CONTROL OF PLANT DISEASES

Most serious diseases of crop plants appear on a few plants in an area year after year, spread rapidly, and are difficult to cure after they have begun to develop. Therefore, almost all control methods are aimed at protecting plants from becoming diseased rather than at curing them after they have become diseased. Few infectious plant diseases can be controlled satisfactorily in the field by therapeutic means.

Depending on the nature of the agents employed, various control methods can be classified as:

1. Regulatory control methods
2. Cultural control methods
3. Biological control methods
4. Physical methods
5. Chemical methods of control.

Regulatory control measures aim at excluding a pathogen from a host or from a certain geographic area. Most **cultural control methods** aim at helping plants avoid contact with a pathogen, creating environmental conditions unfavorable to the pathogen or avoiding favourable ones, and eradicating or reducing the amount of a pathogen in a plant, a field, or an area. Most **biological** and some cultural **control methods** aim at improving the resistance of the host or favoring microorganisms antagonistic to the pathogen.

1. Regulatory Methods

1.1 Quarantines and Inspections: When plant pathogens are introduced into an area in which host plants have been growing in the absence of the pathogen, such introduced pathogens may cause much more catastrophic epidemics than the existing endemic pathogens. This happens because plants that develop in the absence of a pathogen have no opportunity to select resistance factors specific against the pathogen and are, therefore, unprotected and extremely vulnerable to attack. Also, no microorganisms antagonistic or competing with the pathogen are likely to be present, while, on the other hand, the pathogen finds a large amount of available susceptible tissue on which it can feast and multiply unchecked. Some of the worst plant disease epidemics, e.g., the downy mildew of grapes in Europe and the bacterial canker of citrus, chestnut blight, Dutch elm disease, and soybean cyst nematode in the United States, are all diseases caused by pathogens that were introduced from abroad. It has been estimated, for example, that if soybean rust were introduced into the United States it would result in losses to consumers and other sectors of the U.S. economy of several billion dollars per year. Numerous other pathogens exist in many parts of the world but not yet in the United States, and they would most likely cause severe diseases to crops and great economic losses if they were to enter the country.

To keep out foreign plant pathogens and to protect U.S. farms, gardens, and forests, the Plant Quarantine Act of 1912 was passed by Congress. This act prohibits or restricts entry into or passage through the United States from foreign countries of plants, plant products, soil, and other materials carrying or likely to carry plant pathogens not known to be established in this country. Similar quarantine regulations exist in most other countries. Because plant scientists, plant breeders, and agricultural industries need to bring into the country plant germplasm on a more or less continuing basis, a National Plant Germplasm Quarantine Center has been established in Glendale, Maryland, near Washington, DC, where all introductions are kept and tested for certain pathogens for 1 to 4 years before they are released.

Experienced inspectors stationed at all points of entry into the country enforce quarantines of produce likely to introduce new pathogens. Plant quarantines are already credited for the interception of numerous foreign plant pathogens and, thereby, with saving the country's plant world from potentially catastrophic diseases. Plant quarantines are considerably less than foolproof, however, because pathogens may be introduced in the form of spores or eggs on unsuspected carriers, and latent infections of seeds and other plant propagative organs may exist even after treatment. Various steps taken by plant quarantine stations, such as growing plants under observation for certain times before they are released to the importer, repeated serological tests of seed lots (mostly through ELISA), nucleic acid tests involving DNA probes and polymerase chain reaction (PCR) amplification of specific pathogen DNA sequences, and inspection of imported nursery stock in the grower's premises, tend to reduce the chances of introduction of harmful pathogens. With the annual imports of flower bulbs from Holland, U.S. quarantine inspectors may visit the flower fields in Holland and inspect them for certain diseases. If they find the field to be free of these diseases, they issue inspection certificates allowing the import of such bulbs into the United States without further tests. Similar quarantine regulations govern the interstate, and even intrastate, sale of nursery stock, tubers, bulbs, seeds, and other propagative organs, especially of certain crops such as potatoes and fruit trees. The movement and sale of such materials within and between states are controlled by the regulatory agencies of each state.

1.2 Crop Certification: Several voluntary or compulsory inspection systems are in effect in various states in which appreciable amounts of nursery stock and potato seed tubers are produced. Growers interested in producing and selling disease-free plants submit to a voluntary inspection or indexing of their crop in the field and in storage by the state regulatory agency, experiment station personnel, or others. If, after certain procedures recommended by the inspecting agency are carried out, the plant material is found to be free of certain, usually virus, diseases, the inspecting agency issues a certificate indicating that the plants are free from these specific diseases, and the grower may then advertise and sell the plant material as disease free — at least from the diseases for which it was tested.

1.3 Pathogen-Free Seed: Seed that is free of fungal, bacterial, and some viral pathogens is usually obtained by growing the crop and producing the seed in (1) an area free of or isolated from the pathogen, (2) an area not suitable for the pathogen (e.g., the arid western regions of the United States where bean seed is produced usually free of anthracnose and bacterial

blights), or (3) an area not suitable for the vector of the pathogen (e.g., the northern or high altitude fields where aphids, the vectors of many viruses, are absent or rare).
It is very important, and with seed-transmitted and aphid-borne viruses it is indispensable, that seed be essentially free of the pathogen, especially virus. Because, if carried in the seed, the pathogen will be present in the field at the beginning of the growth season, and even a small proportion of infected seeds is sufficient to provide enough inoculum to spread and infect many plants early, thus causing severe losses. It has been shown, for example, that to control lettuce mosaic virus, only seed lots that contain less than one infected seed per 30,000 lettuce seeds must be used. For this purpose, seed companies have their lettuce seed tested for lettuce mosaic virus every year. In past years, seeds were tested (indexed) by growing out hundreds of thousands of lettuce seedlings in insect-proof greenhouses, observing them over several weeks for lettuce mosaic symptoms, and attempting to transmit the virus from suspect plants to healthy plants. Later, indexing was done by inoculating a local lesion indicator plant (in this case *Chenopodium quinoa*) with sap from ground samples of groups of seeds and observing it for virus symptoms. Since the 1980s, testing for lettuce mosaic virus in seed is done with serological techniques, particularly with ELISA, which is faster, more sensitive, and less expensive than the other methods.

2. Cultural methods that eradicate or reduce pathogen inoculum

Many cultural methods aim at eradicating or reducing the amount of pathogen present in an area, a plant, or plant parts (such as seeds). These methods depend primarily on certain actions of the grower, such as host eradication, crop rotation, sanitation, improving plant growing conditions, creating conditions unfavorable to pathogens, polyethylene mulching, trickle irrigation, ecofallow, and, sometimes, reduced tillage farming. Some methods are physical, i.e., they depend on a physical factor such as heat or cold. Examples are soil sterilization, heat treatment of plant organs, refrigeration, and radiations. Several methods are chemical, i.e., they depend on the use and action of a chemical substance to reduce the pathogen. Examples are soil treatment, soil fumigation, and seed treatment with chemicals. Some methods are biological, i.e., they use living organisms to reduce the pathogen inoculum. Examples are the use of trap crops and antagonistic plants against nematodes, use of amendments that favor microflora antagonistic to the pathogen, and use of antagonistic microorganisms. The latter apparently inhibit the growth of the pathogen by producing antibiotics, by attacking and parasitizing the pathogen directly, or by competing for sites on the plant.

2.1 Host Eradication: When a pathogen has been introduced into a new area despite a quarantine, a plant disease epidemic frequently follows. To prevent such an epidemic, all the host plants infected by or suspected of harboring the pathogen may have to be removed and burned. This eliminates the pathogen and prevents greater losses from the spread of the pathogen to additional plants. Beginning in 1915, this type of host eradication controlled the bacterial canker of citrus in Florida and other southern states, where more than three million

trees had to be destroyed. Another outbreak of citrus canker occurred in Florida in 1984, and, by 1992, the disease was apparently brought under control through the painful destruction of millions of nursery and orchard trees in that state. In 1995, citrus canker was again found in Florida, but only on trees in a residential area of Miami. Immediately, an area of approximately 100 square miles was placed under quarantine, and eradication of all infected and all nearby trees, mostly in home gardens or yards, was undertaken; the disease, however, has continued to spread among trees in nearby cities and towns and its eradication has become extremely difficult, if not impossible. In a different disease, since the 1970s, a campaign to contain and eradicate witchweed (*Striga asiatica*) in the eastern Carolinas in the United States has been successful. However, attempts by several European countries to eradicate fire blight of apple and pear (caused by the bacterium *Erwinia amylovora*) and plum pox virus of stone fruits, of the United States to eradicate plum pox virus, and attempts by several South American countries to eradicate coffee rust (caused by the fungus *Hemileia vastatrix*) have not been successful, and the pathogens continue to spread. Host eradication (roguing) is also carried out routinely in many nurseries, greenhouses, and fields to prevent the spread of numerous diseases by eliminating infected plants that provide a ready source of inoculum within the crop.

Certain pathogens of annual crops, e.g., cucumber mosaic virus, overwinter only or mainly in perennials, usually wild plants. Eradication of the host in which the pathogen overwinters is sometimes enough to eliminate completely or to reduce drastically the amount of inoculums that can cause infections the following season. In some crops, such as potatoes, pathogens of all types may overwinter in infected tubers that are left in the field. Many such tubers produce infected plants in the spring that allow the pathogen to come above ground, from where it can be spread further by insects, rain, and wind. Eradication of such volunteer plants helps greatly to reduce the inoculum of these pathogens. Also, in warmer areas, volunteer plants of a crop, e.g., tomato, grow during periods between plantings of the crop. Such volunteers become infected by various pathogens, e.g., tomato mottle and tomato yellow leaf curl viruses, during the crop-free season and serve as reservoirs for the pathogens that are again spread into and cause disease once the cultivated crop is planted.

Some pathogens require two alternate hosts to complete their full life cycles. For example, *Puccinia graminis tritici* requires wheat and barberry, *Cronartium ribicola* requires pine and currant (*Ribes*), and *Gymnosporangium juniperi-virginianae* requires cedar and apple. In these cases, eradication of the wild or economically less important alternate host interrupts the life cycle of the pathogen and leads to control of the disease. This has been carried out somewhat successfully with stem rust of wheat and white pine blister rust through eradication of barberry and currant, respectively. However, due to other factors, both diseases are still widespread and often cause severe losses. In cases like cedar-apple rust, in which both hosts may be important, control through eradication of the alternate host is impractical.

2.2 Crop Rotation: Soilborne pathogens that infect plants of one or a few species or even families of plants can sometimes be reduced in the soil by planting, for 3 or 4 years, crops belonging to species or families not attacked by the particular pathogen. Satisfactory control

through crop rotation is possible with pathogens that are **soil invaders**, i.e., survive only on living plants or only as long as the host residue persists as a substrate for their saprophytic existence. When the pathogen is a **soil inhabitant**, however, i.e., produces long-lived spores or can live as a saprophyte for more than 5 or 6 years, crop rotation becomes less effective or impractical. In the latter cases, crop rotation can still reduce populations of the pathogen in the soil (e.g., *Verticillium*) (Fig. 9-2), and appreciable yields from the susceptible crop can be obtained every third or fourth year of the rotation. In some cropping systems the field is tilled and left fallow for a year or part of the year. During fallow, debris and inoculum are destroyed by microorganisms with little or no replacement. In areas with hot summers, fallow allows greater heating and drying of the soil, which leads to a marked reduction of nematodes and some other pathogens. Other cropping systems utilize herbicides and reduced tillage and fallow (ecofallow). In some such systems, certain diseases, e.g., stalk rot of grain sorghum and corn, caused by *Fusarium moniliforme*, have been reduced dramatically. In contrast, other diseases, such as Septoria leaf blotch of wheat and wheat and barley scab, have been increased.

2.3 Sanitation: Sanitation consists of all activities aimed at eliminating or reducing the amount of inoculum present in a plant, a field, or a warehouse and at preventing the spread of the pathogen to other healthy plants and plant products. Thus, plowing under infected plants after harvest, such as leftover infected fruit, stems, tubers, or leaves, helps cover the inoculum with soil and speeds up its disintegration (rotting) and concurrent destruction of most pathogens carried in or on them. Similarly, removing infected leaves of house or garden plants helps remove or reduce the inoculum. Pruning infected plants or infected or dead branches and then removing infected fruit and any other plant debris that may harbour the pathogen help reduce the inoculum and do not allow the pathogen to grow into still healthy parts of the tree. Such actions reduce the amount of disease that will develop later. In some parts of the world, infected crop debris of grass seed and rice crops is destroyed by burning, which reduces or eliminates the surface inoculums of several pathogens.
By washing their hands before handling certain kinds of plants, such as tomatoes, workers who smoke may reduce the spread of *tobacco mosaic virus*. Also, frequently disinfesting knives used to cut propagative stock, such as potato tubers, and disinfesting pruning shears between trees reduce the spread of pathogens through such tools. Washing the soil off farm equipment before moving it from one field to another may also help prevent the spread of any pathogens present in the soil. Similarly, by washing, often with chlorinated water, the produce, its containers, and the walls of storage houses, the amount of inoculum and subsequent infections may be reduced considerably.

2.4 Creating Conditions Unfavorable to the Pathogen: Stored products should be aerated properly to hasten the drying of their surfaces and inhibit germination and infection by any fungal or bacterial pathogens present on them. Similarly, spacing plants properly in the field or greenhouse prevents the creation of high-humidity conditions on plant surfaces and inhibits infection by certain pathogens, such as *Botrytis* and *Peronospora tabacina*. Good soil drainage also reduces the number and activity of certain oomycete pathogens (e.g., *Pythium*) and nematodes and may result in significant disease control. The appropriate choice of

fertilizers or soil amendments may also lead to changes in the soil pH, which may unfavorably influence the development of the pathogen. Flooding fields for long periods or dry fallowing may also reduce the number of certain pathogens in the soil (e.g., *Fusarium*, *Sclerotinia sclerotiorum*, and nematodes) by inducing starvation, lack of oxygen, or desiccation.

2.5 Polyethylene Traps and Mulches: Many plant viruses, such as cucumber mosaic virus, are brought into crops, such as peppers, by airborne aphid vectors. When vertical, sticky, yellow polyethylene sheets are erected along the edges of susceptible crops, a considerable number of aphids are attracted to and stick to the plastic. This is done primarily to trap and monitor incoming insects, but to some extent it also reduces the amount of virus inoculum reaching the crop. However, if reflectant aluminum or black, whitish-gray, or colored polyethylene sheets are used as mulches between the plants or rows in the field, incoming aphids, thrips, and possibly other insect vectors are repelled and misled away from the field. As a result, fewer virus carrying vectors land on the plants and fewer plants become infected with the virus. Reflectant mulches, however, cease to function as soon as the crop canopy covers them.

3. Biological Methods

Biological control of pathogens, i.e., the total or partial destruction of pathogen populations by other organisms, occurs routinely in nature. There are, for example, several diseases in which the pathogen cannot develop in certain areas either because the soil, called **suppressive soil**, contains microorganisms antagonistic to the pathogen or because the plant that is attacked by a pathogen has also been inoculated naturally with antagonistic microorganisms before or after the pathogen attack. Sometimes, the antagonistic microorganisms may consist of avirulent strains of the same pathogen that destroy or inhibit the development of the pathogen, as happens in **hypovirulence** and **cross protection**. In some cases, even higher plants reduce the amount of inoculum either by trapping available pathogens (trap plants) or by releasing into the soil substances toxic to the pathogen. Agriculturalists have increased their efforts to take advantage of such natural biological antagonisms and to develop strategies by which biological control can be used effectively against several plant diseases. Biological antagonisms, although subject to numerous ecological limitations, are expected to become an important part of the control measures employed against many more diseases.

3.1 Suppressive Soils: Several soilborne pathogens, such as *Fusarium oxysporum* (the cause of vascular wilts), *Gaeumannomyces graminis* (the cause of take-all of wheat), *Phytophthora cinnamomi* (the cause of root rots of many fruit and forest trees), *Pythium* spp. (a cause of damping-off), and *Heterodera avenae* (the oat cyst nematode), develop well and cause severe diseases in some soils, known as **conducive soils**, whereas they develop much less and cause much milder diseases in other soils, known as **suppressive soils**. The mechanisms by which soils are suppressive to different pathogens are not always clear but may involve biotic and/or

abiotic factors and may vary with the pathogen. In most cases, however, it appears that they operate primarily by the presence in such soils of one or several microorganisms antagonistic to the pathogen. Such antagonists, through the antibiotics they produce, through lytic enzymes, through competition for food, or through direct parasitizing of the pathogen, do not allow the pathogen to reach high enough populations to cause severe disease. Numerous kinds of antagonistic microorganisms have been found to increase in suppressive soils; most commonly, however, pathogen and disease suppression has been shown to be caused by fungi, such as *Trichoderma*, *Penicillium*, and *Sporidesmium*, or by bacteria of the genera *Pseudomonas*, *Bacillus*, and *Streptomyces*. Suppressive soil added to conducive soil can reduce the amount of disease by introducing microorganisms antagonistic to the pathogen. For example, soil amended with soil containing a strain of a *Streptomyces* species antagonistic to *Streptomyces scabies*, the cause of potato scab, resulted in potato tubers significantly free from potato scab. Suppressive, virgin soil has been used, for example, to control *Phytophthora* root rot of papaya by planting papaya seedlings in suppressive soil placed in holes in the orchard soil, which was infested with the root rot oomycete *Phytophthora palmivora*. However, in several diseases, continuous cultivation (monoculture) of the same crop in a conducive soil, after some years of severe disease, eventually leads to reduction in disease through increased populations of microorganisms antagonistic to the pathogen. For example, continuous cultivation of wheat or cucumber leads to reduction of take-all of wheat and of *Rhizoctonia* damping-off of cucumber, respectively. Similarly, continuous cropping of the watermelon variety 'Crimson Sweet' allows the buildup of antagonistic species of *Fusarium* related to that causing *Fusarium* wilt of watermelon with the result that *Fusarium* wilt is reduced rather than increased. Such soils are suppressive to future disease development. That suppressiveness is due to antagonistic microflora can be shown by pasteurization of the soil at 60°C for 30 minutes, which completely eliminates the suppressiveness.

3.2 Reducing Amount of Pathogen Inoculum through Antagonistic Microorganisms Soilborne Pathogens: Among the most common mycoparasitic fungi are *Trichoderma* sp., mainly *T. harzianum*. The latter fungus has been shown to parasitize mycelia of *Rhizoctonia* and *Sclerotium*, to inhibit the growth of many oomycetes such as *Pythium*, *Phytophthora*, and other fungi, e.g., *Fusarium* and *Heterobasidion* (*Fomes*), and to reduce the diseases caused by most of these pathogens. Other common mycoparasitic fungi are *Laetisaria arvalis* (*Corticium* sp.), a mycoparasite and antagonist of *Rhizoctonia* and *Pythium*; also, *Sporidesmium sclerotivorum*, *Gliocladium virens*, and *Coniothyrium minitants*, all destructive parasites and antagonists of *Sclerotinia sclerotiorum* and all effectively controlling several of the *Sclerotinia* diseases; and *Talaromyces flavus*, which parasitizes *Verticillium* and controls *Verticillium* wilt of eggplant. Also, some *Pythium* species parasitize species of *Phytophthora* and other species of *Pythium*. Several yeasts, e.g., *Pichia gulliermondii*, also parasitize and inhibit the growth of plant pathogenic fungi such as *Botrytis* and *Penicillium*. In addition to fungi, bacteria of the genera *Bacillus*, *Enterobacter*, *Pseudomonas*, and *Pantoea* have been shown to parasitize and/or inhibit the pathogenic oomycetes *Phytophthora* sp., *Pythium* sp, and the fungi *Fusarium*, *Sclerotium ceptivorum*, and *Gaeumannomyces tritici*; the mycophagous nematode *Aphelenchus avenae* parasitizes *Rhizoctonia* and *Fusarium*; and the

amoeba *Vampyrella* parasitizes the pathogenic fungi *Cochliobolus sativus* and *Gaeumannomyces graminis.*

Mechanisms of Action: The mechanisms by which antagonistic microorganisms affect pathogen populations are not always clear, but they are generally attributed to one of four effects: (1) direct parasitism or lysis and death of the pathogen (2) competition with the pathogen for food, (3) direct toxic effects on the pathogen by antibiotic substances released by the antagonist, and (4) indirect toxic effects on the pathogen by volatile substances, such as ethylene, released by the metabolic activities of the antagonist. Many of the antagonistic microorganisms mentioned earlier are naturally present in crop soils and exert a certain degree of biological control over one or many plant pathogens regardless of human activities. Humans, however, have been attempting to increase the effectiveness of antagonists either by introducing new and larger populations of antagonists, e.g., *Trichoderma harzianum* and *Pasteuria penetrans,* in fields where they are lacking and/or by adding soil amendments that serve as nutrients for, or otherwise stimulate growth of, the antagonistic microorganisms and increase their inhibitory activity against the pathogen. Unfortunately, although both approaches are effective in the laboratory and in the greenhouse, neither has been particularly successful in the field. New microorganisms added to the soil of a field cannot compete with the existing microflora and cannot maintain themselves for very long. Also, soil amendments, so far, have not been selective enough to support and build up only the populations of the introduced or existing antagonists. Thus, their potential for eventual disease control is quite limited. There are several cases of successful biological control of plant pathogens when the antagonistic microorganism is used for direct protection of the plant from infection by the pathogen.

3.3 Control through Trap Plants: If a few rows of rye, corn, or other tall plants are planted around a field of beans, peppers, or squash, many of the incoming aphids carrying viruses that attack the beans, peppers, and squash will first stop and feed on the peripheral taller rows of rye or corn. Because most of the aphid-borne viruses are nonpersistent in the aphid, many of the aphids lose the bean-, pepper-, or squashinfecting viruses by the time they move onto these crops. In this way, trap crops reduce the amount of inoculum that reaches a crop. Trap plants are also used against nematodes, although in a different way. Some plants that are not actually susceptible to certain sedentary plant-parasitic nematodes produce exudates that stimulate eggs of these nematodes to hatch. The juveniles enter these plants but are unable to develop into adults and eventually they die. Such plants are also called **trap crops**. By using trap crops in a crop rotation program, growers can reduce the nematode population in the soil. For example, *Crotalaria* plants trap the juveniles of the root-knot nematode *Meloidogyne* sp. and black nightshade plants (*Solanum nigrum*) reduce the populations of the golden nematode *Heterodera rostochiensis*. Similar results can be obtained by planting highly susceptible plants, which after infection by the nematodes are destroyed (plowed under) before the nematodes reach maturity and begin to reproduce.

3.4 Control through Antagonistic Plants: A few kinds of plants, e.g., asparagus and marigolds, are antagonistic to nematodes because they release substances in the soil that are

toxic to several plantparasitic nematodes. When interplanted with nematodesusceptible crops, antagonistic plants decrease the number of nematodes in the soil and in the roots of the susceptible crops. Antagonistic plants, however, are not used on a large scale for the practical control of nematode diseases of plants for the same reasons that trap plants are not used.

4. Physical Methods to control plant pathogens

The physical agents used most commonly in controlling plant diseases are temperature (high or low), dry air, unfavorable light wavelengths, and various types of radiation. With some crops, cultivation in glass or plastic greenhouses provides physical barriers to pathogens and their vectors and in that way protects the crop from some diseases. Similarly, plastic or net covering of row crops may protect the crop from infection by preventing pathogens or vectors from reaching the plants.

4.1 Control by Heat Treatment

Soil Sterilization by Heat: Soil can be sterilized in greenhouses, and sometimes in seed beds and cold frames, by the heat carried in live or aerated steam or hot water. The soil is steam sterilized either in special containers (soil sterilizers), into which steam is supplied under pressure, or on the greenhouse benches, in which case steam is piped into and is allowed to diffuse through the soil. At about 50°C, nematodes, some oomycetes, and other water molds are killed, whereas most plant pathogenic fungi and bacteria, along with some worms, slugs, and centipedes, are usually killed at temperatures between 60 and 72°C. At about 82°C, most weeds, the rest of the plant pathogenic bacteria, most plant viruses in plant debris, and most insects are killed. Heat-tolerant weed seeds and some plant viruses, such as tobacco mosaic virus (TMV), are killed at or near the boiling point, i.e., between 95 and 100°C. Generally, soil sterilization is completed when the temperature in the coldest part of the soil has remained for at least 30 minutes at 82°C or above, at which temperature almost all plant pathogens in the soil are killed. Heat sterilization of soil can also be achieved by heat produced electrically rather than supplied by steam or hot water. It is important to note, however, that excessively high or prolonged high temperatures should be avoided during soil sterilization. Not only do such conditions destroy all normal saprophytic microflora in the soil, but they also result in the release of toxic levels of some (e.g., manganese) salts and in the accumulation of toxic levels of ammonia (by killing the nitrifying bacteria before they kill the more heat-resistant ammonifying bacteria), which may damage or kill plants planted afterward.

Soil Solarization: When clear polyethylene is placed over moist soil during sunny summer days, the temperature at the top 5 centimeters of soil may reach as high as 52°C compared to a maximum of 37°C in unmulched soil. If sunny weather continues for several days or weeks, the increased soil temperature from solar heat, known as solarization, inactivates (kills) many soilborne pathogen fungi, nematodes, and bacteria near the soil surface, thereby reducing the inoculum and the potential for disease.

Hot-Water Treatment of Propagative Organs:Hot-water treatment of certain seeds, bulbs, and nursery stock is used to kill any pathogens with which they are infected or which may be

present inside seed coats, bulb scales, and so on, or which may be present in external surfaces or wounds. In some diseases, seed treatment with hot water was for many years the only means of control, as in the loose smut of cereals, in which the fungus overwinters as mycelium inside the seed where it could not be reached by chemicals. Similarly, treatment of bulbs and nursery stock with hot water frees them from nematodes that may be present within them, such as *Ditylenchus dipsaci* in bulbs of various ornamentals and *Radolpholus similis* in citrus rootstocks. The effectiveness of the method is based on the fact that dormant plant organs can withstand higher temperatures than those their respective pathogens can survive for a given time. The temperature of the hot water used and the duration of the treatment vary with the different host–pathogen combinations. Thus, in the loose smut of wheat the seed is kept in hot water at 52°Cfor 11 minutes, whereas bulbs treated for *D. dipsaci* are kept at 43°C for 3 hours. It has been reported that a short (15 seconds) treatment of melon fruit with hot (59 ± 1°C) water rinse and brushes resulted in a significant reduction of fruit decay while maintaining fruit quality after prolonged storage. Treated fruit had less soil, dust, and fungal spores at its surface while many of its natural openings in the epidermis were partially or entirely sealed.

Hot-Air Treatment of Storage Organs: Treatment of certain storage organs with warm air (curing) removes excess moisture from their surfaces and hastens the healing of wounds, thus preventing their infection by certain weak pathogens. For example, keeping sweet potatoes at 28 to 32°C for 2 weeks helps the wounds to heal and prevents infection by *Rhizopus* and by soft-rotting bacteria. Also, hot-air curing of harvested ears of corn, tobacco leaves, and so on removes most moisture from them and protects them from attack by fungal and bacterial saprophytes. Similarly, dry heat treatment of barley seed at 72°C for 7 to 10 days eliminates the leaf streak- and black chaff-causing bacterium *Xanthomonas campestris* pv. *translucens* from the seed with negligible reduction of seed germination.

4.2 Control by Eliminating Certain Light Wavelengths: *Alternaria*, *Botrytis*, and *Stemphylium* are examples of plant pathogenic fungi that sporulate only when they receive light in the ultraviolet range (below 360 nm). It has been possible to control diseases on greenhouse vegetables caused by several species of these fungi by covering or constructing the greenhouse with a special ultraviolet (UV)-absorbing vinyl film that blocks the transmission of light wavelengths below 390 nanometers.

4.3 Disease Control by Refrigeration: Refrigeration is probably the most widely used and the most effective method of controlling postharvest diseases of fleshy plant products. Although low temperatures at or slightly above the freezing point do not kill any of the pathogens that may be on or in the plant tissues, they do inhibit or greatly retard the growth and activities of all such pathogens, thereby reducing the spread of existing infections and the initiation of new ones. Most perishable fruits and vegetables should be refrigerated as soon as possible after harvest, transported in refrigerated vehicles, and kept refrigerated until they are used by the consumer. Regular refrigeration of especially succulent fruits and vegetables is sometimes preceded by a quick hydrocooling or air cooling of these products, aimed at removing the excess heat carried in them from the field as quickly as possible to prevent the

development of any new or latent infections. The magnitude of disease control through refrigeration and its value to growers and consumers is immense.

4.4 Disease Control by Radiation: Various types of electromagnetic radiation, such as UV light, X rays, and g rays, as well as particulate radiation, such as a particles and b particles, have been studied for their ability to control postharvest diseases of fruits and vegetables by killing the pathogens present on them. Some satisfactory results were obtained in experimental studies using g rays to control postharvest infections of peaches, strawberries, and tomatoes by some of their fungal pathogens. Unfortunately, with many of these diseases the dosage of radiation required to kill the pathogen may also injure the plant tissues on which the pathogens exist. Also, this method of treatment of foodstuffs, although found safe and properly licensed by the USDA, is vigorously opposed by certain segments of the population. So far, no plant diseases are controlled commercially by radiation.

5. Chemical Methods that Eradicate or Reduce the Pathogen Inoculum

Chemical pesticides are generally used to protect plant surfaces from infection or to eradicate a pathogen that has already infected a plant. A few chemical treatments, however, are aimed at eradicating or greatly reducing the inoculum before it comes in contact with the plant. They include soil treatments (such as fumigation), disinfestations of warehouses, sanitation of handling equipment, and control of insect vectors of pathogens.

5.1 Soil Treatment with Chemicals: Soil to be planted with vegetables, strawberries, ornamentals, trees, or other high-value crops, such as tobacco, is frequently treated with chemicals for control primarily of nematodes but occasionally also of soilborne fungi, such as *Fusarium* and *Verticillium*, weeds, and bacteria. Certain fungicides are applied to the soil as dusts, liquid drenches, or granules to control damping-off, seedling blights, crown and root rots, and other diseases. In fields where irrigation is possible, the fungicide is sometimes applied with the irrigation water, particularly in sprinkler irrigation. Fungicides used for soil treatments include metalaxyl, diazoben, pentachloronitrobenzene (PCNB), captan, and chloroneb, although the last two are used primarily as seed treatments. Most soil treatments, however, are aimed at controlling nematodes, and the materials used are volatile gases or produce volatile gases (fumigants) that penetrate the soil throughout (fumigate). Some nematicides, however, are not volatile but, instead, dissolve in soil water and are then distributed through the soil.

5.2 Fumigation: The most promising method of controlling nematodes and certain other soilborne pathogens and pests in the field has been through the use of chemicals usually called fumigants. Some of them, including chloropicrin, methyl bromide, dazomet, and metam sodium, either volatilize as they are applied to the soil or decompose into gases in the soil. These materials are generalpurpose preplant fumigants; they are effective against a wide range of soil microorganisms, including nematodes, many fungi, insects, certain bacteria, and weeds. Contact nematicides, such as fensulfothion, carbofuran, ethoprop, and aldicarb, are of

low volatility, are effective against nematodes and insects, and can be applied before and after planting of many crops that are tolerant to these chemicals.

Nematicides used as soil fumigants are available as liquids under pressure, liquids, emulsifiable concentrates, and granules. These materials are applied to the soil either by spreading the chemical evenly over the entire field (broadcast) or by applying it only to the rows to be planted with the crop (row treatment). In both cases the fumigant is applied through delivery tubes attached at the back of tractor-mounted chisel-tooth injection shanks or disks spaced at variable widths and usually reaching six inches below the soil surface. The nematicide is sealed in the soil instantly by a smoothing and firming drag or can be mixed into the soil with disk harrows or rototillers. Highly volatile nematicides are covered immediately with polyethylene sheeting, which should be left in place for at least 48 hours. When small areas are to be fumigated, the most convenient method is through injection of the chemical with a hand applicator under a tarp that has been placed over the area. The edges of the tarp are covered with soil prior to injection of the chemical. Applications may also be made by placement of small amounts of granules in holes or furrows six inches deep, 6 to 12 inches apart, which should be covered immediately with soil. In all cases of preplant soil fumigation with phytotoxic nematicides, several days to two weeks must elapse from the time of treatment to seeding or planting in the field to avoid plant injury.
In the abovementioned types of nematicide application, only a small portion of the soil and its microorganisms immediately come in contact with the chemical. The effectiveness of the fumigants, however, is based on their diffusion in a gaseous state through the pores of the soil throughout the area in which nematode and other pest control is desired. The distance the vapors move is influenced by the size and continuity of soil pores, by the soil temperature (the best range is between 10 and 20°C), by soil moisture (best at about 80% of field capacity), by the type of soil (more material is required for soils rich in colloidal or organic matter), and by the properties of the chemical itself. Nematicides with low volatility, such as carbofuran, do not diffuse through the soil to any great extent and must be mixed with the soil mechanically or by irrigation water or rainfall. Except for the highly volatile methyl bromide and chloropicrin, most nematicides can be applied in irrigation water when it is provided as trickle soaks or drenches, but only low-volatility nematicides can be applied through overhead sprinkler systems. In practice, chemical nematode control in the field is generally obtained by preplant soil fumigation with one of the nematicides applied only before planting. These chemicals are nonspecific, i.e., they control all types of nematodes, although some nematodes are harder to control than others no matter what the nematicide. Chloropicrin, methyl bromide, dazomet, and metam sodium are expensive, broad-spectrum nematicides that must be covered on application either with tarps (the first two) or with water or through soil (the others). All nematicides are extremely toxic to humans and animals and should be handled with great caution.

5.3 Disinfestation of Warehouses: Stored products can be protected from becoming infected by pathogens left over in the warehouse from previous years by first cleaning thoroughly the storage rooms and by removing and burning the debris. The walls and floors are washed with bleach, a copper sulfate solution (1 pound in 5 gallons of water), or some other sanitizing

agent. Warehouses that can be closed airtight and in which the relative humidity can be kept at nearly 100% while the temperature is between 25 and 30°C can be fumigated effectively with chloropicrin (tear gas) used at 1 pound per each 1,000 cubic feet. In all cases the fumigants should be allowed to act for at least 24 hours before the warehouse doors are opened for aeration.