    - apple scab
- smut
    - bunt
    - corn smut
- snow mold
- sooty mold
- *Verticillium* wilt

viral

- curly top
- mosaic
- psorosis
- spotted wilt

This article was most recently revised and updated by Melissa Petruzzello.

Contents Ask the Chatbot a Question

plant disease

plant pathology

Ask the Chatbot a Question ⋮ More Actions

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Table of Contents

blight Potato leaf infected with a fungal blight.

plant disease, an impairment of the normal state of a plant that interrupts or modifies its vital functions. All species of plants, wild and

Related Topics: wilt • Dutch elm disease • rot • ash dieback disease • elm phloem necrosis cultivated alike, are subject to disease. Although each species is susceptible to characteristic diseases, these are, in each case, relatively few in number. The occurrence and prevalence of plant diseases vary from season to season, depending on the presence of the pathogen, environmental conditions, and the crops and varieties grown. Some plant varieties are particularly subject to outbreaks of diseases while others are more resistant to them. *See also* list of plant diseases.

See all related content

General considerations

Nature and importance of plant diseases

Plant diseases are known from times preceding the earliest writings. Fossil evidence indicates that plants were affected by disease 250 million years ago. The Bible and other early writings mention diseases, such as rusts, mildews, and blights, that have caused famine and other drastic changes in the economy of nations since the dawn of recorded history. Other plant disease outbreaks with similar far-reaching effects in more recent times include late blight of potato in Ireland (1845–60); powdery and downy mildews of grape in France (1851 and 1878); coffee rust in Ceylon (now Sri Lanka; starting in the 1870s); *Fusarium* wilts of cotton and flax; southern bacterial wilt of tobacco (early 1900s); Sigatoka leaf spot and Panama disease of banana in Central America (1900–65); black stem rust of wheat (1916, 1935, 1953–54); southern corn leaf blight (1970) in the United States; Panama disease of banana in Asia, Australia, and Africa (1990 to present); and coffee rust in Central and South America (1960, 2012 to present). Such losses from plant diseases can have a significant economic impact, causing a reduction in income for crop producers and distributors and higher prices for consumers.

Loss of crops from plant diseases may also result in hunger and starvation, especially in less-developed countries where access to disease-control methods is limited and annual losses of 30 to 50 percent are not uncommon for major crops. In some years, losses are much greater, producing catastrophic results for those who depend on the crop for food. Major disease outbreaks among food crops have led to famines and mass migrations throughout history. The devastating outbreak of late blight of potato (caused by the water mold *Phytophthora infestans*) that began in Europe in 1845 brought about the Great Famine that caused starvation, death, and mass migration of the Irish. Of Ireland's population of more than eight million, approximately one million (about 12.5 percent) died of starvation or famine-related illness, and 1.5 million (almost 19 percent) emigrated, mostly to the United States, as refugees from the destructive blight. This water mold thus had a tremendous influence on economic, political, and cultural development in Europe and the United States. During World War I, late blight damage to the potato crop in Germany may have helped end the war.

Diseases—a normal part of nature

Plant diseases are a normal part of nature and one of many ecological factors that help keep the hundreds of thousands of living plants and animals in balance with one another. Plant cells contain special signaling pathways that enhance their defenses against insects, animals, and pathogens. One such example involves a plant hormone called jasmonate (jasmonic acid). In the absence of harmful stimuli, jasmonate binds to special proteins, called JAZ proteins, to regulate plant growth, pollen production, and other processes. In the presence of harmful stimuli, however, jasmonate switches its signaling pathways, shifting instead to directing processes involved in boosting plant defense. Genes that produce jasmonate and JAZ proteins represent potential targets for genetic engineering to produce plant varieties with increased resistance to disease.

Humans have carefully selected and cultivated plants for food, medicine, clothing, shelter, fibre, and beauty for thousands of years. Disease is just one of many hazards that must be considered when plants are taken out of their natural environment and grown in pure stands under what are often abnormal conditions.

Many valuable crop and ornamental plants are very susceptible to disease and would have difficulty surviving in nature without human intervention. Cultivated plants are often more susceptible to disease than are their wild relatives. This is because large numbers of the same species or variety, having a uniform genetic background, are grown close together, sometimes over many thousands of square kilometres. A pathogen may spread rapidly under these conditions.

Definitions of plant disease

In general, a plant becomes diseased when it is continuously disturbed by some causal agent that results in an abnormal physiological process that disrupts the plant's normal structure, growth, function, or other activities. This interference with one or more of a plant's essential physiological or biochemical systems elicits characteristic pathological conditions or symptoms.

Plant diseases can be broadly classified according to the nature of their primary causal agent, either infectious or noninfectious. Infectious plant diseases are caused by a pathogenic organism such as a fungus, bacterium, mycoplasma, virus, viroid, nematode, or parasitic flowering plant. An infectious agent is capable of reproducing within or on its host and spreading from one susceptible host to another. Noninfectious plant diseases are caused by unfavourable growing conditions, including extremes of temperature, disadvantageous relationships between moisture and oxygen, toxic substances in the soil or atmosphere, and an excess or deficiency of an essential mineral. Because noninfectious causal agents are not organisms capable of reproducing within a host, they are not transmissible.

In nature, plants may be affected by more than one disease-causing agent at a time. A plant that must contend with a nutrient deficiency or an imbalance between soil moisture and oxygen is often more susceptible to infection by a pathogen, and a plant infected by one pathogen is often prone to invasion by secondary pathogens. The combination of all disease-causing agents that affect a plant make up the disease complex. Knowledge of normal growth habits, varietal characteristics, and normal variability of plants within a species—as these relate to the conditions under which the plants are growing—is required for a disease to be recognized.

The study of plant diseases is called plant pathology. Pathology is derived from the two Greek words *pathos* (suffering, disease) and *logos* (discourse, study). Plant pathology thus means a study of plant diseases.

Disease development and transmission

Pathogenesis and saprogenesis

Pathogenesis is the stage of disease in which the pathogen is in intimate association with living host tissue. Three fairly distinct stages are involved:

1. Inoculation: transfer of the pathogen to the infection court, or area in which invasion of the plant occurs (the infection court may be the unbroken plant surface, a variety of wounds, or natural openings—e.g., stomata [microscopic pores in leaf surfaces], hydathodes [stomata-like openings that secrete water], or lenticels [small openings in tree bark])

2. Incubation: the period of time between the arrival of the pathogen in the infection court and the appearance of symptoms

3. Infection: the appearance of disease symptoms accompanied by the establishment and spread of the pathogen.

One of the important characteristics of pathogenic organisms, in terms of their ability to infect, is virulence. Many different properties of a pathogen contribute to its ability to spread through and to destroy the tissue. Among these virulence factors are toxins that kill cells, enzymes that destroy cell walls, extracellular polysaccharides that block the passage of fluid through the plant system, and substances that interfere with normal cell growth. Not all pathogenic species are equal in virulence—that is, they do not produce the same amounts of the substances that contribute to the invasion and destruction of plant tissue. Also, not all virulence factors are operative in a particular disease. For example, toxins that kill cells are important in necrotic diseases, and enzymes that destroy cell walls play a significant role in soft rot diseases.

Many pathogens, especially among the bacteria and fungi, spend part of their life cycle as pathogens and the remainder as saprotrophs.

Saprogenesis is the part of the pathogen's life cycle when it is not in vital association with living host tissue and either continues to grow in dead host tissue or becomes dormant. During this stage, some fungi produce their sexual fruiting bodies; the apple scab (*Venturia inaequalis*), for example, produces perithecia, flask-shaped spore-producing structures, in fallen apple leaves. Other fungi produce compact resting bodies, such as the sclerotia formed by certain root- and stem-rotting fungi (*Rhizoctonia solani* and *Sclerotinia sclerotiorum*) or the ergot fungus (*Claviceps* *purpurea*). These resting bodies, which are resistant to extremes in temperature and moisture, enable the pathogen to survive for months or years in soil and plant debris in the absence of a living host.

Epiphytotics

When the number of individuals a disease affects increases dramatically, it is said to have become *epidemic* (meaning "on or among people"). A more precise term when speaking of plants, however, is *epiphytotic* ("on plants"); for animals, the corresponding term is *epizootic*. In contrast, endemic (enphytotic) diseases occur at relatively constant levels in the same area each year and generally cause little concern.

Epiphytotics affect a high percentage of the host plant population, sometimes across a wide area. They may be mild or destructive and local or regional in occurrence. Epiphytotics result from various combinations of factors, including the right combination of climatic conditions. An epiphytotic may occur when a pathogen is introduced into an area in which it had not previously existed. Examples of this condition include the downy mildews (*Sclerospora* species) and rusts (*Puccinia* species) of corn in Africa during the 1950s, the introduction of the coffee rust fungus into Brazil in the 1960s, and the entrance of chestnut blight (*Endothia parasitica*) into the United States shortly after 1900. Also, when new plant varieties are produced by plant breeders without regard for all enphytotic diseases that occur in the same area to some extent each year (but which are normally of minor importance), some of these varieties may prove very susceptible to previously unimportant pathogens. Examples of this situation include the development of oat varieties with Victoria parentage, which, although highly resistant to rusts (*Puccinia graminis avenae* and *P. coronata avenae*) and smuts (*Ustilago avenae*, *U. kolleri*), proved very susceptible to *Helminthosporium* blight (*H. victoriae*), formerly a minor disease of grasses. The destructiveness of this disease resulted in a major shift of oat varieties in the United States in the mid-1940s. Corn (maize) with male-sterile cytoplasm (i.e., plants with tassels that do not extrude anthers or pollen), grown on 60 million acres (24 million hectares) in the United States, was attacked in 1970 by a virulent new race of the southern corn leaf blight fungus (*Helminthosporium maydis* race T), resulting in a loss of about 700 million bushels of corn. More recently the new *Helminthosporium* race was widely disseminated and was reported from most continents. Finally, epiphytotics may occur when host plants are cultivated in large acreages where previously little or no land was devoted to that crop.

Epiphytotics may occur in cycles. When a plant disease first appears in a new area, it may grow rapidly to epiphytotic proportions. In time, the disease wanes, and, unless the host species has been completely wiped out, the disease subsides to a low level of incidence and becomes enphytotic. This balance may change dramatically by conditions that favour a renewed epiphytotic. Among such conditions are weather (primarily temperature and moisture), which may be very favourable for multiplication, spread, and infection by the pathogen; introduction of a new and more susceptible host; development of a very aggressive race of the pathogen; and changes in cultural practices that create a more favourable environment for the pathogen.

Environmental factors affecting disease development

Important environmental factors that may affect development of plant diseases and determine whether they become epiphytotic include temperature, relative humidity, soil moisture, soil pH, soil type, and soil fertility.

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Temperature

Each pathogen has an optimum temperature for growth. In addition, different growth stages of fungi, such as the production of spores (reproductive units), their germination, and the growth of the mycelium (the filamentous main fungus body), may have slightly different optimum temperatures. Storage temperatures for certain fruits, vegetables, and nursery stock are manipulated to control fungi and bacteria that cause storage decay, provided the temperature does not change the quality of the products. Little, except limited frost protection, can be done to control air temperature in fields, but greenhouse temperatures can be regulated to check disease development.

Knowledge of optimum temperatures, usually combined with optimum moisture conditions, permits forecasting, with a high degree of accuracy, the development of such diseases as blue mold of tobacco (*Peronospora tabacina*), downy mildews of vine crops (*Pseudoperonospora cubensis*) and lima beans (*Phytophthora phaseoli*), late blight of potato and tomato (*Phytophthora infestans*), leaf spot of sugar beets (*Cercospora beticola*), and leaf rust of wheat (*Puccinia recondita tritici*). Effects of temperature may mask symptoms of certain viral and mycoplasmal diseases, however, making them more difficult to detect.

Relative humidity

Relative humidity is very critical in fungal spore germination and the development of storage rots. *Rhizopus* soft rot of sweet potato (*Rhizopus stolonifer*) is an example of a storage disease that does not develop if relative humidity is maintained at 85 to 90 percent, even if the storage temperature is optimum for growth of the pathogen. Under these conditions, the sweet potato root produces suberized (corky) tissues that wall off the *Rhizopus* fungus.

High humidity favours development of the great majority of leaf and fruit diseases caused by fungi, water molds, and bacteria. Moisture is generally needed for spore germination, the multiplication and penetration of bacteria, and the initiation of infection. Germination of powdery mildew spores occurs best at 90 to 95 percent relative humidity. Diseases in greenhouse crops—such as leaf mold of tomato (*Cladosporium fulvum*) and decay of flowers, leaves, stems, and seedlings of flowering plants, caused by *Botrytis* species—are controlled by lowering air humidity or by avoiding spraying plants with water.

Soil moisture

High or low soil moisture may be a limiting factor in the development of certain root rot diseases. High soil-moisture levels favour development of destructive water mold fungi, such as species of *Aphanomyces*, *Pythium*, and *Phytophthora*. Excessive watering of houseplants is a common problem. Overwatering, by decreasing oxygen and raising carbon dioxide levels in the soil, makes roots more susceptible to root-rotting organisms.

potato scab Common scab of potato.

Diseases such as take-all of cereals (*Ophiobolus graminis*); charcoal rot of corn, sorghum, and soybean (*Macrophomina phaseoli*); common scab of potato (*Streptomyces scabies*); and onion white rot (*Sclerotium cepivorum*) are most severe under low soil-moisture levels.

Soil pH

Soil pH, a measure of acidity or alkalinity, markedly influences a few diseases, such as common scab of potato and clubroot of crucifers (*Plasmodiophora brassicae*). Growth of the potato scab organism is suppressed at a pH of 5.2 or slightly below (pH 7 is neutral; numbers below 7 indicate acidity, and those above 7 indicate alkalinity). Scab is not normally a problem when the natural soil pH is about 5.2. Some farmers add sulfur to their potato soil to keep the pH about 5.0. Clubroot of crucifers (members of the mustard family, including cabbage, cauliflower, and turnips), on the other hand, can usually be controlled by thoroughly mixing lime into the soil until the pH becomes 7.2 or higher.

Soil type

Certain pathogens are favoured by loam soils and others by clay soils. *Phymatotrichum* root rot attacks cotton and some 2,000 other plants in the southwestern United States. This fungus is serious only in black alkaline soils—pH 7.3 or above—that are low in organic matter. *Fusarium* wilt disease, which attacks a wide range of cultivated plants, causes more damage in lighter and higher (topographically) soils. Nematodes are also most damaging in lighter soils that warm up quickly.

Soil fertility

Greenhouse and field experiments have shown that raising or lowering the levels of certain nutrient elements required by plants frequently influences the development of some infectious diseases—for example, fire blight of apple and pear, stalk rots of corn and sorghum, *Botrytis* blights, *Septoria* diseases, powdery mildew of wheat, and northern leaf blight of corn. These diseases and many others are more destructive after application of excessive amounts of nitrogen fertilizer. This condition can often be counteracted by adding adequate amounts of potash, a fertilizer containing potassium.

Requirements for disease development

Infectious disease cannot develop if any one of the following three basic conditions is lacking: (1) the proper environment, the most important environmental factors being the amount and frequency of rains or heavy dews, the relative humidity, and the air and soil temperatures, (2) the presence of a virulent pathogen, and (3) a susceptible host. Effective disease-control measures are aimed at breaking this environment-pathogen-host triangle. Loss resulting from disease is reduced, for example, if the host can be made more resistant or immune through such techniques as plant breeding or genetic engineering. In addition, the environment can be made less favourable for invasion by the pathogen and more favourable for the growth of the host plant. Finally, the pathogen can be killed or prevented from reaching the host. These basic methods of control can be divided into a number of cultural, chemical, and biological practices to help control the disease.

Diagnosis of plant diseases

Rapid and accurate diagnosis of disease is necessary before proper control measures can be suggested. It is the first step in the study of any disease. Diagnosis is largely based on characteristic symptoms expressed by the diseased plant. Identification of the pathogen is also essential to diagnosis.

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Three steps involved in diagnosis include careful observation and classification of the facts, evaluation of the facts, and a logical decision as to the cause.

Variable factors affecting diagnosis

A skilled diagnostician must know the normal appearance of an affected plant species, its local air and soil environment, the cultural conditions under which it is growing, the pathogens described for the area, and the disease-developing potential of the pathogen. Diagnosis is best done in the presence of the growing plant. Disease is suspected when, for example, part or all of a plant begins to die. Disease also is indicated when blossoms, leaves, stems, roots, or other plant parts appear abnormal —i.e., misshapen, curled, discoloured, overdeveloped, or underdeveloped. Diseased plants also often fail to respond normally to fertilizing, watering, pruning, insect and mite control, or other recommended practices.

Conditions other than infection with a pathogen, however, may produce similar or identical symptoms. Some of these have been described, but numerous other conditions must be considered as well when plants are adversely affected. For example, an affected plant may not be adapted to the area in which it is growing. It may not be able to withstand the extremes in soil moisture, temperature, wind, light, or humidity of the local situation. Damage to plants may be caused by insects, mites, rodents, pets, or humans. The soil may be poorly drained, gravelly, or overly sandy; it may be covering buried debris such as boards, cement blocks, bricks, or mortar; or it may be too dry or otherwise unfavourable for good plant growth. Problems also are caused by high winds, hail, lightning, blowing sand, a heavy load of snow or ice, flooding, fire, ice-removal chemicals, mechanical injury by garden tools or machinery, and fumes from weed-killing chemicals, trash burners, nearby industrial plants, or motor vehicles. The affected plant may have received treatment different from nearby healthy ones—watering, fertilizing, pest control, pruning, or depth of planting, for example. If different species or kinds of plants in the same area have similar symptoms, the chances are that a pathogen is not involved. Most infectious diseases are highly specific for individual or closely related plant species, and similar symptoms on unrelated plants are usually an indication of some environmental factor rather than a disease-causing organism.

Examination of leaves is usually considered to be the best starting point in diagnosis. The colour, size, shape, and margins of spots and blights (lesions) are often associated with a particular fungus or bacterium. Many fungi produce “signs” of disease, such as mold growth or fruiting bodies that appear as dark specks in the dead area. Early stages of bacterial infections that develop on leaves or fruits during humid weather often appear as dark and water-soaked spots with a distinct margin and sometimes a halo—a lighter-coloured ring around the spot.

Low winter temperatures and late spring or early fall freezes cause blasting (sudden death) of leaf and flower buds or sudden blighting (discoloration and death) of tender foliage.

Insect-injured leaves usually show evidence of feeding, such as holes, discoloration, stippling, blotching, downward curling, or other deformations.

Scorching of leaf margins and between the veins is common following hot, dry, windy weather. Similar symptoms are produced by an excess of water, an imbalance of essential nutrients, an excess of soluble salts, changes in the soil water table or soil grade, gas or fume injury, and root injury or disease.

Viral diseases, such as mosaics and yellows, are sometimes confused with injury by a hormone-type weed killer, unbalanced nutrition, and soil that is excessively alkaline or acid. Nearby plant species are often examined to see if similar symptoms are evident on several different types of plants.

Examination of stems, shoots, branches, and trunk follows a thorough leaf examination. Sunken, swollen, or discoloured areas in the fleshy stem or bark may indicate canker infection by a fungus or bacterium or injury caused by excessively high or low temperatures, hail, tools, equipment, vehicles, or girdling wires.

Fruiting bodies of fungi in or on such areas often indicate secondary infection. Accurate identification of signs as belonging to a pathogenic organism or a secondary or saprophytic one is difficult. Tissues directly infected by pathogenic fungi or bacteria normally show a gradual change in colour or consistency. Injuries, in comparison, are usually well defined with an abrupt change from healthy to affected tissue.

Holes and sawdustlike debris are evidence of boring insects that usually invade woody plants in a low state of vigour. Other borer indications include wilting and dieback (progressive death of shoots that begins at tip and works downward). These symptoms also are produced by fungi and bacteria that invade water- and food-conducting vascular tissue.

Symptoms of wilt-inducing microorganisms include dark streaks in sapwood of wilted branches when the wood is cut through at an angle.

Abnormal suckers or water sprouts on trees can indicate careless pruning, extremes in temperature or water supply, structural injury, or disease.

Galls, which are unsightly overgrowths on stem, branch, or trunk, may indicate crown gall, insect injury, water imbalance between plant and soil, or other factors. Crown gall is infectious and develops as rough, roundish galls at wounds, resulting from grafting, pruning, or cultivating.

crown gall Plant infected with crown gall.

Wood-decay fungi also enter unprotected wounds, resulting in discoloured, water-soaked, spongy, stringy, crumbly, or hard rots of living and dead wood. External evidence of wood-decay fungi are clusters of mushrooms (or toadstools) and hoof- or shelf-shaped fungal fruiting structures, called conks, punks, or brackets.

Aboveground symptoms of many root problems look alike. They include stunting of leaf and twig growth, poor foliage colour, gradual or sudden decline in vigour and productivity, shoot wilting and dieback, and even rapid death of the plant. The causes include infectious root and crown rot; nematode, insect, or rodent feeding; low temperature or lightning injury; household gas injury; poor soil type or drainage; change in soil grade; or massive removal of roots in digging utility trenches and construction.

Abnormal root growth is revealed by comparison with healthy roots. Some nematodes, such as root knot (*Meloidogyne* species), produce small to large galls in roots; other species cause affected roots to become discoloured, stubby, excessively branched, and decayed. Bacterial and fungal root rots commonly follow feeding by nematodes, insects, and rodents.

Diagnosis of a disease complex, one with two or more causes, is usually difficult and requires separation and identification of the individual causes.

Symptoms

The variety of symptoms, the internal and external expressions of disease, that result from any disease form the symptom complex, which, together with the accompanying signs, makes up the syndrome of the disease.

clubroot Cauliflower roots infected with clubroot.

Generalized symptoms may be classified as local or systemic, primary or secondary, and microscopic or macroscopic. Local symptoms are physiological or structural changes within a limited area of host tissue, such as leaf spots, galls, and cankers. Systemic symptoms are those involving the reaction of a greater part or all of the plant, such as wilting, yellowing, and dwarfing. Primary symptoms are the direct result of pathogen activity on invaded tissues (e.g., swollen "clubs" in clubroot of cabbage and "galls" formed by feeding of the root knot nematode). Secondary symptoms result from the physiological effects of disease on distant tissues and uninvaded organs (e.g., wilting and drooping of cabbage leaves in hot weather resulting from clubroot or root knot). Microscopic disease symptoms are expressions of disease in cell structure or cell arrangement seen under a microscope. Macroscopic symptoms are expressions of disease that can be seen with the unaided eye. Specific macroscopic symptoms are classified under one of four major categories: prenecrotic, necrotic, hypoplastic, and hyperplastic or hypertrophic. These categories reflect abnormal effects on host cells, tissues, and organs that can be seen without a hand lens or microscope.

Signs

Besides symptoms, the diagnostician recognizes signs characteristic of specific diseases. Signs are either structures formed by the pathogen or the result of interaction between pathogen and host—e.g., ooze of fire blight bacteria, slime flux from wetwood of elm, odour of tissues affected with bacterial soft rot.

Technological advances in the identification of pathogenic agents

Developments in microscopy, serology and immunology, molecular biology, and laboratory instrumentation have resulted in many new and sophisticated laboratory procedures for the identification of plant pathogens, particularly bacteria, viruses, and viroids. The techniques of traditional scanning microscopy and transmission electron microscopy have been applied to immunosorbent electron microscopy, in which the specimen is subject to an antigen-antibody reaction before observation and scanning tunneling microscopy, which provides information about the surface of a specimen by constructing a three-dimensional image.

Serological tests have been made more specific and convenient to perform since the discovery of a technique to produce large quantities of monoclonal antibodies, which bind to only one specific antigen. The sensitivity of antigen-antibody detection has been significantly increased by a radioimmunoassay (RIA) procedure. In this procedure a “known” antigen is overlayed on a plastic plate to which antigen molecules adhere. A solution of antibody is applied to the same plate; if the antibody is specific to the antigen, it will combine with it. This is followed by the application of radioactively labeled anti-antibody, which is allowed to react and then washed off. The radioactivity that remains on the plate is a measure of the amount of antibody that combined with the known fixed antigen. Another highly sensitive immunoassay is the enzyme-linked immunosorbent assay (ELISA). In principle this assay is similar to the RIA except that an enzyme system, instead of radioactivity, is used as an indicator of an antigen-antibody combination.

New analytic methods in molecular biology have made genetic studies for the characterization and identification of bacteria more practical. The DNA hybridization technique is an example. A strand of DNA from a known species (the probe) is radioactively labeled and “mixed” with DNA from an unidentified species. If the probe and the unknown DNA are from identical species, they will have complementary DNA sequences that enable them to bind to one another. Bound to DNA from the unknown species, the probe acts as a marker and identifies the bacteria.

The growing demand for quick identification of microorganisms has resulted in the development of instrumentation for automated technology that allows a large number of tests to be performed on many specimens in a short period of time. The results are read automatically and analyzed by a computer program to identify the pathogens.

Principles of disease control

Successful disease control requires thorough knowledge of the causal agent and the disease cycle, host-pathogen interactions in relation to environmental factors, and cost. Disease control starts with the best variety, seed, or planting stock available and continues throughout the life of the plant. For harvested crops, disease control extends through transport, storage, and marketing. Relatively few diseases are controlled by a single method; the majority require several approaches. These often need to be integrated into a broad program of biological, cultural, and chemical methods to control as many different pests—including insects, mites, rodents, and weeds—on a given crop as possible.

Most control measures are directed against inoculum of the pathogen and involve the principles of exclusion and avoidance, eradication, protection, host resistance and selection, and therapy.

Exclusion and avoidance

The principle of exclusion and avoidance is to keep the pathogen away from the growing host plant. This practice commonly excludes pathogens by disinfection of plants, seeds, or other parts, using chemicals or heat. Inspection and certification of seed and other planting stock help ensure freedom from disease. For gardeners this involves sorting bulbs or corms before planting and rejecting diseased plants. Federal and state plant quarantines, or embargoes, have been established to prevent introduction of potentially destructive pathogens into areas currently free of the disease. More than 150 countries now have established quarantine regulations.

Eradication

Eradication is concerned with elimination of the disease agent after it has become established in the area of the growing host or has penetrated the host. Such measures include crop rotation, destruction of the diseased plants, elimination of alternate host plants, pruning, disinfection, and heat treatments.

Crop rotation with nonsusceptible crops “starves out” bacteria, fungi, and nematodes with a restricted host range. Some pathogens can survive only as long as the host residue persists, usually no more than a year or two. Many pathogens, however, are relatively unaffected by rotation because they become established as saprotrophs in the soil (e.g., *Fusarium* and *Pythium* species; *Rhizoctonia solani*; and the potato scab actinomycete, *Streptomyces scabies*) or their propagative structures remain dormant but viable for many years (e.g., cysts of cyst nematodes, sporangia of the cabbage clubroot fungus, and onion smut spores).

Burning, deep plowing of plant debris, and fall spraying are used against such diseases as leaf blights of tomato, Dutch elm disease, and apple scab. Destruction of weed hosts also helps control such viral diseases as cucumber mosaic and curly top. For fungi whose complete life cycle requires two different host species, such as black stem rust of cereals and white-pine blister rust, destruction of alternate hosts is effective. Destruction of diseased plants helps control Dutch elm disease, oak wilt, and peach viral diseases—mosaic, phony peach, and rosette. Elimination of citrus canker in the southeastern United States has been one of the few successful eradication programs in history. Infected trees were sprayed with oil and burned.

Pruning and excision of a diseased portion of the plant have aided in reducing inoculum sources for canker and wood-rot diseases of shade trees and fire blight of pome fruits. Disinfection of contaminated tools, as well as packing and shipping containers, controls a wide range of diseases. Direct application of dry or wet heat is used to obtain seeds, bulbs, other propagative materials, and even entire plants free of viruses, nematodes, and other pathogens.

Protection

The principle of protection involves placing a barrier between the pathogen and the susceptible part of the host to shield the host from the pathogen. This can be accomplished by regulation of the environment, cultural and handling practices, control of insect carriers, and application of chemical pesticides.

Regulation of the environment

Selection of outdoor growing areas where weather is unfavourable for disease is a method of controlling disease by regulating the environment. Control of viral diseases of potato, for example, can be accomplished by growing the seed crop in northern regions where low temperatures are unfavourable for the aphid carriers. Another environmental factor that can be brought under control is the storage and in-transit environment. A variety of postharvest diseases of potato, sweet potato, onion, cabbage, apple, pear, and other crops are controlled in storage and shipment by keeping humidity and temperature low and by reducing the quantity of ethylene and other natural gases in storage houses.

Cultural practices

Selection of the best time and depth of seeding and planting is an effective cultural practice that reduces disease impact. Shallow planting of potatoes may help to prevent *Rhizoctonia* canker. Early fall seeding of winter wheat may be unfavourable for seedling infection by wheat bunt teliospores. Cool-temperature crops can be grown in soils infested with root knot nematode and harvested before soil temperatures become favourable for nematode activity. Adjustment of soil moisture is another cultural practice of widespread usefulness. For example, seed decay, damping-off (the destruction of seedlings at the soil line), and other seedling diseases are favoured by excessively wet soils. The presence of drain tiles in poorly drained fields and the use of ridges or beds for plants are often beneficial. Adjustment of soil pH also leads to control of some diseases. Common potato scab can be controlled by adjusting the pH to 5.2 or below; other acid-tolerant plants then must be used in crop rotation, however.

Regulation of fertility level and nutrient balance

Potash and nitrogen, and the balance between the two, may affect the incidence of certain bacterial, fungal, and viral diseases of corn, cotton, tobacco, and sugar beet. A number of microelements, including boron, iron, zinc, manganese, magnesium, copper, sulfur, and molybdenum, may cause noninfectious diseases of many crop and ornamental plants. Adjusting the soil pH, adding chelated (bound or enclosed in large organic molecules) or soluble salts to the soil, or spraying the foliage with these or similar salts is a corrective measure.

Handling practices

Late blight on potato tubers can be controlled by delaying harvest until the foliage has been killed by frost, chemicals, or mechanical beaters. Avoidance of bruises and cuts while digging, grading, and packing potatoes, sweet potatoes, and bulb crops also reduces disease incidence.

Control of insect vectors

There are many examples in which losses by bacteria, viruses, and mycoplasma-like disease agents can be reduced by controlling aphids, leafhoppers, thrips, beetles, and other carriers of these agents. Insect vectors can be controlled with organic or synthetic insecticides or by means of biological control.

Chemical control

A variety of chemicals are available that have been designed to control plant diseases by inhibiting the growth of or by killing the disease-causing pathogens. Chemicals used to control bacteria (bactericides), fungi (fungicides), and nematodes (nematicides) may be applied to seeds, foliage, flowers, fruit, or soil. They prevent or reduce infections by utilizing various principles of disease control. Eradicants are designed to kill a pathogen that may be present in the soil, on the seeds, or on vegetative propagative organs, such as bulbs, corms, and tubers. Protectants place a chemical barrier between the plant and the pathogen. Therapeutic chemicals are applied to combat an infection in progress.

Soil treatments are designed to kill soil-inhabiting nematodes, fungi, and bacteria. This eradication can be accomplished using steam or chemical fumigants. Soilborne nematodes can be killed by applying granular or liquid nematicides. Most soil is treated well before planting; however, certain fungicides can be mixed with the soil at planting time.

Seeds, bulbs, corms, and tubers are frequently treated with chemicals to eradicate pathogenic bacteria, fungi, and nematodes and to protect the seeds against organisms in the soil—mainly fungi—that cause decay and damping-off. Seeds are often treated with systemic fungicides, which are absorbed and provide protection for the growing seedling.

Protective sprays and dusts applied to the foliage and fruit of crops and ornamentals include a wide range of organic chemicals designed to prevent infection. Protectants are not absorbed by or translocated through the plant; thus they protect only those parts of the plant treated before invasion by the pathogen. A second application is often necessary because the chemical may be removed by wind, rain, or irrigation or may be broken down by sunlight. New, untreated growth also is susceptible to infection. New chemicals are constantly being developed.

Biological control

Biological control of plant diseases involves the use of organisms other than humans to reduce or prevent infection by a pathogen. These organisms are called antagonists; they may occur naturally within the host's environment, or they may be purposefully applied to those parts of the potential host plant where they can act directly or indirectly on the pathogen.

Although the effects of biological control have long been observed, the mechanisms by which antagonists achieve control is not completely understood. Several methods have been observed: some antagonists produce antibiotics that kill or reduce the number of closely related pathogens; some are parasites on pathogens; and others simply compete with pathogens for available food.

Cultural practices that favour a naturally occurring antagonist and exploit its beneficial action often are effective in reducing disease. One technique is to incorporate green manure, such as alfalfa, into the soil. Saprotrophic microorganisms feed on the green manure, depriving potential pathogens of available nitrogen. Another practice is to make use of suppressive soils—those in which a pathogen is known to persist but causes little damage to the crop. A likely explanation for this phenomenon is that suppressive soils harbour antagonists that compete with the pathogen for food and thereby limit the growth of the pathogen population.

Other antagonists produce substances that inhibit or kill potential pathogens occurring in close proximity. An example of this process, called antibiosis, is provided by marigold (*Tagetes* species) roots, which release terthienyls, chemicals that are toxic to several species of nematodes and fungi.

Only a few antagonists have been developed specifically for use in plant-disease control. Citrus trees are inoculated with an attenuated strain of tristeza virus, which effectively controls the virulent strain that causes the disease. An avirulent strain of *Agrobacterium radiobacter* (K84) can be applied to plant wounds to prevent crown gall caused by infection with *Agrobacterium tumefaciens*. Many more specific antagonists are being investigated and hold much promise for future control of disease.

Therapy

Therapeutic measures have been used much less often in plant pathology than in human or animal medicine. The recent development of systemic fungicides such as oxathiins, benzimidazoles, and pyrimidines have enabled growers to treat many plants after an infection has begun. Systemic chemicals are absorbed by and translocated within the plant, restricting the spread and development of pathogens by direct or indirect toxic effects or by increasing the ability of the host to resist infection.

Antibiotics have been developed to control various plant diseases. Most of these drugs are absorbed by and translocated throughout the plant, providing systemic therapy. Streptomycin is used against a variety of bacterial pathogens, tetracycline is able to control the growth of certain mycoplasmas, and cycloheximides offer effective control for certain diseases caused by fungi.

Host resistance and selection

Disease-resistant varieties of plants offer an effective, safe, and relatively inexpensive method of control for many crop diseases. Most available commercial varieties of crop plants bear resistance to at least one, and often several, pathogens. Resistant or immune varieties are critically important for low-value crops in which other controls are unavailable, or their expense makes them impractical. Much has been accomplished in developing disease-resistant varieties of field crops, vegetables, fruits, turf grasses, and ornamentals. Although great flexibility and potential for genetic change exist in most economically important plants, pathogens are also flexible. Sometimes, a new plant variety is developed that is highly susceptible to a previously unimportant pathogen.

Variable resistance

Resistance to disease varies among plants; it may be either total (a plant is immune to a specific pathogen) or partial (a plant is tolerant to a pathogen, suffering minimal injury). The two broad categories of resistance to plant diseases are vertical (specific) and horizontal (nonspecific). A plant variety that exhibits a high degree of resistance to a single race, or strain, of a pathogen is said to be vertically resistant; this ability usually is controlled by one or a few plant genes. Horizontal resistance, on the other hand, protects plant varieties against several strains of a pathogen, although the protection is not as complete. Horizontal resistance is more common and involves many genes.

Obtaining disease-resistant plants

Several means of obtaining disease-resistant plants are commonly employed alone or in combination. These include introduction from an outside source, selection, and induced variation. All three may be used at different stages in a continuous process; for example, varieties free from injurious insects or plant diseases may be introduced for comparison with local varieties. The more promising lines or strains are then selected for further propagation, and they are further improved by promoting as much variation as possible through hybridization or special treatment. Finally, selection of the plants showing greatest promise takes place. Developing disease-resistant plants is a continuing process.

Special treatments for inducing gene changes include the application of mutation-inducing chemicals and irradiation with ultraviolet light and X-rays. These treatments commonly induce deleterious genetic changes, but, occasionally, beneficial ones also may occur.

Methods used in breeding plants for disease resistance are similar to those used in breeding for other characters except that two organisms are involved—the host plant and the pathogen. Thus, it is necessary to know as much as possible about the nature of inheritance of the resistant characters in the host plant and the existence of physiological races or strains of the pathogen.

The use of genetic engineering in developing disease-resistant plants

The techniques of genetic engineering can be used to manipulate the genetic material of a cell in order to produce a new characteristic in an organism. Genes from plants, microbes, and animals can be recombined (recombinant DNA) and introduced into the living cells of any of these organisms.

Genetically modified organisms that have had genes from other species inserted into their genome (the full complement of an organism's genes) are called transgenic. The production of pathogen-resistant transgenic plants has been achieved by this method; certain genes are inserted into the plant's genome that confer resistance to such pathogens as viruses, fungi, and insects. Transgenic plants that are tolerant to herbicides and that show improvements in other qualities also have been developed.

Apprehension about the release of transgenic plants into the environment exists, and measures to safeguard the application of this technology have been adopted. In the United States several federal agencies, such as the U.S. Department of Agriculture, the Food and Drug Administration, and the Environmental Protection Agency, regulate the use of genetically engineered organisms. As of 2016, more than 457 million acres (185 million hectares) worldwide were planted with genetically modified

(GM) crops. Among the most successful GM crops are corn (maize), soybeans, and cotton, all of which have proved valuable to farmers with respect to producing increased yields and having economic advantages.

Classification of plant diseases by causal agent

Plant diseases are often classified by their physiological effects or symptoms. Many diseases, however, produce practically identical symptoms and signs but are caused by very different microorganisms or agents, thus requiring completely different control methods. Classification according to symptoms is also inadequate because a causal agent may induce several different symptoms, even on the same plant organ, which often intergrade. Classification may be according to the species of plant affected. Host indexes (lists of diseases known to occur on certain hosts in regions, countries, or continents) are valuable in diagnosis. When an apparently new disease is found on a known host, a check into the index for the specific host often leads to identification of the causal agent. It is also possible to classify diseases according to the essential process or function that is adversely affected. The best and most widely used classification of plant diseases is based on the causal agent, such as a noninfectious agent or an infectious agent (i.e., a virus, viroid, mycoplasma, bacterium, fungus, nematode, or parasitic flowering plant).

Noninfectious disease-causing agents

Noninfectious diseases, which sometimes arise very suddenly, are caused by the excess, deficiency, nonavailability, or improper balance of light, air circulation, relative humidity, water, or essential soil elements; unfavourable soil moisture-oxygen relations; extremes in soil acidity or alkalinity; high or low temperatures; pesticide injury; other poisonous chemicals in air or soil; changes in soil grade; girdling of roots; mechanical and electrical agents; and soil compaction. In addition, unfavourable preharvest and storage conditions for fruits, vegetables, and nursery stock often result in losses. The effects of noninfectious diseases can be seen on a variety of plant species growing in a given locality or environment. Many diseases and injuries caused by noninfectious agents result in heavy loss but are difficult to check or eliminate because they frequently reflect ecological factors beyond human control. Symptoms may appear several weeks or months after an environmental disturbance.

Injuries incurred from accidents, poisons, or adverse environmental disturbances often result in damaged tissues that weaken a plant, enabling bacteria, fungi, or viruses to enter and add further damage. The cause may be obvious (lightning or hail), but often it is obscure. Symptoms alone are often unreliable in identifying the causal factor. A thorough examination of recent weather patterns, the condition of surrounding plants, cultural treatments or disturbances, and soil and water tests can help reveal the nature of the disease.

Adverse environment

High temperatures may scald corn, cotton, and bean leaves and may induce formation of cankers at the soil surface of tender flax, cotton, and peanut plants. Frost injury is relatively common, but temperatures just above freezing also may cause damage, such as net necrosis (localized tissue death) in potato tubers and "silvering" of corn leaves. Isolated, thin-barked trees growing in northern climates and subjected to frequent thawing by day and freezing by night may develop dead bark cankers or vertical frost cracks on the south or southwest sides of the trunk. Alternate freezing and thawing, heaving, low air moisture, and smothering under an ice-sheet cover are damaging to alfalfa, clovers, strawberries, and grass on golf greens. Legume crowns commonly split under these conditions and are invaded by decay-forming fungi.

The drought and dry winds that often accompany high temperatures cause stunting, wilting, blasting, marginal scorching of leaves, and dieback of shoots. Leaf scorch is common on trees in exposed locations following hot, dry, windy weather when water is lost from leaves faster than it is absorbed by roots. Leaf scorch and sudden flower drop are common indoor plant problems because the humidity in a home, an apartment, or an office is usually below 30 percent. Similar symptoms are caused by a change in soil grade, an altered water-table level, a compacted and shallow soil, paved surface over tree roots, temporary flooding or a waterlogged (oxygen-deficient) soil, girdling tree roots, salt spray near the ocean, and an injured or diseased root system. Injured plants are often very susceptible to air and soil pathogens and secondary invaders.

Blossom-end rot of tomato and pepper is prevalent when soil moisture and temperature levels fluctuate widely and calcium is low.

Poor aeration may cause blackheart in stored potatoes. Accumulation of certain gases from the respiration of apples in storage may produce apple scald and other disorders.

All plants require certain mineral elements to develop and mature in a healthy state. Macronutrients such as nitrogen, potassium, phosphorus, sulfur, calcium, and magnesium are required in substantial quantities, while micronutrients or trace elements such as boron, iron, manganese, copper, zinc, and molybdenum are needed in much smaller quantities. When the supply of any essential nutrient falls below the level required by the plant, a deficiency occurs, leading to symptoms that include stunting of plants; scorching or malformation of leaves; abnormal coloration; premature leaf, bud, and flower drop; delayed maturity or failure of flower and fruit buds to develop; and dieback of shoots.

Symptoms of nutrient deficiencies vary depending on the nutrients involved, the stage of plant growth, soil moisture, and other factors; they often resemble symptoms caused by infectious agents such as bacteria or viruses.

The availability of water may affect nutrient uptake by the plant. Blossom-end rot of tomato, a disease associated with a deficiency of calcium, may occur if the water supply is irregular, even if an adequate amount of calcium is in the soil. This discontinuity in availability of water will inhibit uptake of the calcium in a quantity sufficient to nourish a fast-growing tomato plant. Necrosis at the blossom end of the fruit results. This situation generally disappears when water conditions improve.

Excess minerals can damage plants either directly, causing stunting, deformities, or dieback, or indirectly by interfering with the absorption and use of other nutrients, resulting in subsequent deficiency symptoms. A superabundance of nitrogen, for example, may cause deficiency symptoms of potassium, zinc, or other nutrient elements; a lack of or delay in flower and fruit development; and a predisposition to winter injury. If potassium is high, calcium and magnesium deficiencies may occur.

The pH of a soil has a dramatic impact on nutrient availability to plants. Most plants will grow in a soil with a pH between 4.0 and 8.0. In acidic soils some nutrients are far more available and may reach concentrations that are toxic or that inhibit absorption of other nutrients, while other minerals become chemically bound and unavailable to plants. A similar situation exists in alkaline soils, although different minerals are affected. Oats planted in alkaline soils that actually contain a sufficient amount of manganese may develop the manganese-deficiency disease gray speck. This occurs because an elevated soil pH causes manganese to react with oxygen to produce manganese dioxide, a form of the nutrient that is insoluble to plants.

An excess of water-soluble salts is a common problem with houseplants. Salt concentrations may build up as a whitish crust on soil and container surfaces of potted plants following normal evaporation of water over a period of time. Symptoms include leaf scorching, bronzing, yellowing and stunting, and wilting, plus root and shoot dieback. Damage from soluble salts is also common in arid regions and in regions where ice-control chemicals are applied heavily.

Several nonparasitic diseases (e.g., oat blast, weakneck of sorghum, straighthead of rice, and crazy-top of cotton) are caused by combinations of environmental factors—e.g., high temperatures, moisture stress or poor irrigation practices, imbalance of mineral nutrients, and reduced light.

Environmental disturbances alter the normal physiology of the plant, activity of pathogens, and host-pathogen interactions.