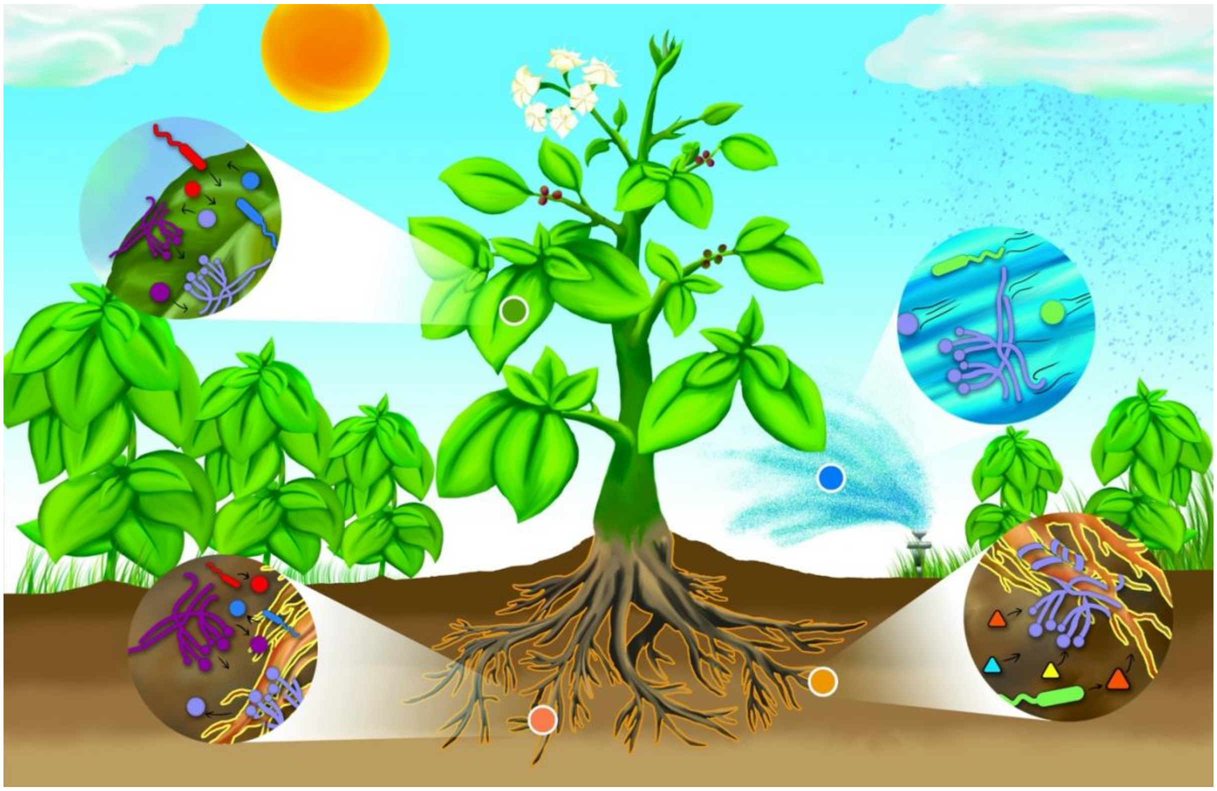
The role of microorganisms in sustainable agriculture

Maisy: Teacher, are microorganisms useful for agriculture?



Microbial roles in agriculture and their applications for sustainable agriculture. *Illustration by Jose Arce Gómez*

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The role of microorganisms in sustainable agriculture

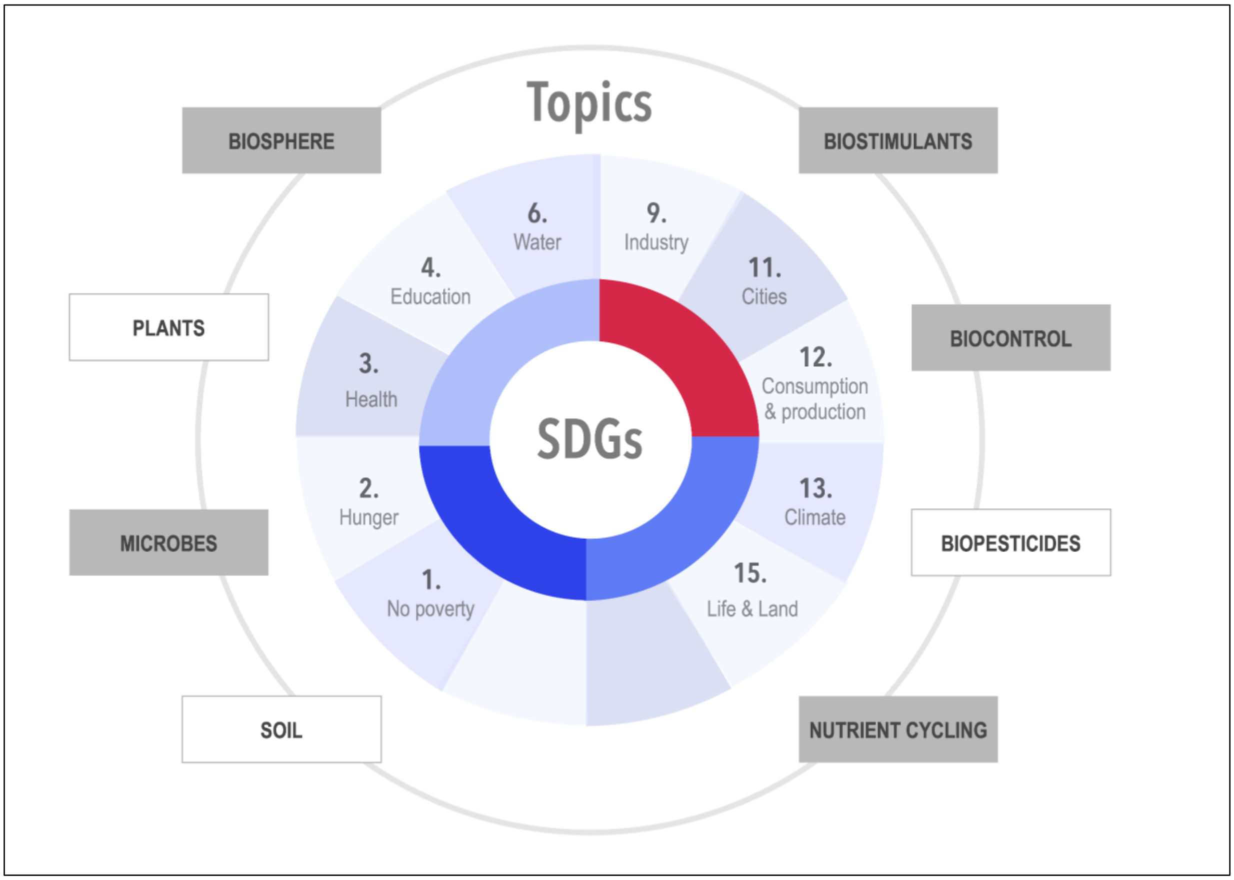
Storyline

The role of microbes in sustainable agriculture is fundamental in terms of promoting plant growth, performance, and wellness. Nevertheless, it is necessary to understand the roles of microbes in soil and plants to explore microbial sustainable agriculture strategies. Soil microorganisms, as critical players in nutrient cycling, maintaining soil fertility, and even protecting plants against pathogens, are fundamental for life on Earth. Despite facing challenging survival conditions in the soil, microorganisms are soil architects that can colonize and transform those environments. Furthermore, they participate in biogeochemical processes by making available nutrients, such as nitrogen, phosphorus, potassium, calcium, and magnesium, that are necessary to plants throughout their life cycles. Plants themselves have evolved intimate relationships with microbes. The key question is: Why are those microorganisms so crucial for the plant? Plants and microbes interact in a close relationship known as symbiosis, in which each obtains a benefit for their survival. Plants provide refuge and carbohydrates essential for growth of their microbial partners; in return, microbes contribute to the plant's growth, health, and protection from pathogens. Therefore, microbes have an incredible potential in natural crop management because they can act as biofertilizers, bio-stimulants, or biocontrol agents to improve plant crop performance. Importantly, microbes have the potential to replace polluting chemical fertilizers and pesticides. The microorganisms associated with the plant's tissues (leaves, roots, stems) define the phytobiome, the critical target for current strategies in sustainable agriculture. Current strategies use microbial bioinoculants as prebiotics to improve the soil quality, or as plant probiotics to enhance biofertilization and biopesticide properties. Nowadays, this vision of phytobiome combined with state-of-the-art technologies is manifesting in the latest strategies for more sustainable agriculture through use of consortia bioinoculants, synthetic microbial consortia, and genetically engineered plants. The different strategies used aim to design the phytobiome in the rhizosphere (roots) and phyllosphere (leaves, stems). These strategies are critical to overcome the agricultural challenges of sustainable production and food security assurance in the context of constant climate change.

The societal context of microbiology

Microbiology: Microorganisms are essential for agriculture: microbes participate in nutrient cycling and soil formation processes; microbes have symbiotic relationships with the plant, providing benefits such as growth promotion and control of pathogens. Therefore, microbes are vital for sustainable agriculture practices in various ways, including microbial soil amendments, microbial bioinoculants, consortia bioinoculants, and synthetic microbial consortia design.
Sustainability issues: Food production and increasing production yields, food security and good health, education, biodiversity loss and environmental pollution, clean water access, soil quality, sustainable innovation, climate action, and responsible production.

Box 1. Microbiology theme and SDGs treated in this chapter. *Illustrated by Sofía Vieto*



Topic framework

I. *Big challenges in agriculture*

With the world's population increasing by 83 million people every year, the global demand for crop production will increase by 60% by 2050[1,2] to ensure global food security. Over the past decades, however, when faced with this same challenge, agricultural production increased only by 28%[1]. Even this modest increase brought adverse effects, including a decrease in soil health from the intense use of chemical fertilizers and pesticides. Thus, agriculture faces not only the challenge of achieving higher production levels to feed a growing population under climate change conditions but also, in the process, the challenge of fostering economic, environmental, and societal sustainability[1-4].

Agriculture aims to produce the highest yield possible, which entails dealing with plant fertilization, pest control, and adaptation of crops to the environment of production. Good agricultural management means providing the required nutrients for a plant to grow and avoiding pests ranging from invasive plants to chewing insects, fungi, bacteria, and viruses[5]. Traditional crop management employs both chemical fertilizers and pesticides to assure yield. Good agricultural practices include the correct applications of these chemicals; when improperly used, only a low portion of the pesticides will reach their target while the remainder leaks into the surroundings[1]. Consequently, the extensive use of agrochemicals has led to a contamination problem that degrades soil health, fills the atmosphere with greenhouse gas emissions, and taints water bodies through eutrophication[1,4]. This environmental imbalance has led to changes in agricultural production, including the adoption of new strategies to promote a more sustainable agriculture that ultimately will improve the environment and human life.

A plant interacts with its surroundings at every level, from biotic (living) to abiotic (non-living) factors[3]. This view is fundamental for understanding sustainable strategies for crop management. More precisely, the term phytobiome defines these types of biotic interactions. It refers to the relationships a plant maintains with all living organisms inside, on, or around it and their interactions with the environment (i.e., soil, water, air, and climate)[6]. One subset of the phytobiome in particular, the plant's microbiome, plays a fundamental role in maintaining plant fitness, plant nutrition, tolerance to abiotic factors, and protection from pests[2]. The plant secretes chemical compounds through the root system to modulate the microbe community around the rhizosphere—that is, the portion of soil attached to roots[6]. Therefore, this mutual interaction between plant and microbes is essential for nutrient uptake and resistance to both diseases and abiotic stress[2,6].

Because the microbiome constitutes an essential part of the plant, it is a perfect target for crop improvement[2]. Therefore, understanding how the plant interacts with its microbiome is a main topic of research to design new sustainable agriculture strategies. Finally, before we can discuss strategies to engineer the phytobiome, describing microbial roles in agriculture is fundamental to understand how they could tackle the current agricultural challenges.

II. Microorganisms as potential tools for agriculture

An ecosystem is the sum of all biotic and abiotic factors, meaning living and non-living components, respectively[4]. In all ecosystems, microbes are interacting at all times with their hosts[4]. In the soil's case, it is a very complex environment that has the most extensive microbial diversity reservoir on the planet[4,7]. Soil microorganisms are fundamental for life on Earth, as they are critical players for nutrient cycling and for maintaining soil fertility, both conditions required for plant and animal health[8–10]. Plants are also characterized as metaorganisms, as they host many associated microbes that are necessary to maintain plant functionality[4]. Consequently, defining those roles is the first step to understanding the impact of microbes in agriculture.

Microbes in the soil

To understand the role of microorganisms in sustainable agriculture, it is essential first to understand their role in natural ecosystems, starting with the soil. Despite facing challenging conditions for survival in the Earth, microorganisms are considered soil architects[11]. Specifically, microbes can both colonize and survive in the soil. They have the capacity to synthesize metabolites, weathering rocks, gluing soil particles together, and creating a matrix formed by molecules that stick together, also known as a biofilm[11]. Even a single small patch of soil comprises different environments with specific conditions; and, even a few centimeters apart, its microenvironments are entirely different from one another[8]. Microbes require certain conditions for their growth, such as water availability, oxygen concentration, nitrogen availability, salinity, temperature, organic carbon sources, and acidity (pH); as these conditions change between the soil macroenvironments or horizons of the soil, so does the microbial diversity and abundance[8]. This variability is the reason why we can find thousands of individual microbes in a single gram of soil; however, in the same gram of soil surrounding a plant's roots (rhizosphere), we could have up to 10 billion microbial cells[8,12].

In terms of macroenvironments or "wider" environments, the soil is classified into four layers or "horizons" that determine the soil profile. These horizons are designated as the O horizon (superficial layer), and the A, B, and C horizons, with C being the deepest[8]. Each horizon has different abiotic conditions, as light and oxygen availability progressively decreases with depth[8]. In terms of microenvironments, by contrast, the soil structure is defined by soil aggregates—particles composed of mineral, organic, and inorganic substances[13]. Besides the smaller scale, conditions can also vary widely within a soil particle. For example, the oxygen concentration can change from 20% on the outside of that particle to 1% inside[8]. This overall diversity provides different microbial habitats where microorganisms can grow and interact with each other and the environment; nevertheless, at the deepest horizons, the abiotic factors usually restrict the growth of microorganisms and hence the microbial community's diversity[8]. There are also biotic factors involved in the soil's microbial dynamics and inhibition. Although bacteria and fungi are the dominant groups on the ground that interact with each other, other organisms such as archaea, viruses, protists, and nematodes interact in distinct forms of symbiosis ranging from mutualism to parasitism[8].

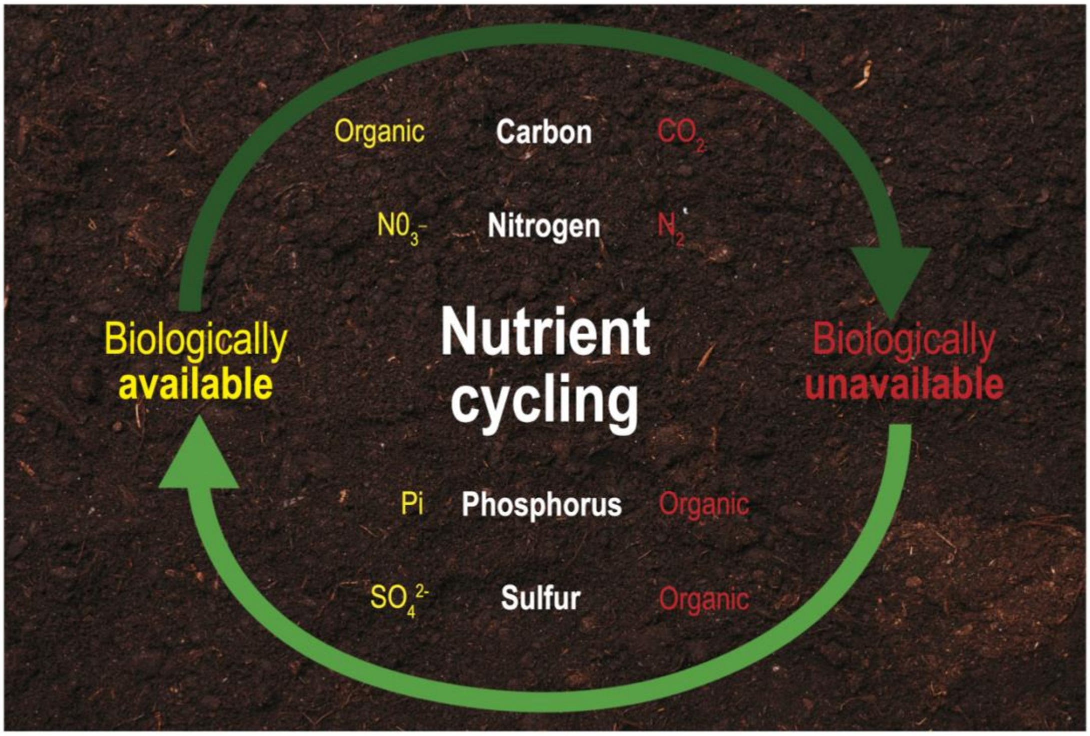
Microbes colonize different soil environments but also influence soil processes through their metabolism[8]. Their involvement in biogeochemical cycles determines the soil profile[11]. Microorganisms are involved in nutrient cycling, processing iron, nitrogen, sulfur, and phosphorus; at the same time, they regulate carbon flux, soil acidity, gas dynamics, and water availability[8]. These functions are vital because although nitrogen and phosphorus are two of the most relevant elements for plant growth and productivity, they are among the elements considered most limiting because they are often present in forms that the plant cannot use. This is one reason for beneficial symbiotic relationships between plants and soil-borne microorganisms. For example, nitrogen-fixing bacteria and archaea (diazotrophs) take atmospheric nitrogen to convert it into ammonia, a biologically available form[14]. Fungi and bacteria can also liberate ammonia by decomposing organic matter[10,14]. Another example is the sulfur and phosphorous solubilization by microbes using enzymes, the universal cellular tools used to separate both elements from organic matter[15]. In addition, saprophytic fungi and certain bacteria decompose dead plants and animals to convert them into organic carbon sources. Finally, actinobacteria participate by degrading the complex structures after bacteria and fungi degrade organic matter[16]. Actinobacteria then contribute to the formation of soil humus, which is rich in organic carbon compounds and nutrients[10,11,16].

Microbes can also interact in the soil, leading to competition. This last interaction can be indirect, as microbes can inhibit others by competing for niches or nutrients, which inhibit colonization. Microbes can also produce antibiotic compounds or lytic enzymes to inhibit the proliferation of other microbes[7,17]. Thus, the soil and rhizosphere are a dynamic microbial network, where microbial colonization success depends on the interaction of multiple microbes. This antagonistic effect is the principle behind a phenomenon known as disease-suppressive soils, where a specific group of microorganisms is responsible for the control of soilborne pathogens[18]. Actinobacteria, for example, are abundant in soil that effectively suppress the pathogen *Rhizoctonia solani*[18]. Furthermore, several bacterial families, such as *Burkholderiaceae*, *Pseudomonadaceae*, *Xanthomonadales*, and *Lactobacillaceae*, have been identified in disease-suppressive soils inhibiting a variety of plant pathogens[18].

To summarize, key features define soil fertility, such as nitrogen availability, phosphorus solubilization, and the pool of organic carbon sources. A broad diversity of microbes in the soil carry out these processes for both providing nutrients to plants and regulating the soil pH[8]. Clearly, the soil profile is defined by which microbes are present. Beyond this, microbial participation in disease-suppressive soils and soil biogeochemical processes are essentials for soil fertility and the dynamics of terrestrial ecosystems[8,10,11].

Box 2. Microbial roles in nutrient cycling. *Illustration by Rafael Montenegro based on Freepik resources.*

Nutrient cycling is a biogeochemical process where microorganisms are involved in many reactions, making a nutrient biologically available and unavailable in a cycling way, as exemplified in the figure. It is essential to focus on the reactions that make nutrients available for the plant toward sustainable agriculture. Some examples are carbon fixation, transitioning from gaseous CO_2 to organic molecules, and nitrogen (N_2) fixation, leading to sources such as nitrate (NO_3^-), whereas nitrogen, sulfur, and phosphorous pass into inorganic forms required for assimilation. All these processes are mediated or influenced by microorganisms[8,15]. Finally, a key feature is that microorganisms are involved naturally in nutrient cycling, leading to the bioavailability of nutrients for the plant, an important aspect to be considered for future sustainable engineering approaches.



Microbes in the plant

To understand biological approaches for sustainable agriculture, we must understand plants themselves as natural microbial environments. In the plant–microbe interaction, a relevant and robust communication is established. Plants have evolved closely alongside microbes since they started colonizing the Earth 300 to 450 million years ago, and they seem to have a close relationship with these microorganisms[19]. In this sense, the plant microbiota is considered fundamental for the plant's growth and health[18]. Significantly, plants use 30 to 40% of the carbon compounds produced in photosynthesis to maintain their communication with the microbes[7,12]. This communication is crucial to maintaining symbiotic relationships with the microorganisms, and it generates a win–win interaction, also called mutualism. Plants provide microorganisms with carbon sources and niches for their growth; in return, microbes contribute to plant growth by providing nutrients, facilitating nutrient uptake, and giving immunity against pathogens[7,12,19,20]. Therefore, microbes have an incredible natural potential for crop productivity in that they can act as biofertilizers or biopesticides[17,20].

The plant–microbe interaction is a direct communication that may occur outside or inside the plant or in the proximity of the root[21]. Therefore, the first step in this symbiotic relationship is the colonization of microbes into plant tissues. Microbes may use a passive mechanism, colonizing accessible plant parts (i.e., damaged tissue or emerging shoot/root points), or an active mechanism via the microbial metabolism[17]. It is worth noting that microbial acquisition is generally determined by horizontal transfer, and some vertical propagation in seeds has also been described. Environmental factors such as soil, air, and rain mediate this acquisition, making the soil a significant source of microbes[17,18,22].

Specifically, the phytobiome refers to the microorganisms living inside the plant or attached to plant tissues (roots, leaves, stems)[3,6,23]. Nevertheless, there is a specific term for the microbiota resident in each part of the plant, as each brings a particular feature to the associated plant organ[17,20]. To start describing the phytobiome, it is essential to clarify that microbes could also be harmful to the plant, causing disease and epidemics, leading to economic losses in agriculture. Historically, pathogenic microbes have drawn plenty of attention, and it is still important to understand microbial pathogenicity to manage plant diseases. However, beneficial microbes are now also emerging as important in agriculture. Nowadays, the primary focus on microbes is their positive impact on the plant's fitness and wellness.

The most critical microbiota in growth and wellness is the rhizosphere, where microbes interact with the plant roots[7,17,18,20]. Microorganisms at the rhizosphere level could live freely in non-symbiotic relationships where they can facilitate and solubilize nutrients[21]. Interestingly, microbes are key players in this process, providing nitrogen, phosphorus, iron, and sulfur[17,18,20]. Microbes near the root can also separate nutrients, such as phosphorus and sulfur, from organic matter. Finally, they can also produce siderophores, chemical compounds that fix the nutrients, making them easily absorbed by the root's xylem[18,20].

There are other remarkable endosymbiotic microbial structures for up taking nutrients in the rhizosphere. In the case of nitrogen, for instance, a well-described example is nitrogen-fixing *Rhizobia* in legume plants. Plants form specialized root organs called nodules that are then colonized by nitrogen-fixing microorganisms[21]. Strains of the genus *Rhizobium* and *Bradyrhizobium* promote the formation of nodules in legume plants belonging to the *Fabaceae* family[21]. The other example of this association is the symbiosis between the plant roots and mycorrhizal fungi (e.g., *Glomeromycota*) that are present in almost all land plants[21,24]. The most common association is the vesicular-arbuscular mycorrhizae (VAM)[21]. However, some mushroom members of *Basidiomycota* engage in another type of interaction, known as ectomycorrhizal association (ECM); its occurrence, however, is relatively rare[21,24]. VAM is able to colonize both the root cell's interior and the intracellular space whereas ECM colonizes only the intracellular space. Nevertheless, both associations provide better absorption of nutrients from the soil, especially phosphate uptake[18,20,21].

More interestingly, microbes can colonize the plant's interior without harming the plant; this type of microbiota is referred to as the endosphere[17,18,20]. Endophyte microorganisms perform functions such as nutrient uptake, biocontrol, and resistance to abiotic stress. Interesting examples are the endophytes of the genus *Trichoderma*[17,25]. Additionally, dark septate endophytes develop endosymbiotic structures known as septate hyphae inside the root[26]. In general, microbes colonize and remain on the root cells; some, though, travel systematically from the root to other organs (leaves, stems, flowers) via the xylem[17]. Endophyte colonization is also possible via horizontal transmission at the phyllosphere level[17,18]—that is, on and around the plant's aerial parts. Overall, microbes live with, inside, or near the plant, improving the plant's fitness and health[17].

Roles of microbes in the plant

One of the well-known functions of microbes is promoting plant growth, specifically by bringing nutrients to the plant. As previously described, the phytomicrobiome is associated with rhizobacteria, nodules, and mycorrhiza. By increasing the bioavailability of nutrients, microbes make them easier for the plant's root system to incorporate[18,19]. This has given rise to a classification of beneficial microbes as plant growth-promoting microbes (PGPM), plant growth-promoting bacteria (PGPB) referring to bacteria in general, plant growth-promoting rhizobacteria (PGPR) for microbes interacting in the rhizosphere, and plant growth-promoting fungi (PGRF) focusing only on fungi[17,20]. Interestingly, endophytes seem to play as equally prominent role in plant-growth promotion as rhizosphere microbes[27]. Overall, microbes are involved in the nutrient uptake required for essential cellular processes that promote plant growth and wellness. Because they provide these vital nutrients in plants, those microbes can be considered biofertilizers[20].

The other example of plant growth promotion by PGPM is hormonal communication between the microbes and the plant. Plant physiology responds by sensing phytohormones, chemicals that can produce stimuli for the plant's different physiological needs such as growth (shoot and root), flowering, and fruit maturity[17,18,20]. Microbes induce metabolite expression, having a direct effect on the plant metabolism via microbial hormonal production. For example, several PGPRs produce auxin, which increases the plant's hormone level, leading to root growth and hence facilitating nutrient uptake[18,20]. Most of the microbes that produce phytohormones are found in the rhizosphere; however, endophytes can make them as well[17,18]. Besides auxin, another important class of phytohormones are cytokinins**,** which enhance shoot growth. Bacterial cytokinin production enhances shoot growth and increases root exudate production, attracting beneficial soil microbes[20].

This microbial interaction with the plant's metabolism is also fundamental to the plant's ability to resist various abiotic stresses. Another example of phytohormone communication is the case of ethylene. This hormone, usually expressed when a plant is under abiotic stress, causes several physiological responses in the plant, such as enhancing fruit maturation, inhibiting plant growth, leaf senescence, and flowering[20]. Several PGPRs contain an enzyme named ACC deaminase that degrades the compound ACC (1-aminocyclopropane-1-carboxylate), the precursor of ethylene, which the plant uses to overcome abiotic stress conditions and other physiological responses[18]. Examples of microbial roles in overcoming those conditions include (i) *Pseudomonas putida* increasing osmolyte accumulation in chickpea plants, improving water retention in drought conditions, (ii) *Pseudomonas fluorescens* producing ACC deaminase and promoting root elongation in flooded rice plants, and (iii) *Bacillus amyloliquefaciens* reducing salt stress by ion homeostasis, thus diminishing sodium levels in maize[20].

Additionally, the endosphere and the phyllosphere are also involved in fostering resistance to abiotic factors. For example, *Bacillus amyloliquefaciens* is an endophyte that neutralizes drought, cold, and salinity stress by accumulating melatonin phytohormones in grapevines[25]. Finally, epiphytes, the microbes living in the aerial plant surface, also promote resistance to abiotic factors at the phyllosphere level. One outstanding example is the case of *Actinobacteria* and *Bacteroidetes* secreting bacterial ice-binding proteins, helping Antarctic moss leaves resist cold[28].

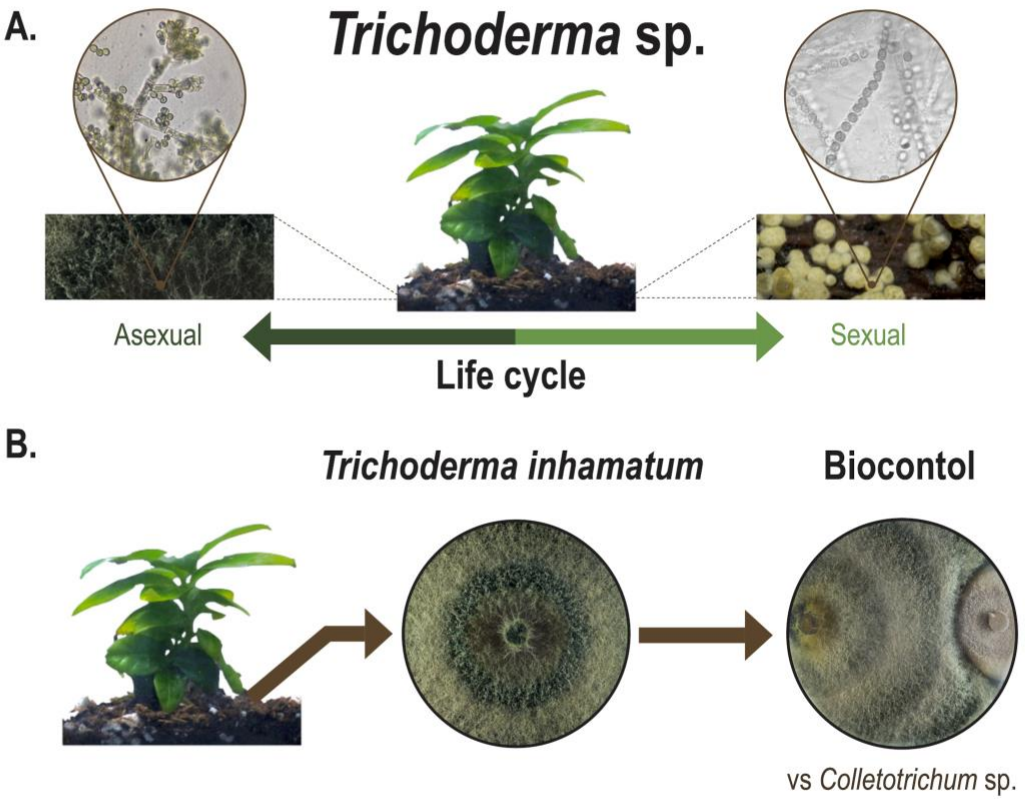
Microorganisms can also protect the plant against pathogens by triggering the plant's immune system[29]. Microbes from the rhizosphere, endosphere, and phyllosphere can activate induced systemic resistance (ISR). This is the plant's primary systemic defense mechanism, which responds to phytohormones such as jasmonate[17,18,25,29]. ISR establishes the early response to pathogen attack that can later lead to the activation of the plant's systemic acquired resistance (SAR), a second defense mechanism[7,17,29]. For example, *Pseudomonas spp.* found in the phyllosphere of *Arabidopsis* plants were responsible for inducing resistance in the presence of the pathogenic fungus *Botrytis cinerea*[18]. Endophytes of the genus *Trichoderma* also induce the ISR immunity in plants[29].

Plant–microbe interactions can also engender a chemical communication to counter biotic stresses such as pathogens, herbivory, and invasive plants (e.g. weeds)[21,30]. Microbes generally perform biocontrol properties via metabolite production (e.g., antibiotic production, alkaloids), lytic enzyme activity, and phytohormone-mediated systemic resistance[17,21]. Microbes, and particularly endophytes, are also able to change the plant's metabolism by producing metabolites that directly integrate into the plant's response to biotic stress[21]. One example of this biotic resistance is *Bacillus spp.* increasing the secretion of jasmonic acid and gossypol to reduce degradation of cotton leaves by the pathogen larva *Spodoptera exigua*[20]. Another well-known type of biocontrol is the microbe–microbe interaction, where single or multiple microorganisms act as biopesticides to avoid pathogen colonization[17]. Among the vast number of studied microbes, *Trichoderma spp.* and *Bacillus spp.* are known antagonists that supply biopesticide properties in a wide variety of plants, nevertheless with an interaction specific to the plant-strain-pathogen activity that cannot be generalized[17,31].

In brief, microorganisms interact with the whole plant or grow near its rhizosphere; but all of them produce multiple reactions that improve the plant's growth, performance, and health[7,12,17–20]. In addition, microbes can produce compounds that integrate into the plant's metabolome to resist biotic and abiotic stresses[21]. This symbiotic interaction between plants and microbes is crucial for plant fitness, to the point that current and future agricultural strategies must take these interactions into consideration for a successful sustainable agriculture.

Box 3. *Trichoderma*, a fungal genus with both biofertilizer and biofungicide activity. *Illustration by Rafael Montenegro based on photographs by Priscila Chaverri and Efraín Escudero-Leiva*

Trichoderma is a fungal genus known for its beneficial role in agriculture. It has both biofertilizer and biofungicide abilities, and several species have shown activity as bioinoculants. The life cycle of the fungus is mostly asexual, some species growing associated with plants as endophytes or saprophytes, or as natural parasites of other fungi; the sexual form is rare for most species (A). In terms of biocontrol potential, *Trichoderma* sp. have been described as fungi reducing several plant pathogens[31]. For example, in this figure *Trichoderma inhamatum* shows biocontrol activity against the plant pathogen *Colletotrichum* (right part of the plate) by reducing its growth (B). When *Trichoderma* is growing on the Petri dish (potato-dextrose-agar nutrient media), only the asexual stage is present.



III. *Current microbial applications in agriculture*

The use of microbes in agriculture is analogous to the use of probiotics for human consumption. These probiotics improve digestion and immune system and the target for human probiotics is in the gut. Similarly, the target of microbes in plants is mainly the roots, where plant–microbe interactions improve plant nutrition and promote the biological control of pests[1]. Knowing the critical role of microbes in soil and plants, there is still one question to answer: How could microbes be managed to enhance sustainable agriculture? Microbes have an incredible innate potential to improve nutrient acquisition and biocontrol ability in plants that may replace the functions of agrochemicals[7,17,18,20,29]. With this in mind, some companies are currently producing and commercializing bioproducts based on microbial properties[12,20]. Current sustainable agricultural strategies include microbial products both as probiotics, bringing beneficial microbes to the plant, and as prebiotics, targeting the soil quality itself[1,2].

Before we describe how a microbial-based product works, it is essential to understand its components. Focusing on the product itself, the formulations more commonly found contain either a solid or liquid carrier[32]. In the solid products, carriers could be peat, biochar, and polymers (such as alginate), which carry a liquid or lyophilized culture of the microorganism of interest. In the case of polymers, microbes are encapsulated into the polymers to protect them and increase soil colonization[20,33,34]. Another strategy to formulate these bioproducts is the direct use of the microorganism, mainly for microbes producing spores which increases the colonization success as demonstrated in *Bacillus spp., Trichoderma spp.* and mycorrhiza[12,32]. This solid approach is best suited for microbial products that aim for colonization in the soil. By contrast, liquid products (typically applied by atomization) have different targets, such as the soil, seeds or seedlings, plant tissues, or wounded tissues of the plants[20,33,34]. Overall, the formulation of the bioproduct in question depends on the plant target area, efficiency, and the success of the microbial colonization.

Regarding the strategies used in sustainable agriculture for improving soil quality and plant nutrition, some bioproducts are based on soil amendments, and thus are considered as prebiotics. Soil microbiome strategies aim to enhance soil quality and health by reducing soil erosion, remediating heavy metal contamination, improving nutrient cycling, and promoting disease-suppressive soils[8]. Any use of microbes in sustainable agriculture must take into account two fundamental aspects, as stated by Fierer[8]: the microbiota in the soil comprises a complex network of interactions, and specific soil conditions shape the composition and function of this microbiota. Some examples of this approach are the use of cyanobacteria and microbial soil consortia for restoring soil and reducing erosion[8,35] and the use of amendments from different microbial families like *Burkholderiaceae*, *Pseudomonadaceae*, *Xanthomonadales*, and *Lactobacillaceae* for reducing the presence of plant pathogens in the soil, forming a disease-suppressive soil[18].

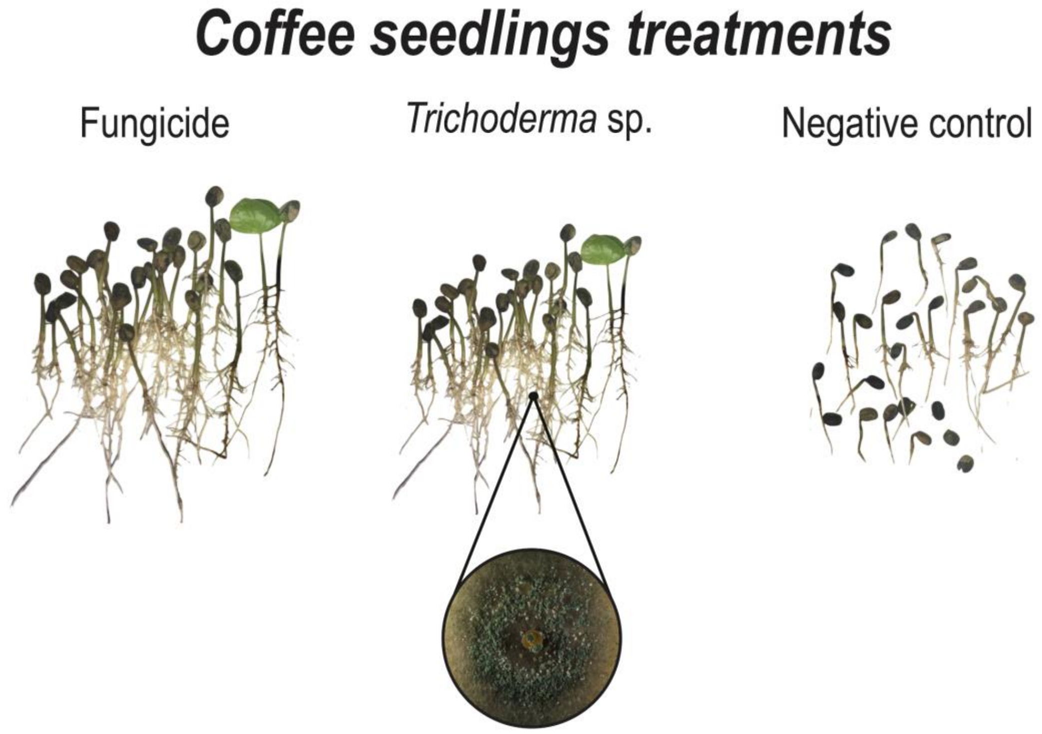
The use of plant bioinoculants is another strategy classified as probiotic. These applications are also referred to as microbial inoculants and follow two main strategies based on their function as biofertilizers or biopesticides[20,34,36,37]. It is necessary to mention that certain products follow only a molecule-based strategy, focusing on adding microbial compounds usually secreted by PGPMs to stimulate physiological responses in plants, including growth, which involves microbial quorum sensing communication[20,33]. The microbial bioinoculant strategy, by contrast, aims for more significant implications leading to colonization of strains in the phytobiome, especially in the roots throughout the rhizosphere. There are several examples of products and research with bioinoculants used as biofertilizers. The earliest microbial products were single bioinoculants, such as *Rhizobia* and *Azospirillum sp.*, which increased nitrogen uptake in leguminous and cereal crops, respectively[20]. In addition, there are consortia of microorganisms, like the bacterium *Bacillus amyloliquefaciens* with the fungus *Trichoderma virens,* which increase yield in corn and tomato plants[20].

Bioinoculant products can also include microbes to control plant pathogens or pests (i.e., biopesticides). Research reveals potential use as biopesticides by leveraging the natural biocontrol activity of different microbes against pathogens, herbivores, and weeds[20,21,30]. The majority of such products incorporate species of *Bacillus* and *Trichoderma* because of their antagonist properties[25]. There are other exciting examples with potential applications in agriculture. A consortium with several *Pseudomonas spp.* strains, colonizing both rhizosphere and phyllosphere, reduces *Phytophthora infestans* fungal development in potato crops[17]. Additionally, in maize, *Trichoderma atroviride* activates the production of volatile terpene compounds to reduce defoliation caused by *Spodoptera frugiperda*[21]. Another interesting approach is the control of weeds by microbes; for example, a consortium of three strains of *Fusarium oxysporum sp. strigae* significantly reduced parasitic weed emergence in maize crops[30].

Another alternative is the use of genetically modified organisms (GMOs) such as those produced by plant genetic engineering. With this approach, microbial genes are transferred into plants to confer resistance against pathogens. For example, we have cotton plants expressing Cry proteins from the genes of *Bacillus thuringiensis*, which show insecticidal activity against *Pectinophora gossypiella* (pink bollworm)[38]. There are fewer examples of this approach, however, mainly because it takes extended periods of time to study the effect of genetic engineering in plants, which have longer life cycles than microorganisms. In addition, there is a recent tendency to modify plant genes associated with microbial communication. This methodology aims to enhance biofertilizer activity and biocontrol mechanisms by improving communications between the plant and the microbiota[39]. The development of modern varieties through genetic improvement of crops considers plant–microbe interactions as a strategy for sustainable agriculture. Next-generation crops will include varieties that are less dependent on inorganic inputs (chemical fertilizers) and resistant to insect pests and diseases and that have major capacity to tolerate climatic perturbations. Of course, plants and their microbial symbionts must be co-propagated as life-long partners in future strategies for plant breeding.

Box 4. *Trichoderma* sp. as a bioinoculant in coffee seedlings. *Illustration by Rafael Montenegro based on photographs by Priscila Chaverri and Efraín Escudero-Leiva from a research project with Coopetarrazú agricultural cooperative (Costa Rica).*

Trichoderma here acting as a bioinoculant. In a coffee seedling, *Trichoderma* sp. was added to increase seedling development. As shown in the figure, the bioinoculant directly affected the overall plant's biomass (root length and foliar area). This observation was confirmed by analyzing the negative control, without any treatment, that showed smaller seedlings and comparing it to the treatment with the fungicide Rizolex®, which showed smaller root density. This positive effect of *Trichoderma* promoting growth in the coffee seedlings clearly shows the expected result of a bioinoculant in the plant's performance.



IV. *Next microbial strategies for an increasingly sustainable agriculture*

Commercially available products already use microbes as probiotics to improve plant fitness and health. Nevertheless, some disadvantages limit a broader utilization of microbial products. The complexity of the phytomicrobiome and the difficulty of modifying it in a standardized manner are key challenges[39]. For example, some microbial products have been developed with strains that are not native to the sites where they are applied; hence the efficiency may decrease or be null. Fortunately, new omics technologies, such as next-generation sequencing and systems biology, are opening new ways to identify the microbiome associated with a given plant and then define the critical beneficial microorganisms to be engineered or added[20,36,37,39]. This new vision, combined with state-of-the-art technologies, informs the latest tools and strategies for more sustainable agriculture.

Current microbial tools have some notable setbacks to overcome to increase their productivity: improving their formulation to find the best carrier for the microbes, identifying the best conditions to validate microbial activity, and predicting the bioinoculant dynamics in the field[1,4,20]. Consequently, microbial product development and validation are now moving into a phase of studying their effects directly under real-world conditions and in stressful environments. For instance, *Enterobacter sp.*, an endophytic bacterium, showed the ability to survive under arid abiotic conditions and promoted plant growth for alfalfa crops in the desert[4]. The ideal scenario is to identify microbes that thrive in the same stressful environment where the crop is located and which are thus already adapted to those stressful conditions[4,20].

Furthermore, makers of microbial-based products are focusing now on the design of artificial consortia bioinoculants, also called synthetic microbial communities (SynComs). SynComs are small consortia designed, based on microbial ecology and genetics principles, to produce desired agricultural traits[40]. This means that the focus is to include more than one type of microbe in the product[1]. This strategy tends to mimic the microbiome in natural conditions at a smaller scale to achieve a repertoire of functions[1,40]. Consequently, estimating the dynamics of adding a microbial consortium is fundamental to predicting its effect at the rhizosphere scale. Accurate predictions could lead to the best consortium combination that exerts a response on plant traits related to crop yield.

Another new trend is to design custom-made SynComs for a particular crop. Recent examples of such consortia applications in specific crops have focused on maize, tomato, and wheat[1,39]. In the case of maize, a consortium containing *Pseudomonas putida* KT2440, *Sphingomonas sp.*, *Azospirrillum brasilense*, and *Acinetobacter sp.* proved tolerant to drought stress[1]. Another example is the SynCom of 25 bacterial isolates that promoted plant growth and *Fusarium* resistance in tomato crops[4]. Overall, the SynComs strategy necessitates optimizing both the co-culturing of the microbes and the compatibility of the various microbial strains; once achieved, it provides several possible advantages, such as adapting the consortia to the local environment, increasing colonization success, and supplying unique traits to improve plant fitness[4].

The final approach is to modify or engineer the rhizosphere through the plant genotype. The permanent communication between the plant and the rhizosphere is a possible target for engineering[2]. This technique aims to genetically modify plants to release exudates or hormones that maintain and enrich beneficial microbes in the rhizosphere[1,2]. For instance, studies in common beans correlate resistant traits of the crop with selected microbial taxa that complement plant resilience[39]. Consequently, engineering for that dynamic communication could be another tool to enhance plant productivity, with or without bioinoculants, by having a designer rhizosphere[2].

To sum up, there are still challenges to address and surpass, such as completely understanding phytomicrobiome dynamics, factoring microbial products into agricultural management to increase productivity, estimating the time scale of the effect, and customizing products for specific crops. That being said, promising new omics technologies, combined with systems biology approaches, are constantly improving microbial-based products[20,36,37,39], especially with the development of consortia of bioinoculants and synthetic communities[1,2,4,6]. In addition, integrating omics data with machine learning and artificial intelligence technologies will increase data acquisition efficiency and speed up microbial product optimization to overcome these challenges[40].

Finally, to achieve sustainable agriculture, we need to have a clear vision that sustainability must be an integral practice[20]. Real sustainability involves not only the improvement of agricultural management (e.g., with the use of microbial products), but also social and economic aspects. From the agronomical point of view, sustainable practices must promote microbial diversity. Consequently, the best approach is to use more organic products than agrochemicals, and to use microbial-based products in particular as the best practice to benefit microbial diversity. Therefore, engineering the phytobiome is a powerful tool, bringing solutions in the form of plant pre- and probiotics in bioinoculants with different functions to enhance plant fitness[1,2,6]. Microbial products, including the most promising new approaches, are essential tools to tackle significant agricultural challenges such as attaining food security, increasing sustainability, and sustaining production under climate change[9,20,32,39].

Relevance for Sustainable Development Goals and Grand Challenges

Agriculture without the intervention of microorganisms is practically impossible to imagine. From the soil profile to the plant's health and resilience, microbes carry out essential roles. Those features make microorganisms a valid alternative to conventional management practices using agrochemicals (i.e., fertilizers and pesticides)[19,41]. Therefore, increasing our knowledge of the microbiome's roles and its interaction with plants will be crucial to enhancing crop management with microbial-based solutions to overcome agriculture challenges[41]. Consequently, to understand the impact of microbial-based strategies in sustainable agriculture, it is imperative to define some considerations and to know their impact as they relate to aspects of the Sustainable Development Goals framework established by the United Nations (UN).

Goal 1. **No poverty.** Crop productivity must increase production by 70 to 100% by 2050 to meet the world's food requirements[41]. Increasing production yields, then, is a priority for food security. Agrochemicals such as fertilizers and pesticides usually increase yields but are associated with disadvantages for the environment and crop management, generally driven by biodiversity loss. Microbial-based solutions for sustainable agriculture are a promising alternative for increasing overall crop yields. Triveldi *et al.*[41] state that developing countries need to improve quality and quantity yields without adding additional costs. Therefore, microbial alternatives are the key to strategies to ensure the food security and access of the entire world, including developing countries.

Goal 2. **Zero hunger.** Microorganisms are critical players in many industrial and agricultural processes required for food production. Focusing on crop management, microbial-based products will enhance crop yields. These products will reach developing countries too. Therefore, this strategy aims to increase food access with the ultimate aim to satisfy world food demand, thereby reducing—or even ending—hunger.

Goal 3. **Good health and well-being.** Crop management is essential for the quality and safety of the final product. Reducing the number of agrochemicals will guarantee lower retention of said chemicals, usually associated with health problems, in the final product. Microbial products and strategies aim to replace those agrochemicals, directly affecting our good health and well-being.

Goal 4. **Quality education.** Awareness of microorganisms' presence and their role in agriculture is the first step to promoting sustainable agriculture. The next step is to educate the society about the role of microbes in soil fertility and plant health and about the microbial network associated with crop management. At the same time, knowledge should first be translated into agricultural practices and later into promotion of microbial solutions to overcome the next challenges in agriculture[41,42].

Goal 6. **Clean water and sanitation.** Microbial solutions in agriculture will avoid possible agrochemical contamination of the land and consequently of various bodies of water. Specifically, movements toward sustainable agriculture aim to reduce the use of agrochemicals, thus mitigating the risk of that type of contamination. Microbial solutions for sustainable agriculture secures access to clean water indirectly and without the need to sanitize agrochemicals.

Goal 8. **Decent work and economic growth.** The use of microbial-based products first requires their manufacture. Biotechnological and agricultural companies are already producing microbial alternatives and are conducting research to create new sustainable goods. Startup firms, as well, are venturing into sustainable options based on microbes. The availability of these kinds of products on the market implies an impact on the economy. Their increased adoption will increase their production, translating eventually into economic growth which would have a gradually more significant effect as time passes.

Goal 9. **Industry, innovation, and infrastructure.** Using or engineering microbes in agriculture implies the discovery of new applications or technologies. Furthermore, the research behind these new approaches is innovative. Aside from the novelty of the various applications, this presents an opportunity for biotechnology companies or startups to develop and commercialize innovative biological products. Eventually, those biotechnological companies or current companies venturing into microbial alternatives will influence economic growth, which will also have relevance for Goal 8, "Decent work and economic growth".

Goal 11. **Sustainable cities and communities.** Agriculture is essential to guaranteeing food production. Examining the various roles of microbes in crop management makes clear that their presence is fundamental for any agricultural production. Microbial products and alternatives increase plant wellness and, consequently, farm productivity. Unlike conventional farming practices, microbes have a sustainable impact on crop management, leading to positive effects on the environment, society, and the economy[41].

Goal 12. **Responsible consumption and production.** As mentioned in the previous goal, the microbial alternative's distinctive feature is its sustainable positive impact. Intensive conventional practices using chemicals lead to degradation of the environment, overall plant performance, and food quality. Conversely, microbes can increase yields by enabling nutrient acquisition and pathogen control without losing biodiversity associated with chemical uses. Thus, microbial strategies and products positively affect the environment and even human health via healthier products, ensuring food production and security.

Goal 13. **Climate action.** Notably, in terms of climate action, microbes are up-and-coming alternatives to replace the considerable amount of synthetic chemicals used in agriculture. Several microorganisms also enhance plants' capacity to adapt to stressful conditions, making microbial bioinoculants and GMO plants promising alternatives to help crops overcome changing weather conditions[9]. Finally, the soil microbiota is essential for bioremediation of soil contamination and for its participation in biogeochemical cycles. Thus, microbial actions in the soil are also crucial in terms of carbon fixing. Overall, microbial strategies in sustainable agriculture are potent tools to mitigate global warming and overcome changing weather conditions associated with climate change.

Goal 15. **Life on land.** Microbes' role in sustainable agriculture has a clear and direct relationship to the "Life on land" goal. Using microbial alternatives to various agrochemicals advances the final goal of reducing the use of those chemicals, with positive follow-on effects on the soil and water environments. The use of agrochemicals in agriculture has different drawbacks, like contamination, biodiversity reduction, plant wellness reduction, and retention of toxins in the final product. By contrast, microbial alternatives allow for sustainable management focused on maintaining biodiversity, reducing contamination risks, and improving production yields. These products can help move agricultural production into the sustainable circular economy model required to achieve the goals of the SDG framework[42]. Overall, sustainable agriculture aims for crop management that is conscious of the environmental situation and the world's food requirement, and in this context microbial alternatives are emerging as ideal strategies.

Potential Implications for Decisions

1. Individual

a. Promote the use of organic or microbial-based products for crop management, even for your backyard garden, always seeking to produce and consume healthier products and inflict no or minimal impact on the environment.
b. Educate yourself and your family or close friends about the relevance of microbiota to soil fertility and plant fitness and about microbial-based products for greener crop management.

2. Community policies

a. Encourage the consumption of agricultural products managed with microbial alternatives and with sustainable management using fewer agrochemicals. This practice promotes the consumption of healthier products.
b. Stimulate the production, commercialization, and use of microbial-based products that use fewer or no agrochemicals, aiming to preserve biodiversity and the environment.

3. National policies related to human health and environmental protection

a. Facilitate and promote the use of microbial-based products and strategies in agriculture. The whole process, including the production, commercialization, and sale of the microbial products, should be promoted to increase their presence and competitiveness in the market. The final goal of promoting this kind of development would be to reduce the environmental footprint caused by agrochemicals and guarantee human health by consuming healthier products.
b. Promote the awareness of the role of microbes in agriculture through educational programs. The subjects covered should focus on relevance of microbiota to soil fertility and plant fitness and on the use of microbial-based products for sustainable crop management. Finally, the overall strategy combining these two policies, commercial and educational, should increase awareness of the impact of microbial methods on agriculture and biodiversity.

Pupil Participation

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

2. Pupil stakeholder awareness

a. Are microorganisms present in the soil? Why would they be there? Explain.
   Search for a positive answer and further discuss reasons why they would be present and have specific roles.
b. Does the plant have associated microorganisms? Shouldn't we eliminate them to protect the plant?
   First, explain the soil microbiota, then ask for the plant microbiota. Finally, research or give a presentation about the relationships between microbes and plants (e.g., symbiosis, mutualism, and pathogenesis [the only scenario where the microorganism should be treated or removed]).
c. How could a microorganism promote plant wellness? And how could a microorganism's intervention influence the plant or its fruit?
   Explain the plant microbiota, then ask for ideas (searching for examples of symbiosis) to correlate it with plant health by introducing the concept of nutrient uptake.
d. How can microbes be used to control other plant pathogens?
   Explain the biological interactions first and later search for examples of microbial interactions. One approach could be to mention one example at a time and discuss what occurs in each of them (competition, depredation, and parasitism).
e. What are some sustainable approaches to healthier products? What is a microbial-based product for agriculture? Are microbial-based products a real alternative for crop management?
   First, define what crop management is and what it implies, then ask for a definition of a microbial-based product in agriculture, and finally ask for the advantages of microbial products in crop management. After the discussion, students should be able to relate the benefits of microbial tools to the Sustainable Development Goals.

3. **Exercises and/or Homework**

a. Microorganism in the soil. How could microorganisms contribute to the nutrient cycles? How could a microorganism resist adverse conditions in the soil?
b. What is the phytobiome? What factors compose it?
c. What is the plant microbiota? Why could microbes be considered biofertilizers?
d. Why is the rhizosphere so defining for plant fitness?
e. Microbial pathogen control: the new pesticides?
f. What is a probiotic? How can microbes act as probiotics for plants?
g. How is an agricultural microbial-based product made? How many types of product are already in the market?
h. Why does the use of microbial-based products have a lower environmental impact?
i. How could microbial products in agriculture contribute to the Sustainable Development Goals framework?

4. **Class experiments (select appropriate experiment from the Class Experiment list)**

a. Growing a soil menagerie: Microbial life in a Winogradsky Column
https://www.sciencebuddies.org/science-fair-projects/project-ideas/Geo_p038/geology/growing-a-soil-menagerie?from=Blog
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. Bacteria can fix it! Nitrogen fixing bacteria vs nitrogen fertilizers
https://www.sciencebuddies.org/science-fair-projects/project-ideas/PlantBio_p010/plant-biology/nitrogen-fixing-bacteria-fertilizers?from=Blog#summary
Topics: microorganisms, rhizobacteria, fertilizers, biofertilizers, plant growth and wellness

The Evidence Base, Further Reading and Teaching Aids

1. **Video:** Soil is a living organism – Plant Health Cure Film
https://www.youtube.com/watch?v=8ugaL6wsXME
Topics: Crop Management, Rhizobacteria, Mycorrhiza, Soil Humus and Sustainable Agriculture

2. **Video:** How we can make crops survive without water – Jill Farrant, TED Global
https://www.ted.com/talks/jill_farrant_how_we_can_make_crops_survive_without_water#t-823910
Topics: Food security, Climate change, Drought tolerant crops, GMO plants.

3. **Video:** The case for engineering our food – Pamela Roland TED 2015
https://www.ted.com/talks/pamela_ronald_the_case_for_engineering_our_food#t-1053583
Topics: Food security, GMO, Sustainable agriculture, Microbial gene-based GMO plants, Biostimulants.

4. **Video:** Microbial biofertilizer – Oak Ridge National Laboratory
https://www.youtube.com/watch?v=5WpADBTd5LY
Topics: Biofertilizers, Symbiosis, Research, Field trials.

5. **Video:** Importance of biopesticides for sustainable crop protection – AHDB Horticulture

https://www.youtube.com/watch?v=pROKcGd7BL8
Topics: Microorganism based biopesticides, Research, Biopesticides technologies and management.

6. **Video:** From farm to table – Jim Richardson, National Geographic
https://www.nationalgeographic.com/environment/habitats/sustainable-agriculture/
Topics: Agriculture management, Food security and safety, GMO, Soil health, Fungi, Sustainable Development Goals.

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Glossary

- **Abiotic factors:** Physical and chemicals factors of a particular place or environment
- **Biotic factors:** All living components in an environment, including macro- and microorganisms
- **Phytobiome:** Refers all living organisms, inside, on, or around a plant and their interaction with the environment
- **Microbiome:** the total microbial genomes that inhabits a defined habitat
- **Rhizosphere:** Defined as the region near the root system where soil microorganisms, also known as root microbiota, are associated to root or the nearby region
- **Soil fertility:** ability of the soil to bring nutrients required for plant growth and wellness
- **Metaorganism:** Multicellular organism that possess a symbiotic microbiota performing specific functions in benefit of the host multicellular organism
- **Biofilm:** layer or matrix of molecules produced by bacteria or other microorganisms that supports grows and sticks to surfaces
- **Soil horizons or macroenvironments:** Distinctive layers of the soil in a depth profile, each of the layers having different chemicals, physicals and biologicals properties
- **Microenvironments:** The soil has different microenvironments even few centimeters apart, in the soil particle or even in different parts of a single the soil particle, each microenvironment having specific chemicals, physicals and biologicals properties
- **Soil aggregate:** Particles formed by the combination of mineral, organic as soil organic carbon and inorganic substances. The gathering of these particles defined largely the soil structure and its physic-chemical properties
- **Symbiosis:** close and long-lasting biological interaction between two different organisms that can be either beneficial or harmful
- **Mutualism:** Type of symbiosis relationship where both species involved take mutual benefit of the relationship
- **Parasitism:** Type of symbiosis relationship where one specie take benefit and the other one is harmed
- **Metabolism:** Series of chemical reactions require to transform a precursor compound into a chemical or molecule of interest, for example amino acids, antibiotics, hormones, enzymes, among a wide variety of other examples
- **Biogeochemical processes:** Series of reactions involved in nutrient cycling for essential elements on earth. Reactions can occur within biotic and abiotic cases, specifically for soil biogeochemical processes microorganism have key participation in the reactions
- **Nutrient cycling:** Referring mainly to nutrients like (Nitrogen, phosphorous, carbon, Sulphur and iron) and how the inorganic form moves to organic forms and backwards, as a cycle, reaction occurring within biotic and abiotic factors
- **Diazotroph:** Microorganisms reducing atmospheric nitrogen gas into biologically available forms.
- **Enzymes:** type of proteins that speed up the reactions that take place within or outside cells

- **Saprophytic fungi:** Fungi specialized for feeding on dead organic matter, as plants and animals, and producing sources of carbon compounds, nutrients and enzymes
- **Actinobacteria:** Phylum of gram-positive bacteria experts in degrading complex structures bur with a slow metabolism, they are usually present in the soil forming (soil humus) and later decomposing its complexes structures for their bioavailability
- **Soil humus:** Fraction of the soil rich in carbon compounds and nutrients, formed by the decomposition of dead organic matter mediated by microorganism. Moisture essential for soil fertility
- **Competition:** Type of symbiosis relationship where one specie takes benefit in detriment of the others fitness, as for example competing for nutrients
- **Colonization:** Capability of microorganisms to arrive at a new niche, stablish into the superficies, then grow using the available resources and finally interact symbiotically with other microorganisms
- **Antibiotic:** Are chemicals, naturally produced by bacteria and fungi, that kill or inhibit bacterial growth. If the compound affects fungi it is refer as antifungal instead
- **Lytic enzymes:** enzymes specialized in breaking down of the cell membranes
- **Antagonist:** Referring to microorganism with the natural availability of been a direct predator, competitor or parasite of a plant pathogen and so on interfering with the pathogen growth
- **Disease-suppressive soils:** Defined soils with reduced susceptibility of plant pathogens usually associated to the presence of certain bacterial families and furthermore as a result of the microbial community present in the soil
- **Soilborne pathogens:** Plant pathogens usually found in the soil that can include bacteria, fungi, oomycetes, nematodes and insects
- **Plant microbiota:** Refers to the totality of the microorganisms interacting with symbiosis to the plant host
- **Photosynthesis:** metabolic reactions capable of using energy from the sun to synthetize nutrients from carbon dioxide and water
- **Niches:** Physical places where microorganisms or organisms interacts with abiotic and biotic factors in order to interact with community, survive and growth
- **Biofertilizer:** Microorganisms or any of their molecules that promote the nutrient uptake and plant wellness as a result of their growth
- **Biopesticides:** Microorganisms or any of their molecules that inhibit plant pests (pathogens, insects) growth and its ability of colonization
- **Pathogen:** biological agent that causes a disease to its host
- **Siderophores:** Chemical compounds that can neutralize charged nutrients that are difficult to incorporated alone and can be incorporated then to the plant via its xylem by physical properties as neutral compounds
- **Xylem:** Plant vascular tissue that transport water and molecules by physical properties from the roots to the areal part of the plant
- **Nodules:** Specific symbiosis with Rhizobia strains capable of colonizing the root and forming specialized structures named nodules that facilitates nutrient uptake, specially nitrogen uptake
- **Mycorrhiza:** group of fungi characterized by living inside or surrounding plant root systems that helps to increase the root system rise and characterized for increasing the nutrient uptake as well as biocontrol activity
- **Endosphere:** Sum of all endophyte microorganisms associated in the inside of plant tissues and organs

- **Hyphae:** Filament branch structure that make the mycelium, the vegetative part of a fungus.
- **Phyllosphere:** Refers to the above ground organs or part of the plants and their associated microorganisms
- **Phytomicrobiome:** Refers only to the microbes living inside, on, or around a plant
- **PGPM:** Referring to Plant Growth Promoting Microbes, which are microorganisms capable of enhancing plant growth and wellness by nutrient acquisition, hormones production, abiotic stress resistance and biocontrol activity
- **Phytohormones:** Chemical compounds produced under certain circumstances in order to achieve a physiological response or need as growing, flowering, fruit maturity and resisting stressful conditions
- **Bioavailability:** Biological forms of nutrients that can be incorporated by the root system, usually accomplished by enzymatic reaction of chemical compounds
- **Auxin:** Phytohormone responsible for cell elongation, root growth and bud formation
- **Cytokinin:** Phytohormone responsible for shoot growth, nevertheless the plant response is based on a cytokinin/auxin ratio. It has been described that it promotes root exudates production aiming to attract PGPM
- **Ethylene:** Phytohormone responsible for fruit maturity and growth inhibition under stressful conditions
- **Osmolyte:** organic compounds with low molecular weight having an influence in biological fluids fluxes
- **Ion homeostasis:** Maintaining or regulating the ion concentration in a biological system searching for the steady state
- **Biocontrol:** Naturally occurring event defined as the elimination of plant pathogens by microorganism and any living organisms
- **Induced systemic resistance (ISR):** Plant basal defense mechanism with more general physiological trait changes for broad spectrum pathogens. Mostly acquired by the mediated communication with microorganism
- **Systemic acquired resistance (SAR):** Plant defense mechanism with a specific response to the pathogen and mediated by phytohormones. Activated by the pathogen communication with the plant
- **Plant probiotics:** Microbes added to enhance plant fitness and wellness as an analogy of human probiotics
- **Prebiotics:** Microbes added to enhance soil quality usually referred as soil amendments
- **Formulations:** Type of microbial product and how it is prepared
- **Peat:** Partially degraded organic matter usually originated from vegetation, and in this case used as a solid carrier for bioinoculants
- **Biochar:** Charcoal produced by the thermal degradation of vegetal matter in order to obtain a product rich in carbon compounds
- **Polymers:** Substance or material composed of multiple repeating subunits of macromolecules
- **Alginate:** Polymer classified as a polysaccharide made of subunits of two carbohydrates
- **Lyophilized culture:** Removing water from liquid or frozen cultures in order to preserve microorganism for longer times in a steady state
- **Spore:** microscopic biological particle that allow fungi, certain bacteria, algae and protozoa to reproduce
- **Atomization:** Spreading liquid into fine particles as fine droplets

- **Soil amendments:** Bioinoculant of microorganism to promote the soil quality, fertility and health
- **Bioinoculants:** Microbes added to interact directly or indirectly with a plant and bringing a beneficial trait
- **Quorum sensing:** Chemical communication between different microorganism involving expressing a molecule that is going to be detected by a receptor in other microorganism aiming for a microbial response
- **Consortia:** Two or more microbial groups or species living symbiotically, usually in mutualism or commensalism for microbial products
- **Next-Generation Sequencing (NGS):** Massive sequencing (Knowing the DNA sequences of microorganisms) in parallel as a high-throughput platform that has change the genomics area, generating lots of genetic information required to study microbiomes
- **Systems biology:** New biological approach that seeks to understand biological systems as interconnected nodes, defining then the key nodes to the engineered, nodes meaning microbes, reactions or any biological process
- **Synthetic microbial communities (SynComs):** Small consortia grown in the laboratory and based on multiple microbes, that together they bring a desirable trait to a defined crop