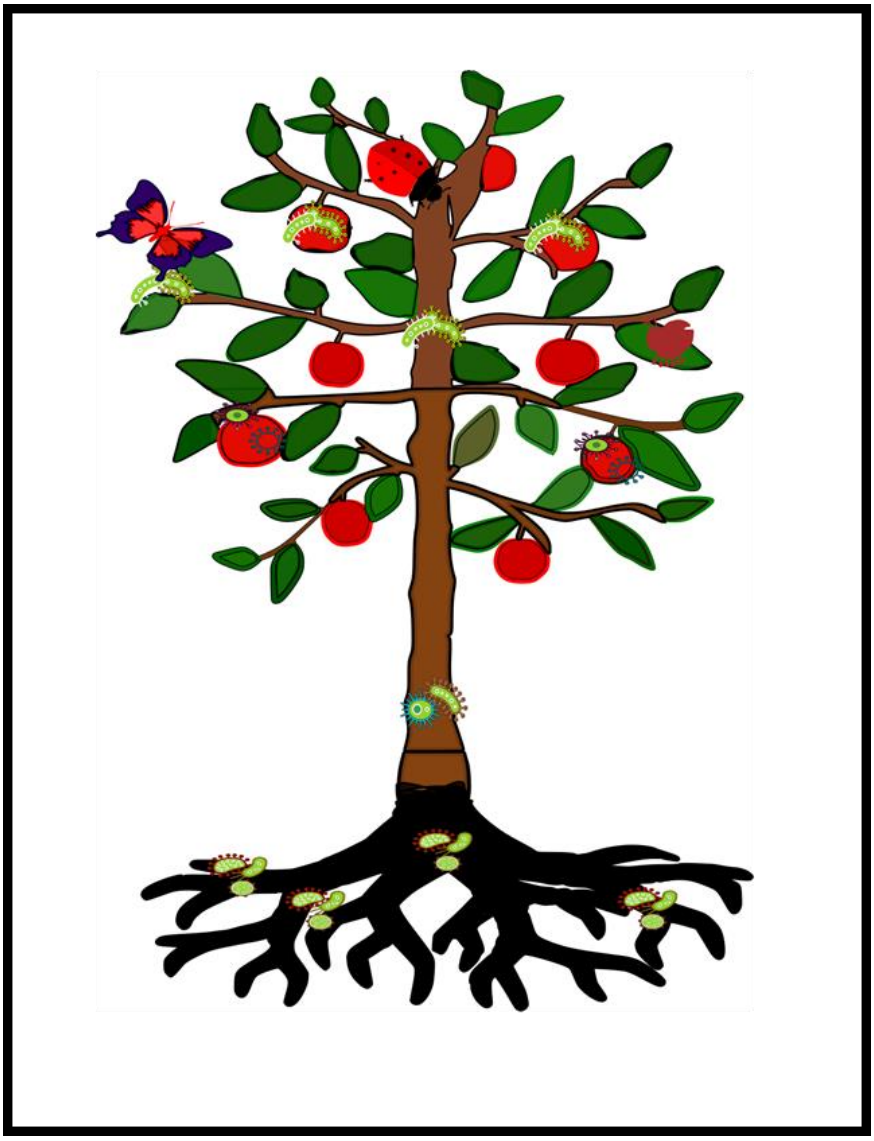
The Plant Microbiome

Miss: We cannot live without plants, but can the plant live without microbes?



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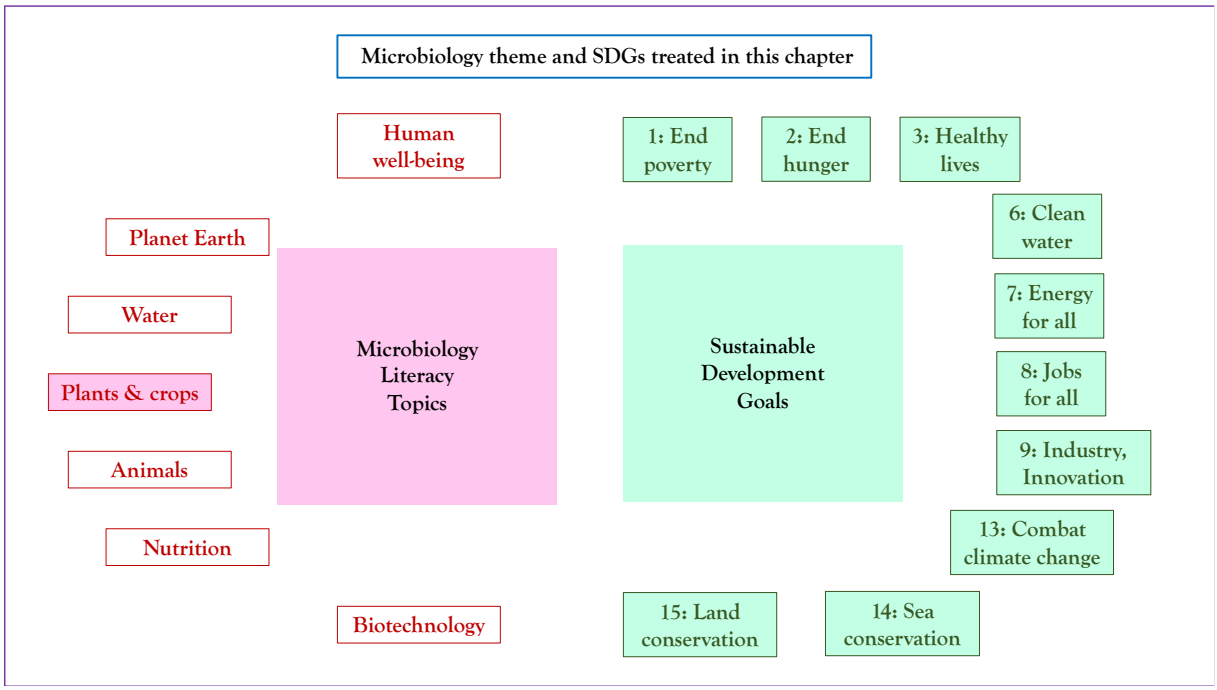
Storyline

Plants are essential for all human beings, animal and insects. They not only serve as a source of food, but are also used to make medicines, cosmetics, bio-fuel and clothing. Plants play a very important role in regulating climate conditions on Earth by removing carbon dioxide from the atmosphere and converting it during photosynthesis into oxygen and cellular material. Plants reduce soil erosion through their extensive root systems. These supply the plant with nutrients from the soil but also provide nutrients to many soil organisms. The soil organisms in turn are responsible for nutrient cycling and supply the plant with nutrients. A large proportion of soil organisms are microorganisms such as bacteria, fungi, protists and viruses. These microorganisms are found not only in soil lacking vegetation, but also in and around the plant in leaves, flowers, stems, roots, fruits and seeds. The entity of microbial communities colonizing the plant environment is called the plant microbiome, with different communities colonizing different plant tissues and compartments. Plant microorganisms can have positive effects on plant health and productivity (see Box 2), which are important for agricultural production and can contribute to achieving United Nations Sustainable Development Goals (SDGs).

The Microbiology and Societal Context

The microbiology: The interaction of the plant with microorganisms ranges from mutualism, neutralism, competition to antagonism. *Sustainability issues:* Plant microorganisms are tightly associated with plants and are a key component of any sustainable crop production, reducing or eliminating the need to apply fertilizers or pesticides. Better and more sustainable plant growth also contributes to reducing air pollution and global warming. Microorganisms may also contribute to the production of biofuel produced from plants.



The Plant Microbiome: the Microbiology

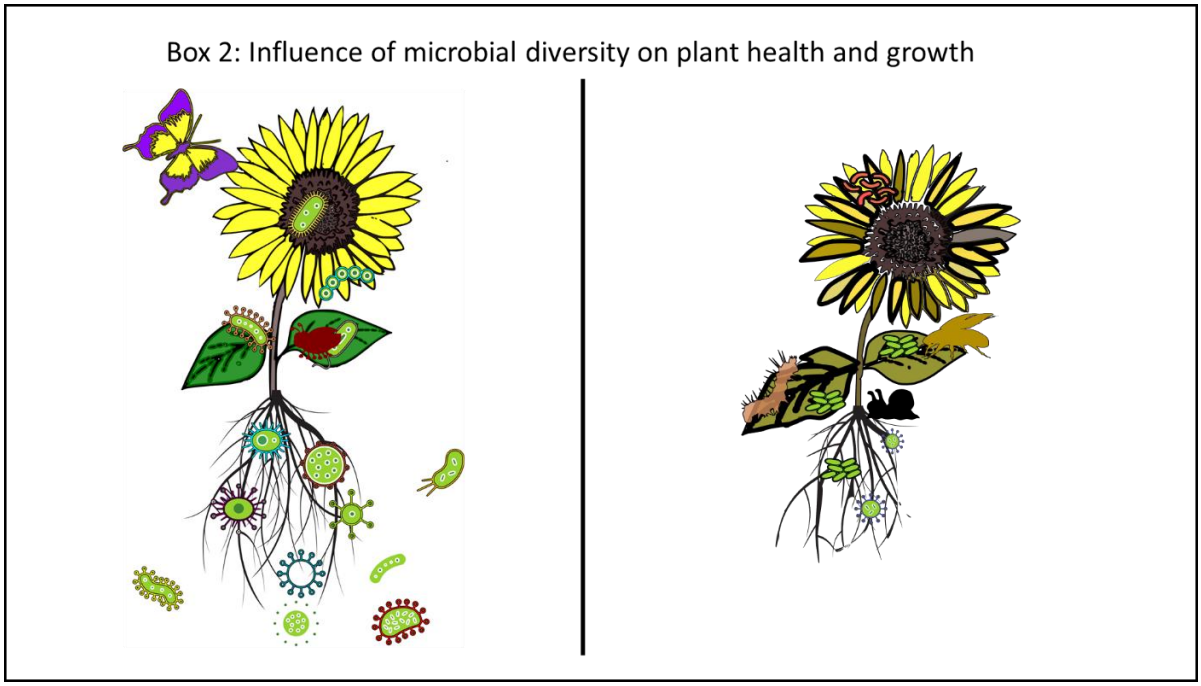
1. ***Where the microbes can be found.*** Plants depend on their microbial partners to survive and defend themselves against diseases and other stresses like drought or high temperatures. All plants are internally and externally colonized by microbial communities comprising different bacteria, archaea, fungi, viruses and protists (amoebae, flagellates, and the like). Particularly the rhizosphere, i.e. the soil around the root system, which is influenced by substances secreted by the root, i.e. root exudates, is heavily colonized by microorganisms. In addition, many different microorganisms colonize the surfaces of plants, e.g. leaves or roots. Furthermore, microorganisms can enter plants and colonize the plants internally in different tissues and organs.

The importance of the microbiome for the plant can be estimated by comparing the number of genes present in the plant and microbial genomes (the totality of all the genes in the chromosomes). The number of genes per plant genome varies between 25,000 genes, in the case of the model organism *Arabidopsis thaliana,* and 100,000 genes for the wheat genome. A bacterial genome contains 3,000 to 8,000 genes. However, thousands of different microorganisms are found in and around the plant, so the number of microbial genes far exceeds the number of plant genes, pinpointing the importance of the microbiome for plant health and productivity. The number of microorganisms varies in the different plant compartments. The highest number of microorganisms is found attached in the rhizosphere. In one gram of rhizosphere soil around 10^8–10^{12} bacterial cells are found, whereas the number of microbes in the leaves is estimated to be 10^6 to 10^7 cells/cm^2. Flowers, fruits and seeds are also colonized by microorganisms, which are well adapted to the specific environment.

2. ***Where do the microbes come from?*** The plant recruits most of the microbes from the surrounding soil. Roots of the plant secrete around 20 to 40% of the carbon (C) produced by its photosynthesis into the soil environment. These root exudates comprise compounds like sugars, amino acids and organic acids, which are used by the microbes as nutrients. Therefore, the rhizosphere is a hotspot of microbial diversity and activity. However, some microbes are able to enter the plant tissues and colonize the interior of the roots. From there, some can translocate to other plant parts, such as stems, leaves or seeds. Alternatively, microorganisms on the plant may also originate from air. These may colonize the leaf surface or enter the plant via the stomata or flowers. A small part of the plant microbiota may be passed vertically from one generation to the next through seeds.

3. ***What is the role of microorganisms for the plant?*** Just as the human microbiome is important for human health, so the plant microbiome is essential for the growth, health and stress resilience of the plant. Plant microorganisms can act as pathogens, beneficial microorganisms, or have no obvious consequence for their host. Pathogens are well known and can be devastating, although only represent a small proportion of the entire microbial community. One key function of beneficial microorganisms is that many microbes support plant nutrition by mobilizing nutrients from the surrounding soil, or providing nutrients via e.g. nitrogen fixation – the conversion of atmospheric nitrogen gas, N_2, to ammonia, which the plant can use as a source of nitrogen for the production of plant proteins and other nitrogen-containing compounds. The latter process is well known in legumes, where N_2-fixing rhizobia inhabit nodules, the white swellings we can see on the roots of clover and pea/bean plants, which the bacteria induce the plant to produce. For the mobilization of nutrients, particularly of phosphorus (P), arbuscular mycorrhizal fungi (AMF) are well known. AMF form a symbiosis with many plants and mobilize P from biologically poorly available phosphates. Also, phosphate solubilizing bacteria mobilize P or also elements like Fe.

Plant microbiomes play an important role in protecting plants against pathogens and diseases. Some microorganisms can directly attack plant pathogens, by producing secondary metabolites, some of which act like antibiotics against some fungal pathogens. Other microorganisms are able to outcompete pathogens by occupying the same niche. Some microorganisms produce (secondary) metabolites to boost plant defense mechanisms. Apart from these beneficial effects, there are many microorganisms known to promote plant growth or to improve stress resilience (e.g. to drought) by modulating hormone levels in plant tissues or degrading stress compounds produced by the plant.



Box 2: Importance of microbial diversity for plant health. The plant on the left is associated with a wide range of microorganisms, which help it to grow and stay healthy. The plant on the right, however, is characterized by a lower microbial diversity, looks unhealthy and its growth is impacted.

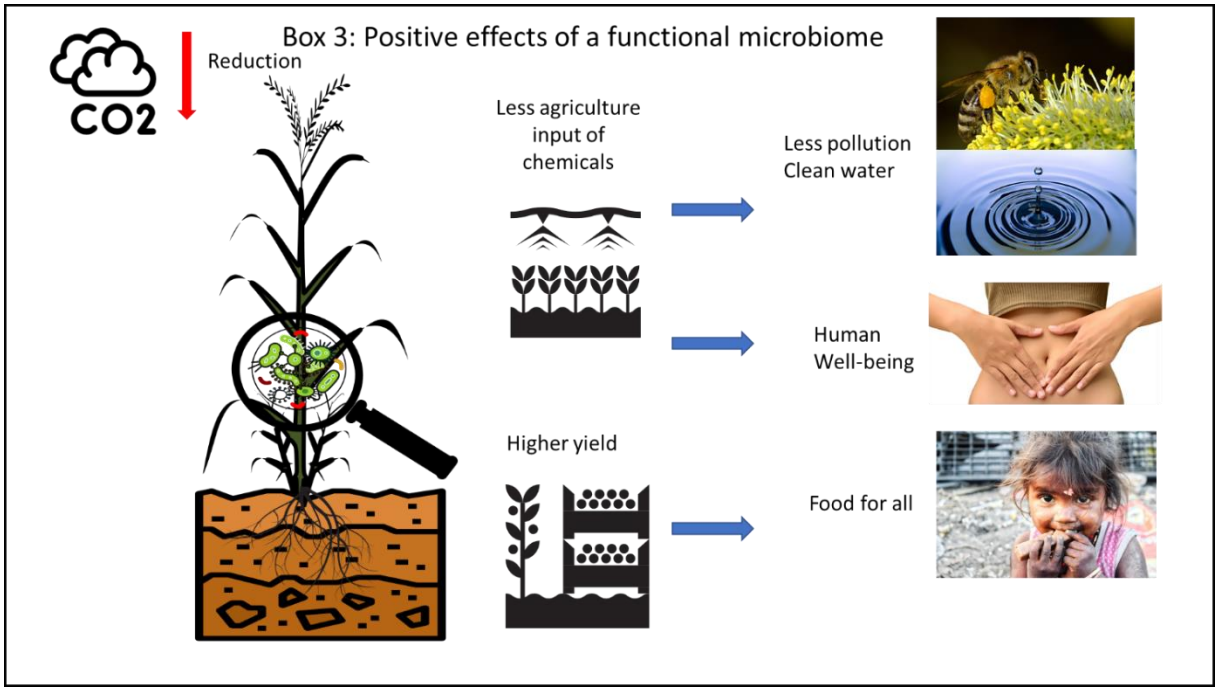
4. ***Which factors influence the microbial composition?*** The establishment of microorganisms around and in the plant is not random but rather controlled by plant and the surrounding environment. The soil type, the plant compartment, host genotype/species, plant immune system, plant developmental stage, climatic conditions, and other factors all influence microbial composition. Plants primarily steer microbial communities via root exudates and metabolites they produce, which in turn are influenced by the physiological condition of the plant. The physiology of a plant greatly depends on stress conditions, e.g. caused by the presence of a pathogen or drought, and a stressed plant will recruit microbial communities different to those recruited by a non-stressed plant.

5. ***How humans influence the composition of the plant microbiome.*** Over the last decades, humans have tried to intensify agriculture in order to obtain high crop yields. Farmers have applied high loads of inorganic fertilizer or pesticides to obtain optimal growth conditions for their crops. However, most agricultural practices do not consider the positive impact of microorganisms for plant growth. Inorganic fertilizers and especially pesticides have a negative effect on microbial communities, reducing or altering their diversities and thereby potentially destroying important microbial functions. Also, herbicides can impact the composition of the microbiome. They target specific pathways in the plant to kill the plants, but also microbes share some of these pathways.

For a sustainable and eco-friendly production of food it will be important to maintain the beneficial interactions between microorganisms and plants. This aspect has to be considered in breeding programs selecting new varieties, which grow well in soils with reduced fertilizer and pesticide input and making use of beneficial interactions. Also, farming practices protecting microbial diversity and functions need to be adopted.

6. ***How does the plant microbiome influence human health?*** The plant microbiome also influences the human microbiome. By eating raw vegetables and fruits, plant-associated microorganisms enter the human body through the digestive tract. These microorganisms can have positive effects on human health but, occasionally, can also include human pathogens that cause outbreaks of infectious disease. Plant-derived secondary metabolites are particularly valuable for human health and these metabolites are not only produced by the plant itself, but also by microorganisms. Microorganisms are also known to boost the production of these compounds. Furthermore, microorganisms can be providers of essential vitamins such as vitamin B12. Particularly healthy are fermented plants, e.g. sauerkraut or kimchi, because they provide a high number of diverse health-promoting microbial strains (e.g. lactic acid bacteria) acting as probiotics in the human gastrointestinal tract

7. ***The plant microbiome and ecosystem functioning.*** The loss of biodiversity has a negative impact on ecosystem functioning. A higher biodiversity is associated with higher resilience to stress conditions. Plant-associated microorganisms also provide plants a tool for more rapid adaptation to biotic and abiotic stress. Furthermore, plant-associated microorganisms play a role in nutrient cycling, which is important for the plant and the whole ecosystem, and is also important for reduced greenhouse gas emissions.



Box 3: Positive effects of a functional microbiome.

Relevance for Sustainable Development Goals and Grand Challenges

Considering the important role of microorganisms for soil health and functioning, the plant microbiome and associated soil microbes relate to a number of SDGs as outlined below:

- **Goal 1: No poverty.** Plant beneficial microorganisms can enhance agricultural productivity and food yield stability and thereby increase the income of farmers, smallholders, homesteaders, and so on.
- **Goal 2: End hunger, achieve food security and improved nutrition, and promote sustainable agriculture.** Using beneficial microorganisms to maintain a healthy microbiome in food production can increase yield and yield stability, especially in areas where difficult growing conditions prevail. Microbe-based sustainable crop production systems will contribute towards achieving food for all.
- **Goal 3: Good health and well-being.** By replacing chemicals with microbial solutions, food products will be healthier and more sustainable.
- **Goal 6: Clean water and sanitation.** By reducing the need for chemical pesticides through the targeted use of beneficial microbes, the use of fertilizers and pesticides can be reduced, thereby decreasing environmental pollution. Also, lower chemical inputs will result in less polluted soil and water.
- **Goal 7: Affordable and clean energy.** The production of energy from plants is the most sustainable source. The cultivation of plants in a healthy environment with the appropriate microbiome promotes the production of plant raw materials for renewable energy production.
- **Goal 8: Decent work and economic growth.** Better, more secure and varied jobs are urgently needed in rural areas where most of the world's poor live and work. Agriculture is the biggest employer, especially in low-to-medium income countries. The use and knowledge of the beneficial effects of the plant microbiome offers the possibility of agriculture under less favourable conditions with fewer inputs. This will promote job creation in rural areas.
- **Goal 9: Industry, innovation and infrastructure.** There is an emerging market for microbial products, such as microbial plant protection products, to be used in crop production. Furthermore, more innovations based on the plant microbiome are to be expected, which will strengthen this industry branch.
- **Goal 13: Climate action.** Plants play a key role in regulating our climate by reducing CO_2 and producing oxygen. Microorganisms which support plant growth and health contribute to this key process. Furthermore, fertilizer and pesticide production entail high energy demands, whereas microbial alternatives have lower resource demands and impacts on our climate, and hence are far more sustainable.
- **Goal 14: Life in water.** Reducing the input of chemicals in the soil and plant system will lead to reduced pollution of water.
- **Goal 15: Life on land.** Healthy ecosystems protect the planet and preserve the foundations of life. Plants are an important habitat for many microorganisms, which contribute to biodiversity and important ecosystem functions.

Potential Implications for Decisions

1. ***Individual***

   a. Which products do I buy in the supermarket? Consideration of the activities of plant-associated microorganisms, and whether beneficial effects were exploited in the context of the production method used, may lead to buying products produced by sustainable or organic farming practises that make best use of microbial activities.

b. What do I use to treat diseases of my garden plants? There are different alternatives available in the garden center

2. ***National policies***

a. Do our regulations promote sustainable farming practises and easily allow the farmer to apply microbial solutions for plant protection or fertilization?

Pupil participation

1. ***Class discussions on how different food products are produced***, from farm to human gut, and what are the implications on ecosystem and human health

2. ***Pupil stakeholder awareness***
   a. Discuss different microbial activities in connection to agricultural management
   b. Discuss about plant disease-causing and beneficial or important microorganisms

3. ***Exercise for the classroom***

a. To see the importance of microbes for the growth and health of the plant, let plants grow on sterilized and non-sterilized soil and compare their growth. For sterilizing the soil, put the soil in an oven for 30 min at 150°C. To see the differences in the bacterial numbers, make culture plates with dilutions of each soil and count the bacteria

b. Sample legume plants (e.g. soybean) from a field and have a closer look at nodules containing active N_2-fixing bacteria

c. Make your own sauerkraut or fermented food product and benefit from the health-promoting microorganisms

d. Mix water and rye flour and leave it for one day at a warm place. Look at the air bubbles in the mixture.

The evidence base, further reading and teaching aids

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Glossary

Photosynthesis: Is a process used by plants and other organisms to convert light energy into chemical energy that can later be used to fuel the organisms' activities.
Genome: is the entire genetic information of an organism
Nutrient cycling: In the nutrient cycle, the usage of the nutrients in the environment, their movement and the processes their recycling are described. Important nutrients include carbon, oxygen, hydrogen, phosphorus and nitrogen are required to be recycled for the existence of organisms.
Protist: Is any eukaryotic organism that is not an animal, plant or fungus
Eukaryotes: Are organisms with a nucleus in the cell
Prokaryotes: Are cellular organisms that lack the nucleus
Mutualism: Different organisms live in a positive interaction together
Neutralism: Two species live together, but do not affect each other
Competition: Interaction of two species or organisms in which the fitness of one species is lowered due to the presence of the other species.
Antagonism: Two species or organisms can not live together, the presence of one organism prevents the presence of the other
Fertilizer: Is a chemical or natural substance that is added to the soil or plants to supply them with nutrients.
Pesticides: Chemical substances which are applied to protect the plant from disease and pests
Archaea: Are a specific domain of Prokaryota, which possess genes and metabolic pathways, which are more similar to Eukaryota
Root exudates: Are compounds released by plant roots containing sugars, amino acids and other compounds providing nutrients to soil microorganisms
Stomata: Is a pore surrounded by specialized cells found in the epidermis of leaves, stems of plants to control the gas exchange.
N_2-fixing rhizobia: Specialized symbiotic bacteria, which are able to fix the nitrogen from the air and convert it to ammonia.
Arbuscular mycorrhizal fungi: Are symbiont fungi which penetrate the cortical cells of plant roots and show several plant beneficial activities
Secondary metabolites: Are specialized metabolites produced by organisms which are not directly involved in growth, development or reproduction.
Genotype: Is an organism containing a specific set of genes, which can be passed to the next generation.
Species: Is a taxonomic classification of organisms
Breeding program: A breeding program is the planned breeding of a group of animals or plants, usually involving at least several individuals and extending over several generations
Rhizosphere: It is the narrow region of soil or substrate that is directly influenced by root secretions.
Endophytes: Microorganisms that live within a plant for at least part of its life cycle without causing apparent disease
Sustainable Development Goals: were adopted by all United Nation Member States in 2015 as a universal call to action to end poverty, protect the planet and ensure that all people peace and prosperity by 2030.
Biotic stress: Stress that occurs as a result of damage done to a plant by other living organisms, like bacteria, fungi, parasites or insects.
Abiotic stress: Stress that occurs as a result of damage done to a plant by non-living environmental factors like water or temperature.

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