Microbial contributions to plant stress tolerance and marginal soil use

How can plants grow under stress without moving? Who helps them?

Photo Credit: Ramona Marasco

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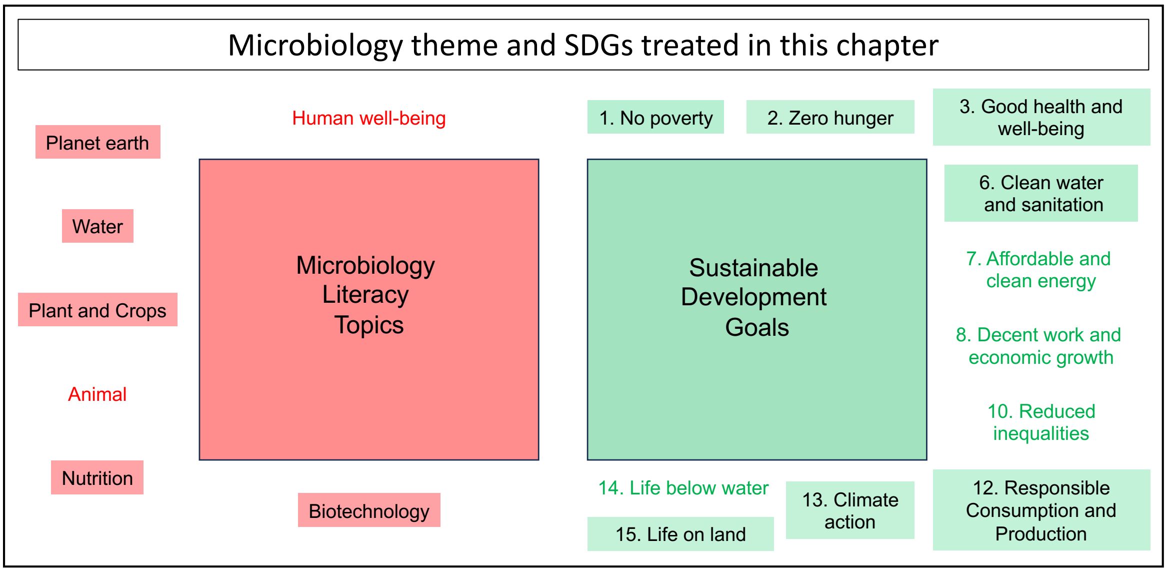
Storyline

Have you ever wondered how plants manage to survive when the weather turns harsh, when they get sick, when they are hungry, or when the soil is not very good? The secret lies in a hidden world right beneath our feet! The soil is alive with tiny superheroes called microbes or microorganisms—bacteria, fungi, and other microscopic creatures. These little helpers work tirelessly to keep plants strong, even in the most challenging conditions, much like friends help each other out. These microbes are like invisible allies: they feed plants, providing nutrients, protect them from harmful bacteria, germs, and pests, and help them retain water when it is dry. They even enable plants to grow in challenging places, such as salty or nutrient-poor soils, making them resilient to several stresses caused by the environment (abiotic stress) and threats from living things (biotic stress). By doing all this, microbes not only support plant growth and health but also make farming possible in areas once thought too hard to use, like drylands and salty coastlines.

This chapter will explore how these tiny but mighty microbes thrive in the soil as vast, diverse communities and in a powerful partnership with plants. Get ready to dive into the fantastic underground world of microbial superheroes!

The Microbiology and Societal Context

The microbiology: soil microbial community (or microbiome/microbiota); plant metaorganism (or holobiont); plant-growth-promoting microorganisms; microbe-mediated adaptation. *Sustainability issues*: sustainable agriculture; climate change; economy and employment; food security; soil biodiversity; soil fertility.



Plants are essential to life on Earth. They sustain terrestrial ecosystems and serve as the backbone of our agriculture and daily diet. They provide us with food, oxygen, and countless resources that support our daily lives. However, unlike animals, plants cannot move. So, they rely entirely on the soil for nutrients, minerals, and water, which are absorbed through their roots and distributed throughout their tissues. Without healthy soils, plant growth and food production would be nearly impossible.

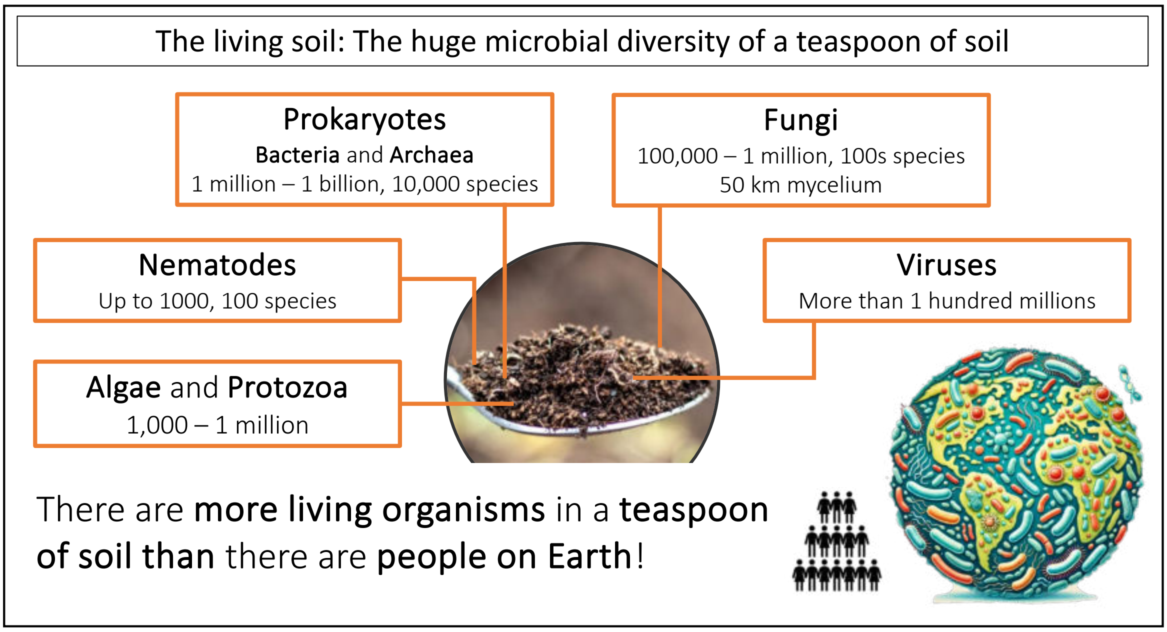
Unfortunately, soils around the world are being degraded by overuse, pollution, climate change and poor management, losing day by day their fertility, structure, and ability to support plant growth. The degradation of soil health makes agriculture increasingly challenging, posing a threat to global food security and livelihoods. Soil degradation has far-reaching impacts and affects (directly and indirectly) several Sustainable Development Goals, including No Poverty (Goal 1), Zero Hunger (Goal 2), Life on Land (Goal 15), and Responsible Consumption and Production (Goal 12). It also undermines progress toward Good Health and Well-being (Goal 3), Clean Water and Sanitation (Goal 6), and Climate Action (Goal 13).

To address this critical issue of soil fertility and ensure plant growth and production, we must turn to nature's main allies: microorganisms. These microscopic but irreplaceable helpers enhance soil fertility, improve plant resilience to stress, and enable crops to grow even in poor or marginal soils. By harnessing the power of beneficial microbes, we can promote sustainable agriculture and natural resources management, restore degraded lands, and ultimately secure food supplies and ecosystem health for future generations.

Plant-Microbe Interaction: The Microbiology

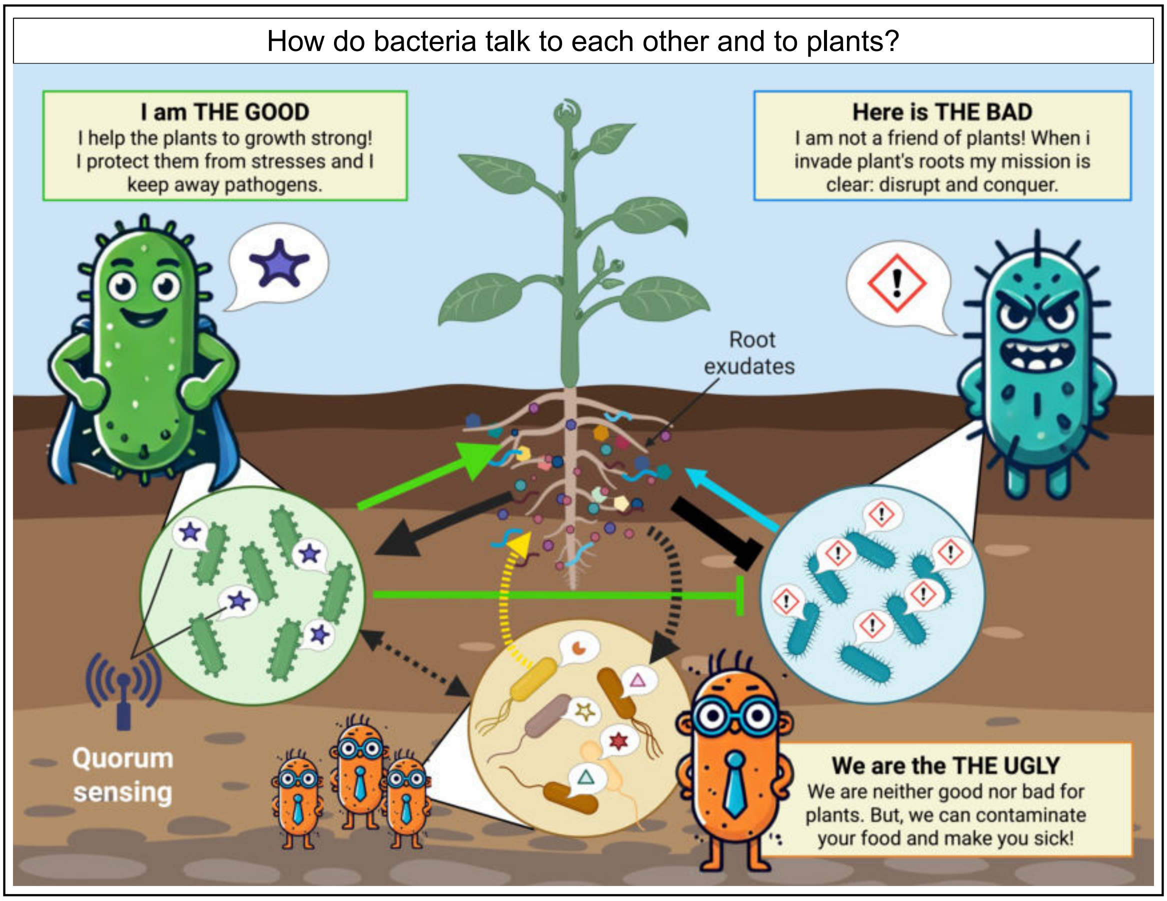
1. Soil and its inhabitants: A hidden world of microscopic allies. The soil is like a bustling underground city, filled with millions of microscopic inhabitants, each with its own job, capacities, and purpose. The diversity of microbes living in the soil is astonishing: bacteria, fungi, viruses, algae, nematodes and protozoa all working together—sometimes collaborating and others competing—to keep soils alive and healthy.

In just one gram of soil, about the size of a teaspoon, we find billions of bacteria, thousands of different species of fungi, and hundreds of thousands of other microorganisms. The number of living microorganisms reaches billions/trillions when considering the Earth's entire soil system. It is incredible to think that a small pinch of soil can hold more living organisms than people on Earth!



This extraordinary microbial diversity is what makes soil so special. So many different types of soil microbes that work in partnership with plants. Some of the most famous micro-stars of the soil and plant worlds include *Pseudomonas*, *Bacillus*, *Rhizobium*, *Streptomyces*, and *Azotobacter*. Each of these microbes has its own superpower that helps keep soils healthy and plants thriving. Just like a diverse community of people brings different skills and perspectives, a diverse community of microbes ensures that the soil can handle a wide range of challenges, such as drought, pollution, or pests. Without this rich microbial life, the soil would lose its ability to support plant life, and agriculture as we know it would struggle to exist.

While compositional diversity tells us who is at the party, functional diversity reveals what role each participant plays and how they contribute. Unfortunately, not all soil microbes are friendly and cooperative with plants. In fact, soil microbes are like characters in a movie—they can be "the good", "the bad", or "the ugly".



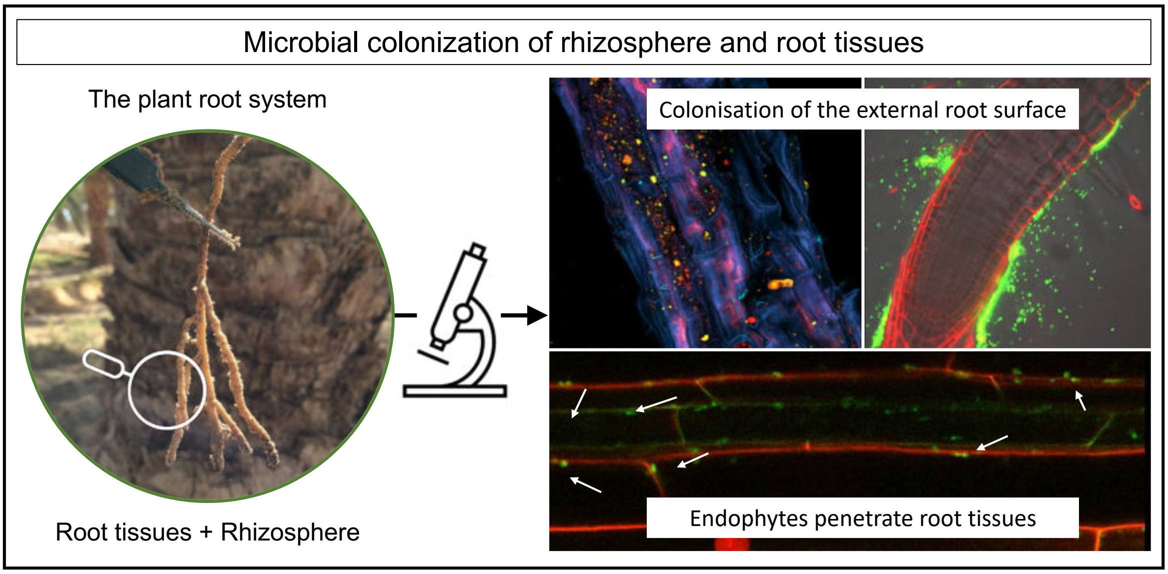
The **good microbes** are the helpful heroes (often called plant growth-promoting, PGP, microorganisms or beneficial microorganisms) that positively influence plants by providing them with nutrients, protecting them against environmental stresses and diseases, and enhancing the health of the soil. These good microorganisms act as tiny gardeners and bodyguards, helping plants grow strong and healthy! They break down organic matter, release nitrogen, produce growth-promoting compounds and defend plants against harmful inhabitants. The **bad microbes**, also known as phytopathogens, are the villains. They can infect roots, leaves, or stems, causing diseases that make plants weak or even lead to their death. Such villains in the soil are constantly threatening the well-being of plants and sometimes killing them. Finally, there are also the **ugly microbes**—they are not directly harmful to the plant itself, but they can become toxic later when humans or animals consume contaminated plants or fruits. In the soil, they hang around as commensals without helping or hurting the plant.

So, soil microorganisms can be heroes, villains, or just bystanders, each shaping the story of the plant life in its own way.

2. How microbes talk to each other and with plants to establish their relationships. When plants send out signals—sometimes like a help/SOS call—microorganisms respond by gathering in the soil surrounding the roots (the rhizosphere) and on the root surface (the rhizoplane). They often build their structured neighbourhood called biofilms. Inside the biofilm, like inside a mediaeval fortress, microbes can share food and protect each other from hostile enemies and their weapons, such as toxins and antibiotics.

Some microbes do not stop at the root surface—the rhizosphere or rhizoplane—but move inside the plant as endophytes, exploiting tiny cracks and small openings in the roots. Once inside, they often reside in the spaces between the cell wall and the cell membrane, known as the apoplast, or in the spaces between plant cells (the intercellular spaces), where they can easily access nutrients and are protected from external threats. A subset of endophytes continues their journey through the plant's "veins" (like tiny highways known as xylem) to enrich and colonise distant tissues of the aboveground portions, such as stems, leaves, and flowers. It is important to note that not all plant-associated microorganisms come from soil. Other sources, such as dust, air, rain, and insects, for example, can also contribute to the plant microbiome. For instance, microbes associated with pollinator insects (like bees) and herbivore insects (such as coleopterans, lepidopterans, and orthopterans) can introduce and spread microbes on the plant surfaces and internal tissues during their activities, such as sucking, chewing, or pollinating.

One of the most incredible things about the plant microbiome interaction is that its members can even reach seeds, ensuring that the next generation of plants begins with their own community of microbial helpers. Indeed, this relationship between plants and microorganisms is not just a one-time interaction, but is perpetuated through generations. When plants drop their seeds, they are not only leaving behind a future plant, but they are also ensuring that beneficial microbes are passed on to support the growth and health of the next generation.



3. The role of "the good" microbes in helping plants. Diversity, both in terms of microbial species (who is at the party?) and functional role (what do they bring to the party?), is crucial for fruitful plant-microbe interactions. In particular, what makes this association successful is the fact that plants can attract and interact with many microbial allies, each performing different functions the plants need to improve or maintain their growth, health and fitness (i.e., functional diversity). At the same time, microbial communities are also functionally redundant: different microbial species can perform similar functions or metabolic processes, thereby maintaining the stability and resilience of the community. It becomes crucial when environmental conditions change (such as global change disturbances), because if one species cannot adapt to the new conditions and is wiped out, others that can perform the same function can step in and replace it.

Below are some of the most important functions that show how microbes support plants:

(i) Creating healthy soil. Microorganisms improve the soil's structure by making it more aerated and better at retaining water. Fungi, like mycorrhizae, create networks of filaments -termed hyphae- that bind soil particles together, improving soil stability and water retention capacity and preventing erosion. All these are crucial for sustainable farming and dryland agriculture.

(ii) Breaking down complex organic matter and recycling nutrients. Microorganisms decompose complex organic matter, such as dead plants and animals, into small molecules that plants and other living things can absorb and directly use. For example, when leaves fall from trees, specific enzymes are released, mainly by bacteria and fungi, to break down the complex organic plant material into smaller, usable pieces, such as sugars and minerals. In this way, they enrich the soil with nutrients that keep it fertile for plants.

(iii) Helping plants to access their food. Just like you need food to grow, plants need food too. But plants don't eat as we do—they get nutrients from the soil through their roots. Sometimes, the soil lacks sufficient nutrients, especially in areas that are too dry, salty, or unsuitable for growing plants. This is where microbes come in to save the day! This group of microbes is also called biofertilisers. Plants need nitrogen to grow their leaves, stems, and flowers, but they cannot fix it alone. Certain bacteria, called nitrogen-fixers, can fix nitrogen from the air and turn it into ammonium, a form that plants can use. Some of these bacteria create a very tight association with plants that live in special little bumps on plant roots called nodules. Similarly, a special group of fungi, the mycorrhizae, form symbiotic relationships with plants by connecting to their roots and acting like extra-long roots (the fungal hyphae), reaching out into the soil to find water and nutrients plants need to grow. Yet, other bacteria contribute to phosphorus solubilisation from soil minerals, making it available for plants. Without this teamwork, plants would struggle to access all the nutrients needed for growth, especially in challenging soils where nutrients or water are scarce.

(iv) Boosting plant growth. Some microorganisms, called biopromoters or biostimulators, produce natural chemicals such as plant hormones that enhance plant growth. As we saw before, hormones are like messages that guide plants on what to do, such as when to grow taller, make more roots, or even how to handle stress like drought or poor soil. Biostimulators, through the production of the auxin hormones, stimulate the growth of root hairs, which are tiny, hair-like extensions of the plant's roots. Root hairs are super important because they increase the surface area of the roots, allowing the plant to absorb more water and nutrients. Others produce gibberellins, which help plants grow faster and stronger, and cytokinins, which help with the development of new leaves and shoots.

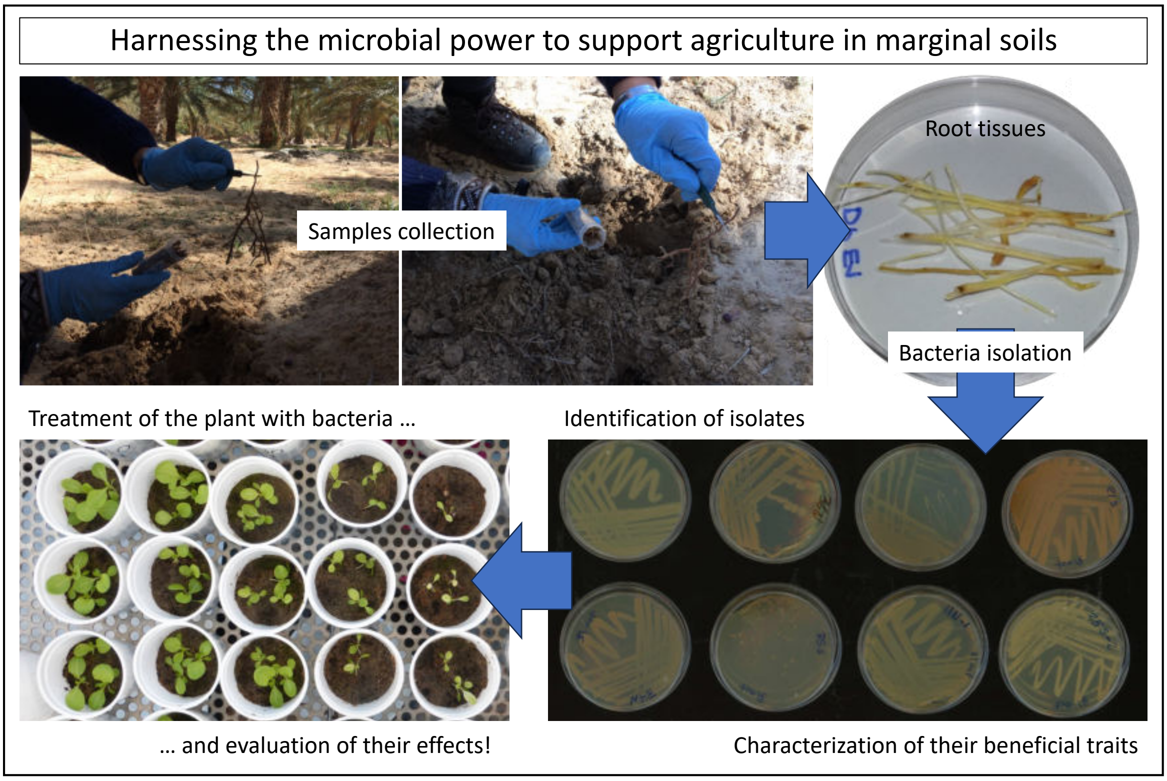
(v) Helping plants hold on during droughts. Imagine trying to survive without enough water and without being able to move and get it. Plants face this problem in dry places, such as drylands, deserts, or regions where it hasn't rained for a long time. Water is essential for plants to grow, just like it is for you. But what happens when water is hard to find? Certain microbes form a protective, sticky layer rich in polysaccharides around plant roots. This layer is like a shield that protects the roots and keeps the water from drying up too quickly. Even when it hasn't rained for months, these microbes help the plants keep just enough water to stay alive. These microbes can also help plants grow deeper and more branched roots, allowing them to reach water further underground, as in the case of cacti and succulent plants.

(vi) Fighting too salty conditions. Have you ever tasted salty water at the beach? It doesn't taste good to us and is not suitable for most plants, except in a few cases like mangroves (see **The Global Mangrove Microbiome** framework). Salt makes it hard for plants to grow, uptake, and retain water. However, in places like coastal farms or areas irrigated/flooded with salty water, microbes can resist salty conditions and have PGP activities. Therefore, these can help food crops like tomatoes, barley, and rice grow in salty places where they usually couldn't. Fun Fact: Astronauts are testing salt-tolerant beneficial microbes to see if they can help plants grow on Mars' soil!

(vii) Microorganisms acting as bodyguards. Plants can get sick just like you can catch a cold. Harmful bacteria and fungi ("the bad") can attack plants. But the good microbes are always ready to protect their plant friends, acting like bodyguards. They produce natural chemicals that kill harmful bacteria and fungi, including antibiotics and toxins, before they can harm the plant. Others gather around plant roots, making it hard for the harmful microbes to penetrate and colonise internal plant tissues. Some microorganisms even send signals for the plants to boost their defences. Farmers use these microbial bodyguards (also known as bioprotectors) to protect their crops as a sustainable alternative to pesticides. This not only helps keep the plants healthy but also protects the environment by reducing reliance on harmful chemicals.

We are sure that you are now convinced that, from the soil surrounding plant roots to their internal tissues and their seeds, microorganisms support plants through every stage of their life. So, the next time you see a plant thriving in a crack in the sidewalk or flourishing in a dry, salty field, remember: It is not just a plant, but it is a meta-organism (or holobiont) in which plant and microorganisms cooperate and co-evolve to stay healthy and strong, generation after generation. This mirrors what happens in our bodies! Like plants, we have millions of microbes in our gut that help us digest food, fight harmful germs, and stay healthy (see **Human Microbiome**). Both plants and humans need their special microorganisms to remain strong and thrive!

4. Harnessing microbial powers to support agriculture in marginal soils. All the above-mentioned functional services provided by microorganisms contribute to plant health and resilience. This is critical as our world is changing and globally getting hotter. Rising temperatures are accelerating global desertification and land degradation, while extreme events such as intense droughts, floods and hurricanes are more frequent. And plants are facing these new and life-threatening challenges without being able to run away and find better conditions. But once again, microbes are stepping in to help. In fact, microbes don't just help plants grow in good, rich soil; they also make it possible for plants to survive in places that seem too harsh for farming. These are known as marginal soils that are too salty, too dry, too sandy, or too nutrient-poor. These soils are typical in extreme environments, including arid lands (or drylands), high-altitude mountains, or coastal-saline systems, where traditional crops often fail. However, in the last decades, scientists have discovered that by selecting the correct microbes and by applying them to the marginal soil and/or directly on the seeds and/or the plant tissues, food crops can be cultivated in such difficult soils and when water is scarce. For instance, it has been proven that plants growing in dry, salty, or nutrient-poor soils recruit and pass to their seeds those microbes that are best suited to help the next generation overcome the challenges they have experienced.



Such discoveries are driving the development of microbial probiotics to support and boost sustainable agriculture in marginal soils. The use of microbes in agriculture and even ecosystem restoration is part of the so-called Nature-based Solutions, approaches that reduce the use of chemicals and make the world a healthier place. For example, in some parts of Africa and Asia, farmers use beneficial microbes to grow rice and other crops in salty or dry soils, feeding millions of people where food was once hard to produce. Among these microorganisms are the *Rhizobia* bacteria that help legumes such as beans get nitrogen from the air. This is super important because plants can grow strong and healthy without needing extra chemicals, which is better for the environment. Yet, in China, scientists have successfully used microorganisms to support plant growth in degraded land, turning deserts into productive lands. This type of sustainable farming provides more food and helps people living in dry and marginal lands become less dependent on imported food, thereby increasing their food security. The best part is that nature-based solutions not only benefit people but also protect the environment by reducing the need for chemical fertilisers and excessive water use. By working in harmony with nature, we can mitigate the effects of climate change, water pollution, and food shortages, all while preserving our planet's health and beauty.

Desert farming and microbial treatments to support agriculture in drylands

Why does this matter to you? You might wonder why all this talk about microbes and plants is important to your life. The truth is, these tiny organisms play a huge role in ensuring we have enough food to eat, clean air to breathe, and healthy environments to enjoy. By understanding how soil microbes work and how they interact with and ultimately help plants, we can make better decisions on how and where to grow our food, protect our environment, and respond to climate change in more responsible and eco-friendly ways.

Can you make a difference? And How? Yes, you can! Even as kids, you can help support these microbial superheroes and the plants they protect. Here are some fun and easy ways to make a difference: *(i) Start a garden*: Whether it's a small garden in your backyard or a few pots on your windowsill, growing plants helps support good microbes in the soil. You can even start a school garden with your friends! *(ii) Compost*: Composting food scraps and garden waste creates rich, microbe-friendly soil that plants love. It is a great way to recycle and support the tiny heroes working below the surface. *(iii) Learn and share*: Talk to your friends and family about the fantastic world of microbes and how they help plants. The more people know, the better we can protect and use these essential resources.

Relevance for Sustainable Development Goals and Grand Challenges

The microbial contributions to plant growth and adaptation to stresses are directly linked to several Sustainable Development Goals (SDGs) and can help address some of the world's most pressing grand challenges related to food security, climate change, biodiversity, and sustainable land management. Here's an overview of the SDGs impacted and how microbial contributions can play a role:

Goal 2 - Zero hunger. Microbes that enhance plant tolerance to drought and salinit enable crop growth and sustainable agricultural expansion into marginal lands or degraded soils, which are typically unsuitable for agriculture. They can support food production in regions facing water scarcity and/or poor soil quality, which is becoming increasingly prevalent due to climate change.

Goal 6 - Clean water and sanitation. Microbial inoculants that promote plant growth in degraded soils indirectly reduce the demand for irrigation and, therefore, help conserve freshwater resources. It can also help reduce the use of chemical fertilisers and pesticides that pollute surface and groundwater, thereby preserving water quality.

Goal 12 - Responsible consumption and production. By harnessing microbial communities promoting plant growth in harsh environments, we reduce the need for chemical fertilisers and pesticides, which are environmentally harmful and energy-intensive to produce. As a Nature-Based Solution, microbial inocula promote sustainable agricultural practices that minimise the environmental footprint, preserve soil health, and promote efficient resource use.

Goal 13 - Climate action. Plants supported by stress-tolerant microbes can better withstand the effects of climate change. Consequently, future farming could become more resilient and sustainable even under drier/hotter conditions. Additionally, microbes can contribute to soil carbon sequestration, playing a role in climate change mitigation.

Goal 15 - Life on land. Applying beneficial microorganisms in marginal soils helps restore and rehabilitate degraded lands, as it can improve soil fertility and support biodiversity both in the soil and among plants. Consequently, it has overall repercussions on land life diversity, such as those of insects and animals. Microbial consortia could also be used to prevent soil erosion.

Goal 1 - No poverty (indirectly). By enhancing the productivity of marginal soils, microbial-based biotechnologies can empower farmers in low-resource settings by creating economic opportunities, promoting sustainable agricultural livelihoods, and helping lift rural populations out of poverty. Sustainable use of marginal lands also reduces the need to apply expensive fertilisers and irrigation, which reduces farming costs.

Goal 3 - Good health and well-being (indirectly). A more stable and diverse food supply contributes to better nutrition and health, which reduces malnutrition and food-related health issues. In addition, healthier ecosystems (via reduced chemical inputs) lead to cleaner water and air, reducing disease burdens related to environmental pollution.

Potential Implications for Decisions

1. Individual behaviours and initiatives for protecting microbial diversity and exploring its treasure. Microbial diversity in soils is a hidden treasure that we must preserve and continue to investigate. Individuals, such as farmers, gardeners, and even everyday consumers, can take small but powerful steps to help. Farmers and gardeners can focus on sustainable practices like composting to enrich their soils in organic matter, which reduces the need to use chemical fertilisers and pesticides. These practices not only protect beneficial microbes but also promote their diversity, ensuring this in the process. Consumers can support sustainable agriculture by choosing organic or eco-friendly products, which help protect soil microbes against harmful chemicals. Education and awareness are also crucial.

Understanding the value of microorganisms in food production and ecosystem health can encourage people to engage in sustainable land management and support initiatives that protect microbial diversity.

2. Community policies for supporting the application of microbial inocula in agriculture. Communities, especially those dependent on agriculture, can play a vital role in promoting the use of microbial inocula (beneficial microbes) in farming. Local governments and community organisations can introduce policies that encourage farmers to adopt microbial inoculants to enhance soil health and plant growth. Community initiatives, such as providing workshops and training on the benefits of using microbes in farming, can increase awareness and their adoption as biofertilisers. Cooperative purchasing programs for microbial inocula can make these resources more affordable for small-scale farmers. Furthermore, community-supported agricultural projects can offer testing plots where farmers can observe firsthand the benefits of applying microbial inoculants.

3. National policies for promoting sustainable agriculture. National governments can implement policies that promote sustainable agriculture. Governments can invest in research to develop microbial inocula specifically designed to help plants grow in marginal soils. They can provide subsidies or financial incentives to farmers who adopt sustainable practices, including the use of microbial technologies, to restore soil health and boost productivity in marginal lands. National policies could also support large-scale educational campaigns to raise awareness about the benefits of sustainable farming techniques and how microbial inoculants can help transform unproductive land into fertile ground. By encouraging collaboration between agricultural researchers, local farmers, and businesses, national policies can accelerate the shift towards sustainable farming practices that are both environmentally friendly and capable of feeding growing populations.

Pupil participation

1. Class discussion on the importance of plant-microbe interactions

Microbes and Global Challenges: Ask pupils to think about a country that faces food shortages due to climate change and degraded soils. Then, discuss how microbes could be part of the solution. Discussion Prompt: How could microbes help to improve food security in a country where the soil is degraded and where it rarely rains? What would happen if we didn't have microbial solutions?
Debate on organic vs. chemical farming: Organise a debate where one group argues for using chemical fertilisers to grow more food, while the other group argues for using microbes and natural methods. This will get pupils thinking about sustainable farming practices. Discussion Prompt: What are the benefits of using microbes instead of chemicals to grow plants? How does this help the environment and ensure long-term food production?

2. Pupil awareness

Microbe awareness campaign: Have students design posters, presentations, or infographics describing how microbes help plants grow and resist harsh environmental conditions and pathogens and why this is crucial for food security. Display student work around the school to educate classmates, teachers and parents.
Microbial soil experiment: Have pupils set up a simple experiment where they plant seeds in two pots—one with soil treated with beneficial microbes (e.g., compost or biofertiliser) and one

without. Throughout the growing process, they can observe and compare how the plants grow differently. This hands-on activity reinforces how essential microbes are to healthy plant growth.

The evidence base, further reading and teaching aids

List of videos and books

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Glossary

Abiotic stress: When plants are stressed because of non-living things, like too much heat, cold, or not enough water.
Algae: Plant-like organisms that live in water or moist places and can make food from sunlight.
Antibiotic: A substance that kills or stops the growth of harmful bacteria.
Apoplast: The spaces in a plant where water and nutrients move through the plant's cells.
Auxin: A plant hormone that helps plants grow tall and signals the roots when to elongate.
Bacteria: Microscopic, single-celled organisms.
Biofertilizer: Natural fertilisers made from microbes that help plants grow better without harmful chemicals.
Biofilm: A sticky layer of microorganisms that attaches to surfaces, like plant roots.
Biopromoters or Biostimulators: Natural substances, often made by microbes, that boost plant growth and health.
Bioprotectors: Helpful microbes that protect plants from harmful organisms. Bioprotectors act like bodyguards for plants, keeping them safe from attacks without using chemical

pesticides. These natural defenders can boost the plant's immune system or directly combat harmful microorganisms, helping the plants remain healthy and strong.
Biotic stress: When plants face stress from living things like pathogenic bacteria and fungi, viruses, or other harmful organisms.
Chemical signals of microbes: Special chemicals microbes use to communicate with each other, like sending messages between friends.
Climate change: It refers to the overall global climatic changes we are experiencing that are related to increasing greenhouse gas concentrations, such as those of carbon dioxide (CO_2), nitrous oxides (N_2O) and methane (CH_4), which human activities have driven since the Industrial Revolution. This has led/is leading to global and regional modifications of climate (temperature and precipitation patterns). For example, with climate change, it is expected that hot drylands will experience hotter temperatures globally.
Coevolution: Reciprocal evolutionary influence between two or more interacting species, where changes in one species may drive adaptations in the other, leading to a joint evolutionary path.
Compositional diversity: The different kinds of microbes in a community, such as the number of types of bacteria or fungi in a soil sample.
Cooperation: When different living things work together to help each other, like plants and microbes do in the soil.
Cytokinins: Plant hormones that tell cells to divide and grow, helping plants grow more leaves and branches.
Degradation of soil: When soil loses its health, making it harder for plants to grow, usually because of overuse, pollution, or erosion.
Eco-friendly: Something that is good for the environment and doesn't cause harm to nature. Eco-friendly products or actions help protect the Earth by reducing pollution, saving energy, or using natural resources in a way that doesn't damage ecosystems. For example, growing plants without harmful chemicals is an eco-friendly choice.
Endophytes: Microbes that live inside plant tissues.
Fertility of soil: How rich and healthy the soil is, with lots of nutrients for plants to grow.
Food security: As defined by the United Nations Committee on World Food Security, it is the principle that all people must have access to sufficient, safe, and nutritious food for an active and healthy life.
Functional diversity: The different jobs that microbes do in a community.
Functional redundancy: When different microbes can perform the same function, so if one microorganism is absent, another can step in and perform that role.
Functional services: The important jobs that microbes and other living things perform in an ecosystem.
Fungal hyphae: Long, thread-like parts of fungi that spread through the soil.
Fungi: Organisms like mushrooms, mould, and yeast that live in many environments, including soil. Fungi can break down dead plant material, helping recycle nutrients back into the soil. Some fungi form special partnerships with plant roots (like mycorrhizae) to help plants absorb water and nutrients. While many fungi are helpful, some can cause diseases in plants, animals, and humans.
Gibberellins: Plant hormones that help seeds grow and tell plants when to grow bigger.
Marginal soils: Soils that are not suitable for farming due to being too salty, dry, or lacking essential nutrients.

Metaorganism (or Holobiont): A host organism and its associated microorganisms (such as bacteria, fungi, and viruses) considered collectively, functioning as a single, integrated organism.
Microbes (or Microorganisms): Tiny creatures like bacteria, fungi, and viruses that live all around us in the air, water, and soil, but we cannot see them with the naked eye.
Microbe-mediated adaptation: When microbes help plants or animals survive under challenging conditions by developing special traits (modifying their physiology or morphology) to fit their surrounding environment better and changing conditions. For example, microbes help plants to grow deeper roots to find water.
Microbial community (or Microbiome): All the microorganisms, including bacteria, fungi, and viruses, that inhabit a particular ecological niche, such as plant or animal organs or soils. Altogether, these microorganisms play a crucial role in various biological processes and can have significant effects on the health and functioning of the host organism or system.
Mutualistic relationship: A friendship between two living things where both sides help each other, like plants and microbes working together.
Mycorrhizae: Special fungi that form a symbiotic relationship with plant roots. These fungi assist in nutrient absorption by the plant roots, especially minerals like phosphorus, in exchange for carbohydrates from the plant.
Nature-based Solutions: Solutions to environmental problems that utilise nature's own tools, such as microbes, plants, or trees, to address issues like climate change or soil degradation.
Nematodes: Tiny, worm-like creatures that live in soil and can be helpful or harmful to plants.
Nitrogen fixation: It generally refers to the fixation of atmospheric nitrogen (N_2) by diazotrophic microorganisms into a more assimilable form of nitrogen, such as ammonia (NH_3/NH_4^+).
Nodule: Small lumps on plant roots where special bacteria live and help the plant take in nitrogen from the air.
Pesticides: Chemicals that are used to kill or control pests, such as insects, weeds, or fungi, that can harm plants. While pesticides help protect crops and increase food production, excessive use can harm the environment, including beneficial insects, animals, and even the soil. That is why eco-friendly farming often seeks natural solutions, such as using beneficial microorganisms, to protect plants instead of relying on chemical pesticides.
Phytohormones: Special chemicals that plants make to control their growth, like telling the plant when to grow taller or make roots.
Phytopathogens: Harmful microbes that cause diseases in plants, such as bacteria or fungi that infect and harm plants.
Phosphate solubilisation: It is the process that transforms inorganic/insoluble phosphorus compounds into soluble forms assimilable by plants and other organisms. This process is mainly mediated by phosphate-solubilising bacteria living in the soil.
Plant-Growth Promoting (PGP): Special microbes, like certain bacteria and fungi, that help plants grow better. These tiny helpers provide plants with essential nutrients, protect them from diseases, help them absorb water, and make them stronger against harsh conditions, such as drought or poor soil. They act like natural fertilisers and bodyguards, supporting healthy plant growth without the need for harmful chemicals.
Polysaccharide: A type of sugar made by plants and microbes that helps them build strong structures or store energy and water.
Protozoa: Single-celled organisms that live in water or soil and help control the number of bacteria in the soil.

Quorum Sensing: A way that microbes communicate with each other by sending out chemical signals. When enough microbes are present, they can sense each other and act together to perform essential tasks, such as breaking down food or fighting off harmful microbes.
Resilience: The ability of plants or microorganisms to recover quickly from damage or difficult situations.
Rhizoplane: The surface of the plant's roots.
Rhizosphere: The narrow portion of soil (a few millimetres) that is in contact with the roots; it is directly influenced by plant-root secretions (root exudates) and is rich in nutrients, such as sugars and proteins.
Root exudates: Special substances that plants release from their roots to attract beneficial microbes and obtain essential nutrients.
Root hairs: Singular cells that develop from the root tissues as long hairs that help the plant absorb water and nutrients from the soil.
Secondary metabolites: Special chemicals made by plants and microbes that help them survive in their environment. These chemicals are not needed for basic growth but play essential roles in protecting the organism from things like pests, diseases, or harsh conditions. For example, plants produce secondary metabolites to defend themselves from insects or attract helpful microbes.
Soil biodiversity: All the different kinds of living things, like microbes, insects, and worms, that live in the soil.
Sustainable Development Goals are a collection of 17 global goals designed to be a "blueprint to achieve a better and more sustainable future for all"; these were set in 2015 by the United Nations General Assembly and are intended to be achieved by the year 2030.
Symbiotic relationship: Close and often long-term interaction between two different species living in direct contact with each other. It can be mutually beneficial (mutualism), one-sided benefit (commensalism), or detrimental to one of the species (parasitism).
Structure of soil: How soil is made up of different parts, like sand, silt, and clay, which affects how plants can grow in it.
Sustainable agriculture: Growing food in a way that is good for the planet, using natural methods like microbes, and without harming the environment.
Terrestrial ecosystems: Refer to natural environments on land, such as forests, deserts, and grasslands, where various plants, animals, and microbes coexist.
Toxin: A harmful substance produced by plants, animals, or microbes that can make other living things sick.
Viruses: Tiny microbes that can infect plants, animals, and humans, causing diseases. Unlike bacteria or fungi, viruses need to invade the cells of other living things to grow and reproduce.
Xylem: A part of the plant that acts like a highway, carrying water and nutrients from the roots up to the leaves, stems, and flowers. The xylem is composed of tiny tubes that help keep the plant hydrated and strong, much like our veins carry blood throughout our bodies.