Plant Disease Transmission

How to recognize a diseased plant?

Visible symptoms such as yellow to brown spots or lesions on above-ground plant parts are an indication of a diseased plant. Such symptoms can be caused by bacterial or fungal pathogens. Powdery spots on the leaves and stems are also disease symptoms caused by so-called powdery mildew pathogens which can be observed on a wide range of crops and natural plants. Left two photos by Fred Springborn: https://www.canr.msu.edu/news/signs_and_symptoms_of_plant_disease_is_it_fungal_viral_or bacterial; Right photo: https://extension.umd.edu/resource/powdery-mildew-vegetables

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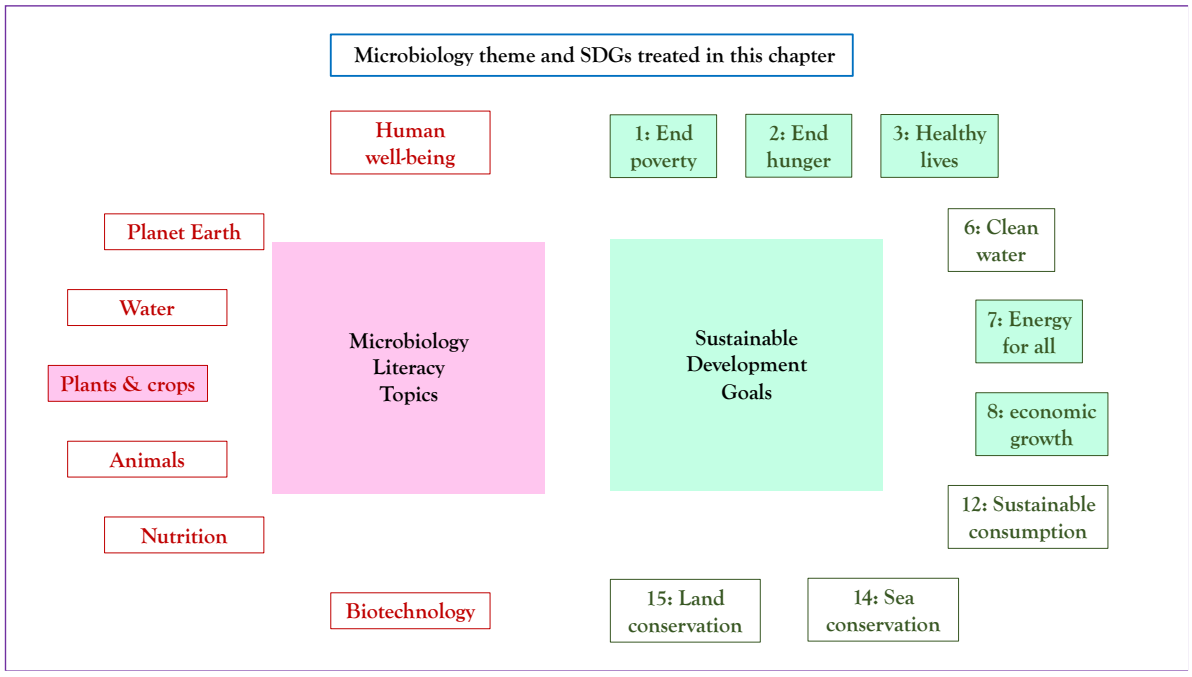
Storyline

Microorganisms are important for the health of higher organisms such as animals and plants. In addition, microorganisms are an important component of the soil ecosystem as they decompose organic matter to provide nutrients for plants. Thus, microorganisms contribute fundamentally to the productivity of agricultural systems. Microorganisms are the basis of our global food web as they are crucial for the growth of plants, which are the main source of nutrition for the world's population. Without plant production no food would be available either for humans or for animals. Plants have evolved in association with microorganisms, and the majority of them are beneficial and support the host plant, for instance, by protecting against diseases and providing nutrients. Microorganisms require nutrients for their growth. During the evolution of interactions between plants and microorganisms, some microbes have developed specific life strategies for nutrient acquisition that have negative effects on plants. These microorganisms are designated as plant pathogens and cause diseases. Outbreaks of plant diseases may have devastating effects on crop yield and quality and therefore on our lives and economy. Plant pathogens are able to cause disease by different infection strategies involving colonization of their surfaces and, in some cases, invasion of their tissues. Most plant pathogens are transmitted passively by wind, in rain/rain-splashes, by insects, animals, and contaminated plant material or farm equipment (e.g. tractor, plough) but some move actively by the use of flagella (e.g. bacteria). The infection of a plant by a pathogen result in diseases which are in most cases visible for us by symptoms especially on the above-ground plant parts. The occurrence of plant diseases has multiple consequences for Sustainable Development Goals.

The Microbiology and Societal Context



The microbiology: plant pathogens; pathogen transmission; pathogen vectors. *Sustainability issues:* poverty; hunger; health; energy, economy and employment.

Plant Disease Transmission: the Microbiology

1. The importance of microorganisms. An enormous number of microorganisms (archaea, bacteria, fungi, and protists) exist everywhere on our Earth. Although they are so small that we cannot see with the naked eye, microorganisms are crucial for our life. For example, each human body contains about the same number of microorganisms as human cells (30 trillion). Humans and other organisms cannot live without microorganisms, because they provide many essential services such as food digestion, detoxification of harmful chemicals, and protection against infection. Besides the various functions, these microorganisms play key roles in human health or in overall well-being.

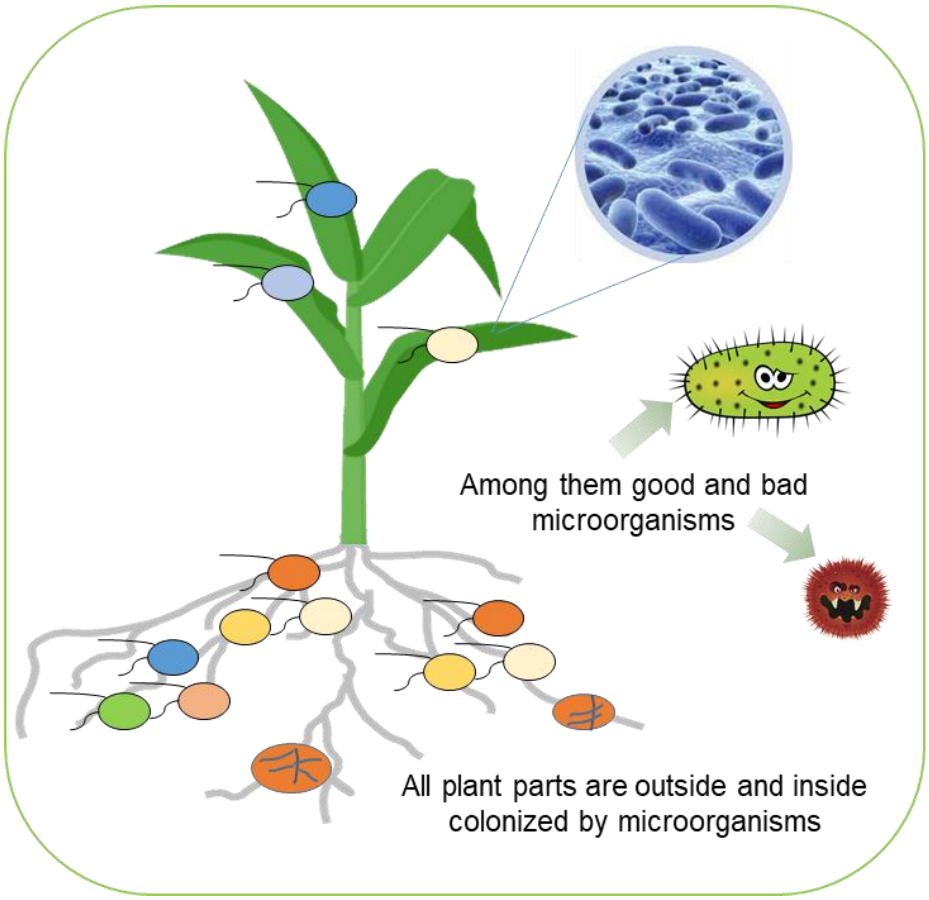
In addition, humanity have used microorganisms to process food such as curd, yogurt and fermented drinks, like beer as the oldest drink. More than 3500 traditionally fermented foods are known currently. Hence, food technology is unimaginable without microorganisms.

2. Helpful and harmful microorganisms for plants. As in humans and virtually all other living beings, microorganisms colonize all surfaces of plants like leaf and root surface. Plants can host microorganisms also within various tissue compartments, which live there as endophytes. The totality of these plant-associated microorganisms is called the plant microbiome. The majority of plant-associated microorganisms are known to benefit plant health by positively influencing plant physiology, development, and response to stress factors (e.g. drought, plant pathogens). For example, plants need nutrients, like nitrogen and phosphorus, for their growth. Helpful microorganisms in the soil, such as fungi and bacteria, increase nutrient availability for the plant, thereby improving the nutrient status of the plants. Mycorrhizal fungi are a well-known group of beneficial microorganisms that colonize plant roots and provide especially phosphorus to the plants. Most plant species have evolved such beneficial interaction or so-called symbiosis with mycorrhizal fungi.

Numerous members of the microbiome support the host plant by protecting against diseases (good microbes). They trigger defense response or increase tolerance to stress conditions such as drought or salinity. The photosynthetic capability can also be enhanced by microorganisms. All these services improve plant growth and yield.

In addition, microorganisms living in the soil are also of relevance for the plant. Some of them are degraders of organic matter and crucial for nutrient recycling. These microorganisms break down organic matter such as plant residues into their basic components. In this way, microorganisms support the availability of nutrients to the plants, while the plants provide food (sugars) to the microorganisms in return.

However, in the evolution of plant-microorganism interactions, not only positive effects have developed, and some microorganisms are very harmful and cause diseases in plants (bad microorganisms). Although the majority of microorganisms are beneficial, harmful microorganisms have economically relevant negative impacts on the outcome of agriculture and limit crop yield and quality.



The majority of plant diseases are caused by pathogenic fungi and fungal-like organisms (oomycetes), but also by bacteria, phytoplasmas, viruses, and viroids. All these organisms are designated as plant pathogens. Pathogenic fungi and fungal-like organisms are not able to feed themselves, and have filamentous growth and use the host plant as a food source. In contrast to bacteria, phytoplasmas and viruses, pathogenic fungi and fungal-like organisms are able to actively invade host plant tissue. A lot of them produce spores or specific survival structures that are able to overwinter on plant debris. Fungi can survive as chlamydospores or sclerotia, and oomycetes as oospores, for long periods of time in soil, just to become active when a host plant is cultivated again in this soil.

Some of these pathogens are very specialized on a distinct plant host whereas others are able to infect a broad range of host plants.

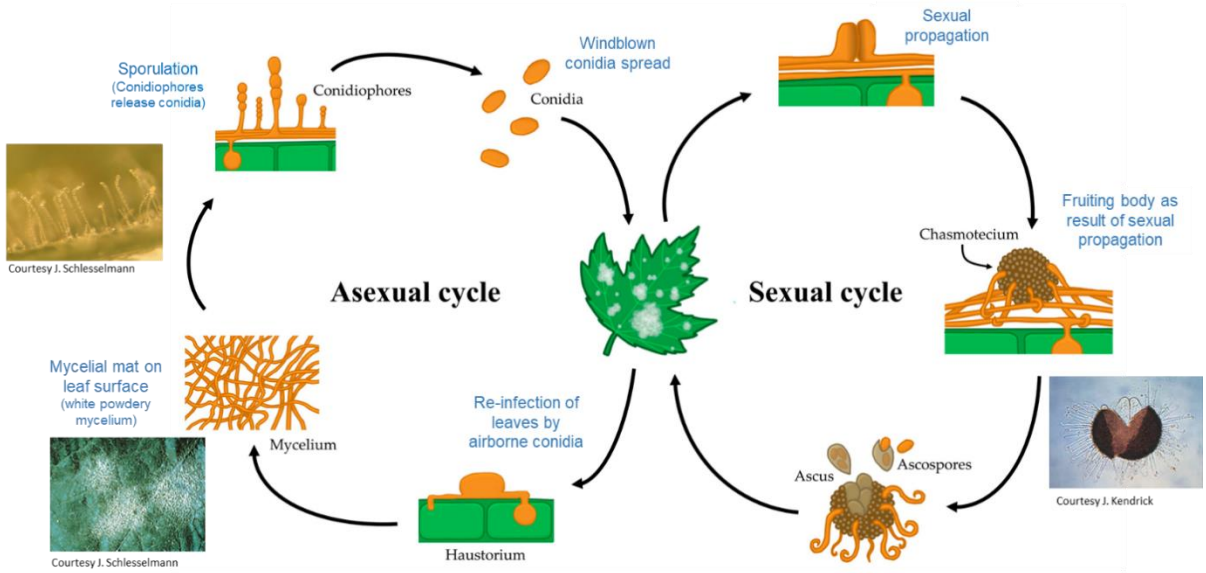
Although both above-ground and below-ground parts of the plant may become infected, we only notice disease symptoms through changes in the visible above-ground plant parts.

3. ***The disease cycle.*** Plant pathogens are a very heterogeneous group of organisms that differ in their mode of nutrition acquisition, type of reproduction, and manner of transmission. They have evolved specific properties that enable them to enter a host and establish a parasitic relationship between themselves and the plant.

Pathogens have developed diverse lifestyles, and are traditionally classified in three main categories on the basis of their nutrition acquisition, namely biotrophs, necrotrophs and hemibiotrophs.

An obligate biotrophic pathogen derives nutrients from living plant cells and is not able to complete its life cycle without the host. Examples are rust fungi on barley (*Puccinia hordei*) and powdery mildew fungi on cerelas (*Erysiphe graminis*), which cause severe yield losses worldwide.

In contrast, necrotrophic bacterial, fungal or oomycete pathogens are very destructive and destroy plant cells/tissues, for instance by producing enzymes or toxins that degrade the cell wall of the host plant. Hence, they derive nutrient and energy from dead or dying cells. These strategies result in extensive necrosis, tissue maceration and plant rot, and ultimately may kill their hosts. Examples are the fungal pathogens *Botrytis cinerea* (grey mold) and *Sclerotinia sclerotiorum* (white mold) which both have a broad host range, i.e. they are able to cause disease on a number of plant species.



Typical life cycle of powdery mildew fungi (Vielbach-Fernandez A. et al. *Microorganisms* 2020, 8(9), 1431)

Hemibiotrophic pathogens are characterized by an initial biotrophic phase followed by a necrothrophic phase. These pathogens keep the host alive while establishing themselves within the host tissue and extract nutrients from these cells during the biotrophic phase. Later, the pathogen switches to a necrothrophic life-style, killing the host cells and obtaining its nutrients from dead or dying cells. Examples of such pathogens are *Magnaporthe oryzea* (rice blast fungus) and *Mycosphaerella graminicola* (leaf blotch on wheat).

Some plant pathogens can invade plant tissue and live within the internal environment of plants whereas others live on plant surfaces. Fungal or bacterial pathogens that cause wilting of plants colonize the vascular system of the plant and block the transport of water in the plant. The plant become limp like some plants do in hot dry weather conditions. The widespread powdery mildew fungi appear on leaf surfaces as white powder-like fungal growth and do not invade deeper plant tissue. Spores of these fungi produced on the leaf surface can be easily distributed for instance by wind.

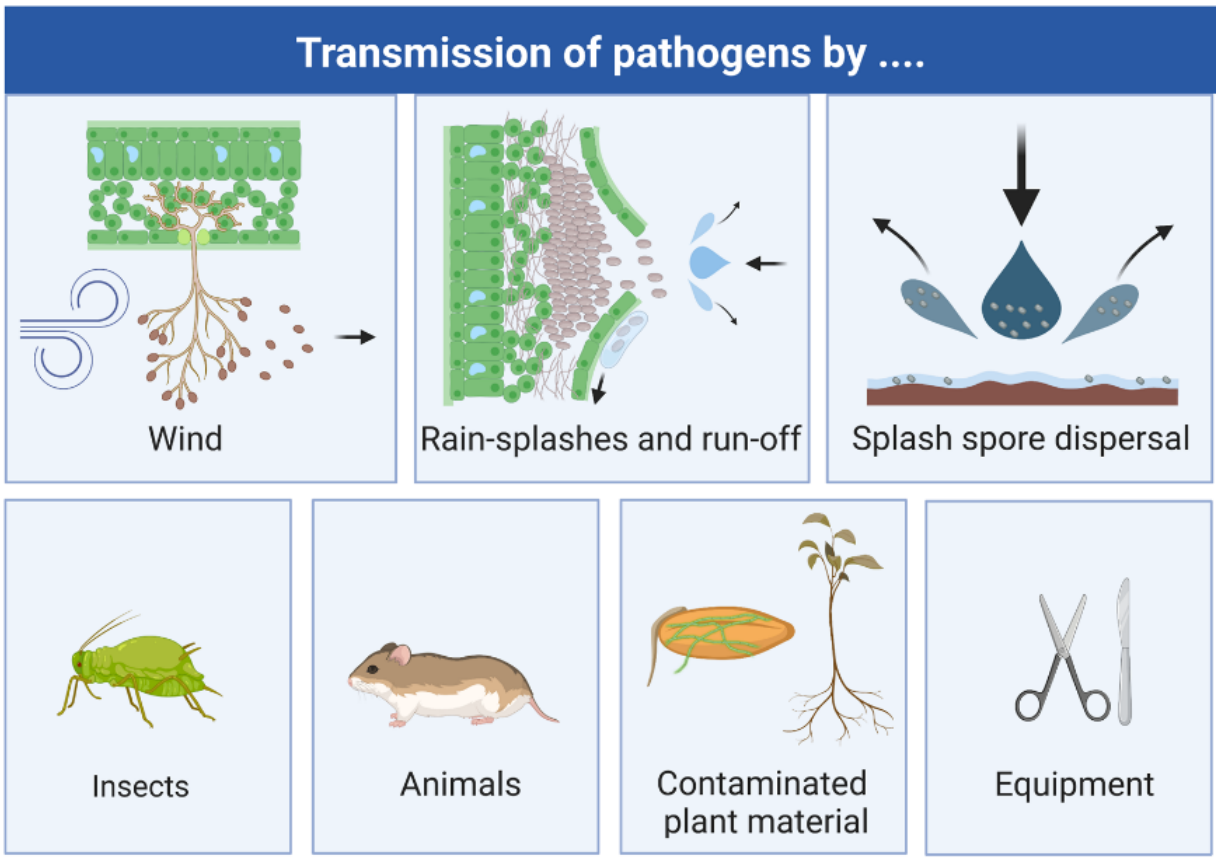
Both a pathogen and a susceptible host plant are necessary components of a disease, but the disease develops only when environmental conditions, such as temperature and humidity, are favorable for both the plant and the pathogen in the ecosystem or the plant production system.

When a disease spreads in an ecosystem from one plant to another, an epidemic can develop. This raises the questions:

- What could move a pathogen or pathogen structure like a fungal spore within plant production systems? and
- What factors influence the transmission of a pathogen within a crop and how?

4. ***Pathogen transmission.*** In general, pathogens may infect all types of plant tissue such as leaves, shoots, stems, crowns, roots, fruits, and seeds. And, as mentioned, they can colonize surfaces and internal plant tissues, such as the vascular system or the seeds. Which part a pathogen infects depends on the pathogen itself. Both the pathogen and its infection strategy influence its transmission from plant to plant.

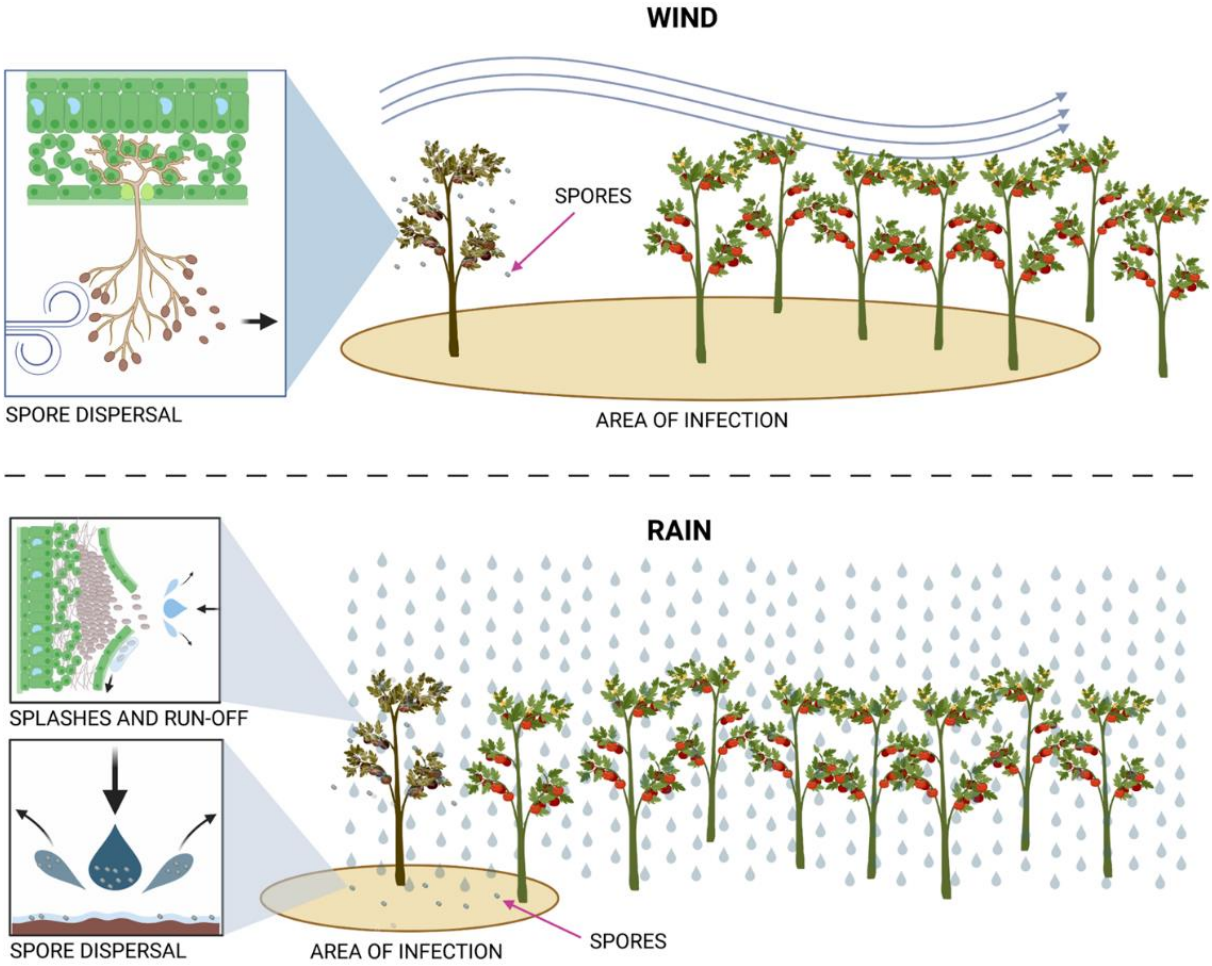
In general, plant pathogens can be distributed passively by wind, water or animals, but also actively. For instance, fungal-like pathogens produce zoospores that can swim, for instance to the plant roots, if the soil is moist. Many bacteria are also motile and can actively swim to target plant tissue under wet conditions.



(Figure created with biorender.com)

Plant pathogens can be transmitted as well by tools and machinery that make contact with infected plant tissues or pathogen-laden soil particles. So humans disseminate pathogens through the transport of infected or diseased plant materials, cultivation of infected plants, grafting or pruning. Disease symptoms are not always visible so it is not always possible to avoid the handling and transmission of infected plants.

a. *Distribution by wind and rain.* Most fungi and fungal-like organisms produce spores (often referred to as conidia) and their dispersal is the most common process to initiate new infections on host plants both near and far. A number of fungal leaf pathogens, like rust or powdery mildew fungi, and fungal-like pathogens, such as downy mildew or late blight, that infect the leaves of a plant spread primarily by wind. These pathogens produce spores in lesions on the leaf surface, or colonize within plant tissue (e.g. downy mildew pathogens) and drop out via stomata.



(Figure created with biorender.com)

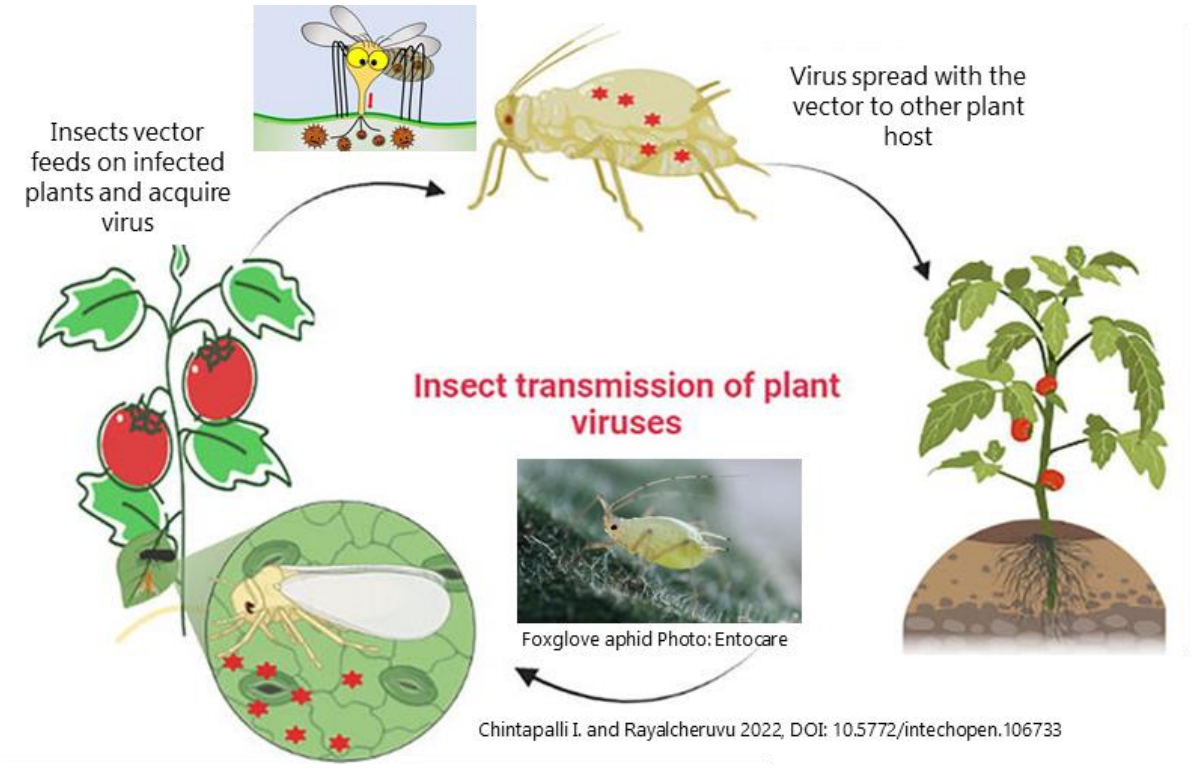
Within a crop, the spores are readily distributed by wind over short distances. Contact between neighboring plants also leads to new infections. And during episodes of rain, spores of fungal or fungal-like pathogens can spread by raindrops that splash down on infected leaf tissue and disperse spores via tiny splash droplets to neighboring plants.

A number of plant pathogens, including the so-called foliar pathogens (leaf pathogens), live and/or survive in the soil. Soil-borne pathogens are natural soil inhabitants or become incorporated into the soil via infected plant material such as seeds and harvest residues. Raindrops can also splash on pathogen-laden soil and thereby distribute infective material to aboveground plant parts.

Spores in soil or other pathogen structures like hyphae attached to soil particles disseminate in wind-driven dust for significant distances ranging from meters to hundreds of kilometers, as seen by disease appearance on plants in fields of other agricultural areas. The distribution of pathogens via soil particles happens especially in fallow lands.

Transmission of pathogens that relies mainly on wind and rain-splash modes is usually limited to relatively short-distance spread. In this case, the survival of distributed pathogen spores/structures depends on the possibility to make contact with a susceptible host and suitable environmental conditions. However, although fungal spores are commonly short-lived and susceptible to UV-radiation and desiccation, some cases of long-distance dispersal are also known. For instance, the coffee leaf rust (*Hemileia vastatrix*) was probably transmitted by wind from Africa to Brazil in the 1970s.

b. *Vector-mediated transmission.* Birds which come into contact with spores of pathogens produced in lesions of infected plant leaves or with pathogen-laden soil particles can carry fungal spores via their feathers over short and long distances. Furthermore, all sorts of insects can act as passive vectors to spread pathogens from infected plants to new hosts.



Interestingly, pathogens have evolved mechanisms to attract insects to increase the chance of transmission. For instance, the ergot pathogen (*Claviceps purpurea*) infects young, usually unfertilized ovaries of various cereals and grasses. The fungus produces sugary honeydews to allure insects. Millions of spores occur in the honeydews and attracted insects spread these spores (conidia) to other florets.

Sclerotia of the ergot pathogen *Claviceps purpurea* (Photo: Franz Xaver Schubiger, pflanzenkrankheiten.ch)

Some plant pathogenic bacteria, especially those causing spots, cankers, blight or soft rots, also attract insects by sugary bacterial exudates. The bacteria living within or between plant cells escape to the surface of the host plant and release droplets of a sticky exudate through cracks or natural openings like stomata. Bacteria in this exudate stick to the legs and bodies of all sorts of insects, such as flies, aphids and whiteflies that come into contact with the exudate, and are thereby carried to new host plants. When the insects land on a fresh wound or natural opening of a susceptible plant, and the moisture conditions are appropriate, the new host plant will become infected. The same thing happens when the insects themselves cause wounds.

In addition, all sucking insects can transmit pathogens that occur systemically in the plants, especially in the vascular tissues. The phloem in particular serves as the long-distance transport system of the plant, responsible for translocating the products of photosynthesis, like sugars, to all parts of the plant, and offers a nutrient-rich source for pathogens.

Most known plant viruses are transmitted by sucking vector insects like aphids, whereas important vectors of bacterial pathogens are leafhoppers and psyllids that transmit the bacteria between plant hosts during feeding periods. All vector-borne bacteria share the ability to propagate in both the plant and the insect vector.

c. *Transmission by seeds or plants.* Many of human's earliest crops such as cereals were carried to agricultural areas as seeds, along with their pathogens. Since then, as humans have collected and moved seeds of interested crops to new sites, they have unknowingly distributed plant pathogens.

Seed-carried pathogens are either located internally, inside the seeds (endosperm, perisperm, fruits), or externally, on the seed coat surface. Viruses, for instance, can be present in the embryo and thereby assure infection of the seedling.

Seed infection/infestation is often characterized by no visible symptoms (asymptomatic) which favours long-distance dispersal. In this way, pathogens can enter new field sites and

establish in foreign regions and go unnoticed for years. This is one reason why it took so long to appreciate the role of seeds as vectors for passive pathogen transmission. The distribution of *Fusarium* spp. by contaminated seeds in every major asparagus-producing area worldwide is an example. *Fusarium* spp. are responsible for crown and root rot disease of asparagus, a plant species that was brought from Asia to Europe and later to the USA. Commercial cultivation of asparagus in the USA started already in the late 1800s, but the disease appeared first in 1908.

Pathogens transmitted by seeds can survive much longer than those distributed by wind and rain-droplets that are exposed directly to the elements.

Relevance for Sustainable Development Goals and Grand Challenges

Plant diseases are relevant for a number of SDGs. Because they reduce crop plant yields, they reduce the income of farmers (SDG 8, decent work for all), some of which are subsistence farmers who can easily be pushed into poverty (SDG 1: end poverty). Decreasing crop yields also negatively impacts the ability of farmers to feed the world and hence avert hunger (SDG 2: end hunger) and, because good health requires adequate nutrition, avert malnutrition-caused ill health (SDG 3 ensure healthy lives). Plants are the basis of renewable energy (SDG 7 access to sustainable energy).

Potential Implications for Decisions

1. ***Individual***

a. Respect the pivotal role of plants on Earth in general for our lives (e.g. food source, provide oxygen, influence our well-being)

b. Consider visible symptoms on plant based foods and do not eat these foods.

c. Handle symptomatic plant parts in a way that avoid spread of pathogens.

d. When you visit a farm make sure that you not touch plants with visible symptoms to avoid the spread of diseases. Clean your shoes to avoid the transmission of pathogen that live in the soil.

e. Introduction of any living plant material is not allowed when entering the European Union (EU)

2. ***Policies related to plant protection for European countries***

a. Rules to protect the EU against the introduction of new plant diseases and tackling existing plant diseases more effectively.

b. Screening for new devastating diseases worldwide.

c. Preventing the entry of new diseases in the EU territory to avoid destruction of agricultural production potential in the EU.

d. Early detection and eradication of quarantined diseased plants when found in the EU territory.

e. Import of plant products, especially living plant material, requires phytosanitary certificate confirming their compliance with the EU legislation (exception: banana, coconuts, dates, pineapples and durian).

f. Plant passports are required for movement of all plants for planting within the internal market at commercial level.

g. EU Member States are responsible in the implementation of the rules.

h. The EU legislation is in accordance to the principles and standards of the International Plant Protection Convention (IPPC) and

Pupil Participation

1. ***Class discussion of the issues associated with plant diseases***
   - **a.** Agriculture practice under consideration of plant disease management,
   - **b.** Role of plant disease for food security,
   - **c.** Impact of climate change on incidence of diseases.

2. ***Pupil stakeholder awareness***

a. The occurrence of plant diseases has positive and negative consequences for the SDGs. Which of these are most important to you personally/as a class?

b. The used control strategy for plant protection has impact on the environment and human health. Which of these are most important to you personally/as a class?

c. Can you think of anything that might be done to avoid the negative consequences of control strategies of plant diseases on human health and the environment especially in the food supply chain?

d. Can you think of anything you might personally do to reduce the environmental footprint of plant diseases?

3. ***Exercises***

a. The majority of our food is produced by intensive agricultural production related with high input of agrochemicals (mineral fertilizer, synthetic pesticides). What sustainable options are there for disease control or plant protection without synthetic pesticides?

b. Looking at the SDGs, how can we transform the recent agricultural production into a sustainable farm system? What are the challenges and opportunities? Create a sustainable farm system under consideration of their associated environmental impacts.

The Evidence Base, Further Reading and Teaching Aids

Benefits of microorganisms for plant health

https://www.youtube.com/watch?v=J6B_oI-N9Qs

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Introduction of plant diseases

Plant disease: pathogens and cycles https://cropwatch.unl.edu/soybean-management/plant-disease

Preventing and managing plant disease https://extension.missouri.edu/publications/mg13

https://www.youtube.com/watch?v=NjCaytf2e9U

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Biological control of plant diseases
What is biological control? https://www.youtube.com/watch?v=OrMKHhb6jgs.
Raid R. Plant Pathology Guidlines for Master Gardeners https://erec.ifas.ufl.edu/plant_pathology_guidelines/module_07.shtml
O'Brien P. A. 2017. Biological control of plant diseases. Australasian Plant Pathol 46:293-304. https://doi.org/10.1007/s13313-017-0481-4.
Köhl J., Kolnaar R., Ravensberg W. J. 2019. Mode of action of microbial biological control agents against plant dieseases: relevance beyond efficacy. Front plant Sci 10:845. . https://doi.org/10.103389/fpls.2019.00845.

Glossary

microorganism or microbe: is an organism of microscopic size and include bacteria, protozoa, algae, and fungi
microbiome: is the specific group of microorganisms such as bacteria, fungi and viruses that exist in a particular organism (or environment) and interacting with them.
plant microbiome: are the specific group of microorganisms that colonize plant surfaces and tissues and interacting with the plant.
endophyte: are the specific group of microorganisms that are common exist within plant tissue.
plant symbionts: are microbes that live in very close interaction with the plant and derive an advantage form the interaction.
mycorrhiza: define a mutually beneficial relationship between the plant roots and the fungus colonize the roots. Mycorrhiza fungi can grow inside the plant roots or on the surface of the roots.
plant pathogen: is an organism such as bacteria, fungi, oomycetes, viruses and nematodes that cause disease on a plant.
plant pathogen life cycle: represent a series of interconnected stages of development including, dormancy, reproduction, dispersal and pathogenesis under consideration of pathogen biology.
pathogenesis: include production of inoculum, spread of inoculum to susceptible plant host, penetration of inoculum into host plant and infection.
biothrophic pathogen: obtain food from the living plant cell and establish a long-term feeding relationship with the living plant cells.
necrothroph pathogen: kill the plant host cells by intense enzymatic and toxigenic activity, derive nutrients from the dead or dying cells and invade afterwards the plant host by maintaining saprophytic activity.
hemibiothroph pathogen: invade initially living plant host cells (biotrophic phase), spread throughout the Infected plant tissue, and switches later to a necrotrophic phase to derive nutrients from the dead cells.
hyphae: is a long, branching filamentous structure of fungi and oomycete.
chlamydospore: is a solitary asexual thick-walled large resting spore of several kinds of fungi and the main mode of vegetative growth, and are collectively called a mycelium.
sclerotium (sclerotia): is a compact mass of hardened fungal mycelium containing food reserves. The role of sclerotia are to survive under various environmental conditions.
oomycetes: are a class of the phylum Oomycota and include some of the most devastating plant pathogens.
protists: are a diverse taxonomic group of eukaryotic organisms that are predominantly unicellular and not true animal, plant or fungus and lack multicellular stage.
viroids: consists only of naked RNA without any protective layer and infects plants.