (e.g., good soil management, use of biofertilizers and biocontrollers, instead of toxic pesticides) and management of farm animals (correct use of antibiotics in, for example, livestock and poultry, as well as good cleaning and manufacturing practices).

- ***Goal 3.*** **Good health and well-being.** Knowing that microorganisms are ubiquitous, some harmful and others beneficial, will help us implement healthier personal practices. A greater understanding that our microbiota defines our health, invites us to eat well, exercise, avoid smoking and take care of our personal hygiene (avoiding over sanitization to avert eliminating the beneficial microbes).

- ***Goal 4.*** **Quality education.** The COVID-19 pandemic has shown us the urgent need for society and general population to gain knowledge of the microbial world. What is a virus? How do we remove it? How is it spread? These are some of the questions that became imperative in society at large. A greater understanding of the omnipresence of microorganisms and the way in which they interact with the medium (for example, with humans), will allow us to have a better response to the next challenges that microbes present to us. Therefore, education is one of the pillars for the development and preservation of our planet and society.

- ***Goal 6.*** **Clean water and sanitation.** In order to have clean water and sanitation for all, it is of vital importance to implement sustainable waste water management strategies; which commonly make use of microorganisms to remove organic load, excess nutrients and contaminants (bioremediation). Besides, to maintain good water quality, it is important to prevent eutrophication in water bodies, which induces excessive algae growth, caused by anthropogenic contamination with nitrate and phosphate-containing wastes.

- ***Goal 7.*** **Affordable and clean energy.** Microorganisms can be used for the production of energy from biological raw materials in a sustainable and clean way. Methanogenic bacteria, for example, are sources of biogas, since they digest organic material in the absence of oxygen to produce methane. Besides, fungi are needed to degrade complex polymers like lignin to obtain sugars that serve as substrate for microorganisms that convert it to ethanol or other alcohols. Lastly, *Geobacter sulfurreducens*, an interesting bacterium that is able to conduct electricity, could be used to generate clean electricity in the future.

- ***Goal 9.*** **Industry, innovation and infrastructure.** Biotechnology offers several biological and microbial-based innovative solutions to improve Earth's sustainability and for building circular economies. Some examples are: bioplastics, bioremediation, the use of enzymes (some of them obtained from extremophiles) in industrial processes, biofuels, biopesticides, biofertilizers and sustainable clothing.

- ***Goal 11.*** **Sustainable cities and communities.** Microbes play an important role in the ecology of urban cities; specifically, in water and waste management, food production, health and disease. On the other hand, to protect and safeguard a city's cultural and natural heritage, microorganisms and their power to modify the environment in which they grow (e.g. biodeterioration), must be also taken into consideration.

- ***Goal 12.*** **Responsible consumption and production.** Once we understand the importance of microorganisms to maintain healthy and balanced ecosystems, we can practice individual, communitarian and national sustainable consumption and production patterns that help protect and restore these ecosystems. Microorganisms can be used to increase agricultural and industrial productivity with less environmental damage, for biofuel production and in waste management. These strategies may contribute to a circular and more sustainable economy.

- ***Goal 13.*** **Climate action.** Knowing that microorganisms are the support system of the biosphere, and taking into consideration the devastating effects global warming will cause to microbial communities, and thus to our ecosystems, it is imperative to take climate action. Microbes are the greatest agent of change we have, and we can use them to mitigate climate change by harnessing microbial activities that reduce methane emissions, use bacteria and fungi to generate less contaminating fuels and food, enhance soil fertility for a more sustainable and less contaminating agriculture, or by applying microbes to bioremediate water-bodies in order to combat pollution and eutrophication.

- ***Goal 14.*** **Life below water.** Considering that microbes in the ocean produce at least 50% of the oxygen we breathe, fix half of the world's carbon dioxide, and support the entire oceanic food web; if they were to decrease due to global warming, or proliferate in excess (specifically algae and cyanobacteria) because of eutrophication, the world would face catastrophic consequences. For this reason, microbes are fundamental for the preservation of marine resources and sea biodiversity.

- ***Goal 15.*** **Life on land.** Now that we know the importance of having soils rich in microorganisms, it is imperative to promote sustainable agricultural practices, such as: crop rotation, the use of biofertilizers, biocontrol strategies, and reducing the use of human-made fertilizers and toxic pesticides, to promote and restore healthy soils and balanced terrestrial ecosystems.

Potential Implications for Decisions

Individual

a. How strict are we in our personal hygiene? Having knowledge of the invisible microbial world and its effects on our health can help us prevent an over sanitized world and decide the way we do our personal hygiene (e.g., hand washing, time, frequency, selection of disinfection and cleaning strategies for homes, buildings, workplaces).
b. Greater knowledge of microorganisms and the importance of having healthy microbiomes, will help us choose between having a natural delivery or cesarean birth, doing responsible use of medication (e.g., antibiotics), understanding the importance of breastfeeding, vaccination and for newborns and kids to be in contact with healthy microorganisms.

c. Encourage individual sustainable consumption patterns and lifestyles to reduce environmental footprint; by for example: making informed decisions concerning the use of agricultural products generated with microbial biofertilizers and free of pesticides, reducing plastic use and dispose wastes correctly.

Community policies

a. Promote the use of bioremediation and sustainable waste management strategies of electronic, food, plastics and other materials, in a way they can be disposed and recycled correctly to reduce pollution burden and help restore healthy balanced ecosystems.
b. Encourage the use of biofertilizers, biological pest control, crop rotation and other sustainable agricultural practices, to promote healthy soils and reduce chemical contamination of soils and water.

National policies related to human health and environmental protection

a. The awareness of microorganisms will help in designing vaccination strategies, disease prevention and healthy lifestyle, promoting campaigns that support healthy human microbiomes; but most importantly, a microbiology educated society will have a better understanding of the importance of these policies.
b. Facilitate and promote the development of a circular economy and support biotechnology-based products and solutions (e.g., biofertilization, bioremediation and biological pest control, among others) that contribute to healthy and balanced microbial-rich ecosystems.

Pupil Participation

General discussion of the habitats of microbes and the effect they generate on the ecosystem.

Pupil stakeholder awareness

a. Where do microorganisms live? Why don't we see them?
b. Discuss in class the existence of microorganisms that can affect our health but point out that a large majority of microorganisms are beneficial, keep us healthy, and have allowed the development of our society. Can you give examples of beneficial microorganisms and others that harm us?
c. The physicochemical variables (e.g., pH, temperature, nutrients, metals, pressure, etc.) determine the types of microorganisms that colonize an environment? Can a microorganism modify or adapt to these conditions?
d. Do you think that a microorganism capable of living inside a plant could also be able to live inside an animal? Explain.
e. How is a microorganism capable of defining or modifying an ecosystem?
f. How important are microorganisms for planetary health? Could we live without microorganisms?
g. Which foods do we enjoy because microorganisms exist?
h. What would our society look like now if microbiologists had not discovered the antibiotic penicillin?

Exercises and/or Homework

a. Why must microorganisms and their effect on the biosphere be considered for decision-making in terms of health laws, environment, infrastructure development and new technologies?
b. How can microorganisms help us comply with Sustainable Development Goals (SDGs)?
c. Do you know of any technology in your country that involves microorganisms?
d. Does your country have an extreme environment? Are there studies of the microbiota that inhabits this extreme site? What type of microorganisms inhabit this environment? Could any of these microorganisms be applied for the benefit of society (industry, agriculture, etc.)?
e. Mention (or investigate) the names of some microorganisms that inhabit your (i) mouth, (ii) intestine, (iii) skin. Are these microorganisms beneficial or dangerous to your health?
f. What are some ways that you can change your own practices or behaviours to promote beneficial microbes to flourish?

Class experiments (select appropriate experiment from the Class Experiment list)

a. Microbial life in a Winogradsky Column
https://www.asmscience.org/content/journal/jmbe/10.1128/jmbe.v16i1.847
https://www.amnh.org/explore/ology/microbiology/make-a-home-for-microbes
Topics: microorganisms, habitats, soil, water, ecosystem

b. Bread Mold
https://www.epa.gov/sites/production/files/documents/holdthemold.pdf
Topics: mold, microbes are ubiquitous, spores, air

Fun with fungi: fungi safari, mold garden, yeast balloon, mushroom prints, make bread dough with and without yeast.
https://www.kidsdiscover.com/teacherresources/fungi/
Topics: mold, fungi, yeast, mushroom, food

The Evidence Base, Further Reading and Teaching Aids

1. **Video:** A World Without Microbes: An Apocalyptic Thought Experiment - I Contain Multitudes
https://www.youtube.com/watch?v=80tPR5HH9Zo
Topics: microorganisms are ubiquitous and are essential for life at the biosphere.

2. **Video:** You are your microbes - Jessica Green and Karen Guillemin, TED-Ed
https://ed.ted.com/lessons/you-are-your-microbes-jessica-green-and-karen-guillemin
Topics: human microbiome, functions in the gut, diet.

3. **Video:** Extremophiles 101 – National Geographic
https://www.youtube.com/watch?v=MY1d5Saqrc4
Topics: extremophiles, habitats, adaptations, biotechnological importance.

4. **Video**: You did not know that mushrooms [fungi] could do all that – National Geographic

https://video.nationalgeographic.com/video/news/00000155-c797-dc79-aff5-e7ff0f350000
Topics: fungi for antibiotics, building materials, water filtration, toxic waste cleanup, pest abatement, textiles, and other purposes.

5. **Video**: Protists and Fungi – Amoeba Sisters
https://www.youtube.com/watch?v=zK7Ckmxxqds
Topics: amoebe, fungi, protists

6. **Video**: How trees secretly talk to each other? – BBC News
https://letstalkscience.ca/educational-resources/stem-in-context/talking-trees-how-do-trees-communicate
Topics: mycorrhizae, healthy trees and forests, forests, fungi

7. **Video**: How trees secretly talk to each other? – BBC News
https://www.youtube.com/watch?v=3ivMSCi-Y2Q
Topics: animal-microbial symbiosis, squid, bacterial luminescence.

References

1. Bar-On, Y. M., Phillips, R. & Milo, R. The biomass distribution on Earth. *Proc. Natl. Acad. Sci. U. S. A.* (2018). doi:10.1073/pnas.1711842115
2. Dubey, A. *et al.* Soil microbiome: a key player for conservation of soil health under changing climate. *Biodivers. Conserv.* **28**, 2405–2429 (2019).
3. Pascale, A., Proietti, S., Pantelides, I. S. & Stringlis, I. A. Modulation of the Root Microbiome by Plant Molecules: The Basis for Targeted Disease Suppression and Plant Growth Promotion. *Front. Plant Sci.* **10**, 1–23 (2020).
4. De Vrieze, J. The littlest farmhands. *Science (80-.).* **349**, 680–683 (2015).
5. Huws, S. A. *et al.* Addressing global ruminant agricultural challenges through understanding the rumen microbiome: Past, present, and future. *Front. Microbiol.* **9**, 1–33 (2018).
6. Matarrita-Carranza, B. *et al.* Evidence for widespread associations between neotropical hymenopteran insects and Actinobacteria. *Front. Microbiol.* **8**, 1–17 (2017).
7. Marsh, S. E. *et al.* Association between Pseudonocardia symbionts and Atta leaf-cutting ants suggested by improved isolation methods. *Int. Microbiol.* **16**, 17–25 (2013).
8. Kroiss, J. *et al.* Symbiotic streptomycetes provide antibiotic combination prophylaxis for wasp offspring. *Nat. Chem. Biol.* **6**, 261–263 (2010).
9. Sender, R., Fuchs, S. & Milo, R. Are We Really Vastly Outnumbered? Revisiting the Ratio of Bacterial to Host Cells in Humans. *Cell* **164**, 337–340 (2016).
10. Winter, G., Hart, R. A., Charlesworth, R. P. G. & Sharpley, C. F. Gut microbiome and depression: What we know and what we need to know. *Rev. Neurosci.* **29**, 629–643 (2018).
11. Sen, R. *et al.* Generalized antifungal activity and 454-screening of Pseudonocardia and Amycolatopsis bacteria in nests of fungus-growing ants. *Proc. Natl. Acad. Sci. U. S. A.* **106**,

17805–17810 (2009).
12. Lynch, S. V. & Pedersen, O. The human intestinal microbiome in health and disease. *N. Engl. J. Med.* **375**, 2369–2379 (2016).
13. Schwabe, R. F. & Jobin, C. The microbiome and cancer. *Nat. Rev. Cancer* **13**, 800–812 (2013).
14. Thombre, R. S., Shinde, V. D., Oke, R. S., Dhar, S. K. & Shouche, Y. S. Biology and survival of extremely halophilic archaeon Haloarcula marismortui RR12 isolated from Mumbai salterns, India in response to salinity stress. *Sci. Rep.* (2016). doi:10.1038/srep25642
15. Hynek, B. M., Rogers, K. L., Antunovich, M., Avard, G. & Alvarado, G. E. Lack of microbial diversity in an extreme mars analog setting: Poás Volcano, Costa Rica. *Astrobiology* **18**, 923–933 (2018).
16. Arce-Rodríguez, A. *et al.* Thermoplasmatales and sulfur-oxidizing bacteria dominate the microbial community at the surface water of a CO 2 -rich hydrothermal spring located in Tenorio Volcano National Park, Costa Rica. *Extremophiles* **23**, 177–187 (2019).
17. Allen, M. A. *et al.* The genome sequence of the psychrophilic archaeon, Methanococcoides burtonii: The role of genome evolution in cold adaptation. *ISME J.* **3**, 1012–1035 (2009).
18. Arora, N. K. & Panosyan, H. Extremophiles: applications and roles in environmental sustainability. *Environ. Sustain.* **2**, 217–218 (2019).
19. Gilbert, J. A. & Stephens, B. Microbiology of the built environment. *Nat. Rev. Microbiol.* **16**, 661–670 (2018).
20. Cavicchioli, R. *et al.* Scientists' warning to humanity: microorganisms and climate change. *Nat. Rev. Microbiol.* **17**, 569–586 (2019).
21. Akinsemolu, A. A. The role of microorganisms in achieving the sustainable development goals. *J. Clean. Prod.* **182**, 139–155 (2018).

Glossary

- **bacteria:** microscopic single-celled prokaryotic organisms that belong to the Bacteria domain
- **archaea:** ancient single-celled prokaryotic organisms that belong to the Archaea domain
- **virus:** microscopic infective agent that consist of a nucleic acid (RNA or DNA) in a protein coat and is not able to thrive or reproduce outside of a host (living cell)
- **fungi:** group of eukaryotic organisms that include yeasts, molds and mushrooms
  protist: any eukaryotic organism that is not a fungus, animal or plant
  pathogen: biological agent that causes a disease to its host
- **extremophile:** microorganism that thrives in environmental conditions that are considered extreme
- **circular economy:** model of production and consumption that aims to eliminate waste and use renewable resources
- **pandemic:** worldwide spread of a new disease
- **phytoplankton:** diverse microscopic organisms that perform photosynthesis, live in water ecosystems and are a crucial food source for other aquatic organisms
- **photosynthetic:** refers to organisms that use energy from the sun to synthetize nutrients from carbon dioxide and water

- **algae:** group of photosynthetic eukaryotic organisms that include both macroscopic and microscopic organisms
- **cyanobacteria:** phylum of photosynthetic bacteria
- **algae bloom:** excessive proliferation of algae in water ecosystems, which lowers oxygen levels and kills marine life
- **symbiosis/symbiotic association:** close and long-lasting biological interaction between two different organisms that can be either beneficial or harmful
- **animal carcass:** cadavers and rests of dead animals
- **nitrogen-fixing bacteria:** microorganisms that are able to transform atmospheric nitrogen into fixed nitrogen, which is essential for plant growth
- **ammonia:** nitrogen compound that is volatile
- **actinobacteria:** type of bacteria that are mostly found in the soil and are essential for humus formation
- **humus:** the organic component of the soil that is formed by the decomposition of leaves and plant material
- **microbiome:** a characteristic microbial community that inhabits a defined habitat
- **mycorrhiza:** symbiotic association between plant roots and fungi
- **toxin:** a poisonous substance that is produced by a living organism
- **agroecosystem:** the organisms and environment of an agricultural area
- **ruminant:** mammals that ferment plant-based food in a special stomach compartment named rumen
- **rumen:** part of one of ruminant's stomach compartments in which microorganisms ferment food
- **anaerobic bacteria:** bacteria that live in the absence of oxygen
- **protozoa:** single-celled eukaryotic microorganisms
- **fiber:** plant-based material that contains substances such as cellulose, lignin and pectin that are difficult to degrade by digestive enzymes
- **ferment:** to undergo fermentation, a process that extracts energy from carbohydrates in the absence of oxygen
- **dinoflagellate:** single-celled eukaryotic microorganisms that constitute part of marine phytoplankton
- **photosynthesis:** process used by plants and some algae in which energy in produced out of sunlight
- **antimicrobial compound:** substance that inhibits the growth of microorganisms
- ***Pseudonocardia:*** genus of bacteria that live in the cuticle of leafcutter ants
- **cuticle:** insect's exoskeleton
- **luminescence:** emission of light

  mutualist: symbiotic relationship that is mutually beneficial for both species involved

  ***Escovopsis*:** genus of parasitic microscopic fungi
- **human microbiota:** the set of all the microorganisms that inhabit a human body
- **dysbiosis:** imbalance in a microbial community associated with disease
- **thermophile:** microorganisms that live in hot environments (45°C -80°C)
- **hyperthermophile:** microorganisms that proliferate in extreme hot environments (>80°C)
- **psychrophile:** microorganisms that live in cold environments (<15°C)
- **permafrost:** area of land that has been frozen continuously for a minimum of two years
- **acidophile:** microorganisms that thrive in acidic (low pH) environments

- **acid rock drainage:** acidic water laden with iron, sulfate and other metals that can form during natural conditions or caused by anthropogenic activities such as mining
- **alkaliphile:** microorganisms that thrive in alkaline (high pH) environments
- **barophile:** microorganisms that support high pression conditions
- **xerophile:** microorganisms that prosper in low water conditions
- **metallophile:** microorganisms that can grow in the presence of high heavy metal concentrations
- ***Hortea werneckii*:** species of black yeast that is tolerant to high salt concentrations
- ***Acidiphilium*:** genus of acidophile bacteria
- ***Sulfurimonas*:** genus of bacteria that can live in a wide variety of environments due to their different hydrogen, nitrogen sulfur and carbon metabolisms
- **methanogenic:** anaerobic microorganisms that produce methane, a natural gas, as a byproduct of their metabolism
- ***Methanococcoides*:** genus of anaerobic archaea that obtain energy by producing methane gas
- ***Thermus aquaticus*:** species of bacteria that tolerates high temperatures
- **hydrothermal vent:** fissure on the seafloor from which geothermally heated water issues
- **mold:** fungus that grows in the form of multicellular structures called hyphae
- **horizontal gene transfer:** movement of genetic material between neighboring organisms that can be from the same of different genus or species
- **biodeterioration:** any undesirable chance in the properties of a material caused by the action of living organisms
- **lichen:** dual organisms that consist of fungus living in symbiotic relationship with algae or cyanobacteria.
- **lignocellulolytic residue:** waste products that are rich in lignin
- **biodeteriogen:** a living organism that is the causal agent of biodeterioration
- **bioremediation:** use of microorganisms to remove contaminants and reduce pollution
- **lignin:** complex organic polymer that is present in plant cell walls
- ***Geobacter sulfurreducens*:** bacteria species that has the ability to create an electric current and produce electricity
- **bioplastic:** biological plastic that is derived from biological substrates rather than from petroleum
- **biofuel:** fuel that is produced from renewable sources such as plant, algae or animal material, instead of fossil fuels
- **biopesticide:** products made out of living organisms that control pests
- **biofertilizer:** substance that contains living microorganisms, that when applied to plants, promotes their growth by increasing availability of nutrients
- **eutrophication:** excessive plant and algae growth in water bodies due to increased nutrient and mineral concentrations