Plant disease management in protected horticulture

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Abstract
This review article was originally prepared for use as supplemental reading material of "Special Course for Protected Horticulture I" in the Graduate School of Horticulture, Chiba University. The contents, therefore, are directed mainly to graduate students majoring in horticulture-related studies. However, professionals in the field of research and implementation of disease management in protected horticulture might well be interested in some sections. First, the article presents discussion of cultural practices for controlling plant diseases that affect vegetable and ornamental crops grown in protected environments such as greenhouses and plastic tunnels. The major diseases are then described based on pathogen types: fungi, bacteria, and viruses that are common in protected horticulture facilities in Japan. This section specifically examines symptoms of host plants, characteristics of pathogens, and control measures that are currently available to prevent each disease from infection and development. Finally, a prospective assessment will also be presented regarding plant disease management in protected horticulture.

Introduction

The term "protected horticulture" refers to any means applied to protect cultivated horticultural crops from environmental stress. The meaning therefore specifically applies to climatic control aimed at (i) eliminating the effects of meteoric events such as rain, hail, and snow, (ii) alleviating the severity of environmental stresses such as extreme temperatures and irradiance, and (iii) modifying one or more environmental parameters, e.g., CO₂ concentration, light intensity, or day-length to enhance crop growth and yield [22]. Considering facility structures and cultivation techniques, protected horticulture systems of various types are currently practiced, including greenhouses, plastic shelters, shading houses, and low and walk-in tunnels. In this article, protected horticulture is considered to include these "open system" facilities but not what are called "closed system" with all environmental parameters controlled artificially by computers with soil-less culture.

Ornamental and vegetable crops in protected horticulture systems grow under environmental conditions that differ substantially from those in open fields. For example, on a sunny winter day, a greenhouse might have air temperatures exceeding 30°C during the day, although the temperature might quickly drop down to the level equivalent to the outside during the night, unless it is artificially heated. Humidity in a greenhouse might easily become humid, plant pathogens that favor low temperature and high humidity proliferate. In contrast, during days in spring and autumn, operating artificial ventilation often produces a drier environment, giving rise to diseases that are common in such conditions [9]. Table 1 presents major vegetable diseases in protected horticulture systems along with their optimal temperatures and humidity conditions.

Application of agricultural chemicals has been the main control measure used against plant diseases in protected environments. However, improper management of cultivation environments decreases the efficiency of chemicals, occasionally inducing tolerant pathogenic strains to fungicides, and thereby destabilizing crop production systems. Because development of a plant disease consists of three components—a virulent pathogen, susceptible plant, and disease-prone conditions of the environment—it is a key to reducing the magnitude of these three components for controlling plant diseases, thereby leading to healthy crop production.
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<td>Gray mold</td>
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<td>Downy mildew</td>
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<td>Corynespora leaf spot</td>
<td>Corynespora cassicola</td>
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<td>Sclerotinia stem rot</td>
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<td>Bacterial spot / Angular leaf spot</td>
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<td>Monosporascus root rot</td>
<td>Monosporascus cannonballus</td>
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<td><strong>Strawberry</strong> (Fragaria × ananassa)</td>
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<td>Sphaerotheca humali</td>
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<td>Gray mold</td>
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<td>moist &gt; dry</td>
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<tr>
<td></td>
<td>Anthracnose / Crown rot</td>
<td>Colletotrichum acutatum / C. fragariae / Glomerella cingulata</td>
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<td>Fusarium wilt</td>
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<td>Verticillium wilt</td>
<td>Verticillium dahiae</td>
<td>20–25</td>
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</tbody>
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Modified from Handbook of Protected Horticulture (2003), n/i: no information is available.
Cultural practices for controlling plant diseases in protected horticulture

When left uncontrolled, plant diseases of various types can damage crops in protected horticulture. Environmental parameters are more manageable in such conditions than in out-fields. Therefore, controlling plant diseases in protected environments is generally more effective if the cultural practices are coordinated well with disease control measures. Temperature and humidity, and the dew formation that occurs with an appropriate combination of them strongly affect plant diseases. Potent means to control diseases are to manipulate these factors effectively and to apply appropriate sanitation practices.

Temperature management: Temperature is the primary element affecting the growth rate of plants. In general, the warmer the temperature, the higher the plant growth rate will be. Because the plant growth rate depends on the temperature, temperature fluctuation can cause plants to undergo stress or develop diseases. Consequently, plant growth gradually decreases or plants are damaged. For that reason, it is important to maintain a suitable temperature in protected horticulture facilities by placement of air circulation fans or an electronic thermostat. Such equipment helps control temperature levels, which are important for plant growth and which reduce crop stress.

Humidity: Humidity levels also affect plant growth. The higher the humidity, the more the plants are susceptible to diseases. For example, appropriate humidity for greenhouse plants in the daytime is 25-70%. However, humidity levels are generally 90-100% at night. During periods of rainy weather in winter, the relative humidity might remain near 100% for several days and nights. Maintaining appropriate plant gaps and spacing are usually effective to control humidity levels in protected horticulture facilities. If plants are crowded together, then the humidity level increases; thereby the rate of disease development increases as well.

Air circulation also reduces the relative humidity in protected horticulture facilities. For example, on winter evenings, cool air surrounding the greenhouse raises the humidity to saturation (100%); such a condition is likely to encourage disease development. However, operating an exhaust fan in the late afternoons can help to eliminate warm moist air from the greenhouse, and help to control the humidity levels and disease development in plants.

Most plant pathogens need water on the plant surface for normal growth. Moreover, splashing water is the primary means of spreading disease from plant to plant. The risk of plant diseases is therefore reduced when the foliage and flowers are kept dry. Ideally, water should only be applied directly to the growing medium, rather than "showering" the whole plant. Water should be given early in the day; and not after 4 p.m., except in the summer. The amount of water needed for a plant changes according to the levels of light, temperature, and humidity; thus watering should be done with attention to these parameters. For example, plants located beneath overhead plants will not dry as quickly as neighboring plants in full sun [4].

Sanitation: Proper sanitation can keep the plants disease-free and healthy in protected horticulture facilities. Diseased plant debris should always be removed immediately from the facility. For example, leaving debris inside of the facility can allow plant pathogens to develop their inoculum sources rapidly, and can therefore produce a major incidence of disease. Weeds along walkways and under benches of greenhouses or even weeds growing just outside can harbor diseases and insects that can be transmitted to crops inside the facility.

Improper or non-sterile soil, which might be contaminated with soil-borne plant pathogens from outdoors should not be allowed into protected horticulture facilities. Because plant diseases can spread easily through non-sterilized pots, used pots, contaminated tools, and dirty floors, proper care, e.g. surface sterilization of tools and equipment, must be performed to prevent diseases from spreading.

Fungal diseases common in protected horticulture

The survival and performance of most plant pathogenic fungi depend greatly on the prevailing conditions of temperature and moisture or the presence of water in their environment. Fungal mycelium survives only within a certain range of temperature and in contact with moist surfaces inside or outside of the host. In contrast, fungal spores of most kinds can withstand broader ranges of temperature and moisture, and carry the fungus through low winter temperatures and hot, dry summer periods. Spores, however, also require favorable temperatures and moisture to germinate. Furthermore, fungi producing zoosporae, i.e., oomycetes, require free water for the production, movement, and germination of zoosporae [1].

Air-borne pathogens attack plants aboveground and produce symptoms on leaves, stems, flowers, and fruits. They are likely to be influenced by temperature, humidity, duration of plant wetness, and light for certain fungi. Winter production of major vegetable crops including tomato, eggplant, pepper, cucumber, melon, and strawberry mainly necessitate maintenance of adequate temperatures for plant growth by heating. Temperatures that suit these vegetables also allow fungal pathogens to grow. Therefore, it is important to manage other factors to control disease development.

Most air-borne fungal pathogens, except for powdery mildew, require certain durations of leaf wetness to infect plants effectively. For example, spores of anthracnose, gray mold, and leaf mold of tomato require leaves to wet for sticking to the surface for germination, and for
forming mycelia and secondary conidia. Leaf wetness also allows conidiophores and conidia bulge; therefore it enhances the release and spread of conidia into the air. Powdery mildew, in contrast, favors drier conditions for releasing and spreading its conidia except when they germinate. Certain other pathogenic fungi require ultraviolet (UV) radiation for sporulation. In fact, UV-absorbing vinyl film, by filtering out wavelengths shorter than 390 nm, reduces the incidence of gray mold of tomato and cucumber caused by Botrytis cinerea, and stem rot of eggplant and cucumber caused by Sclerotinia sclerotiorum [18].

Although major symptoms of many plant diseases appear above-ground, most plant pathogenic fungi spend part of their lives on their host plants and part in the soil or in plant debris on the soil. Some fungi spend their entire life on the host; only the spores might land on the soil, where they remain inactive until they are again carried to a host on which they can grow and multiply. The following describes some major fungal diseases in protected horticulture, with particular regard to their symptoms, ecological characteristics of pathogens, and appropriate control measures.

**Late blight of tomato and Phytophthora blight of bell pepper**

Late blight of tomato and Phytophthora blight of bell pepper are blight diseases that might devastate these crops in protected horticulture circumstances. The former was responsible for the Irish potato famine of the 1840s, and has continued to be important to the present.

**Symptoms:** The blight disease appears on leaves of tomato or bell pepper as circular or irregular lesions, often concentrated on the sides or upper fruit surfaces. Abundant white mold will grow on the lesions if conditions remain moist. If secondary bacteria infect the lesions, a slimy wet rot might develop on the entire fruit. During periods of high humidity and prolonged leaf wetness, a cotton-like white mold usually becomes visible on lower leaf surfaces at the edges of lesions. Infected areas on stems appear brown to black; entire vines might be killed in a short period when moist conditions persist. In dry weather, however, infected leaf tissues quickly dry up and the white mold disappears [16].

**Pathogens:** Late blight of tomato and Phytophthora blight of bell pepper are caused, respectively, by Phytophthora infestans and P. capsici. For the disease to begin in a protected horticulture facility, the fungi must survive the winter in plant debris or oospores in soil; alternatively, zoospores must be introduced by transplanting seedlings or by some similar means. Disease development is favored by cool, moist conditions accompanied by mist and heavy dew. Under such conditions, lesions might appear on leaves within 3-5 days of infection, followed by white mold growth soon thereafter. Zoospores formed on the mold are easily dislodged and spread readily by water and equipment in the facility, thereby beginning another cycle of disease [11].

**Control measures:** For proper control of the disease, temperature and humidity management is particularly important. Mulching in greenhouses effectively reduces the disease severity because less moisture is supplied from the soil surface and warmer soil temperatures prevail [19]. In addition, all infected debris should be removed from the greenhouse. Registered chemicals might be applied for prevention (protectant fungicides) including oxadixyl-copper, TPN, coppermetalaxyl, and mancozeb [9].

**Downy mildew of cucurbits**

Downy mildew disease is caused by the fungus Pseudoperonospora cubensis, which attacks only cucurbit species, e.g., melons, gourds, pumpkins, and watermelons. This disease primarily affects foliage and can cause severe yield losses in the protected horticulture industry.

**Symptoms:** Initial symptoms of downy mildew typically include angular yellow spots on leaf surfaces, usually of the lower, older leaves. On the undersides of the spots, a dark-gray fungal growth might be visible when high relative humidity prevails. As the disease progresses, the yellow spots enlarge and become necrotic or brownish in the center, with browning spreading to the margins of the spots. Such spots might merge to form large brown areas on the leaves [5].

**Pathogen:** P. cubensis is an obligate parasite, requiring living host tissue to survive. Under optimum conditions, the fungus might develop thick-walled spores called oospores that are resistant to low temperatures and dry conditions. However, forming of oospores is rare and not considered an important source of inocula. Infections in protected horticulture systems likely originate from spores of another type (zoospores in sporangia) that enter the facilities from the outside.

Wetness of the leaf surfaces is necessary for the fungus to infect plants. When spores land on a wet leaf surface, they can readily germinate and invade plants through stomata of leaves, followed by production of zoospores and their release several days later. In the film of surface water on leaves that occurs during humid periods, the secondary zoospores enter and infect leaves again. Optimum temperatures for infection are 20°C–25°C. Spores can quickly spread within protected horticulture facilities via moist air currents, contaminated tools, equipment, hands and clothing.

**Control measures:** The disease occurs less in sufficiently spaced plants and in well-pruned canopy because of good air circulation. Overwatering not only engenders overly soft and vulnerable plants but also produces water droplets at the leaf margins. These conditions provide a perfectly supportive set of circumstances for the pathogen’s infection. Zoospores become less infective under conditions of high temperatures
and low humidity. Therefore, dew formation should be avoided by providing adequate heating and ventilation in protected horticulture facilities. Any cultural practice that increases leaf wetness such as misting can enhance disease development when the spores are present in the air. Special care is recommended for purging moist air from the facility during the evenings and keeping the plant foliage dry, particularly during the night. A maximum of 75% relative humidity is recommended at normal temperatures. Furthermore, although not as effective as it might be for late blight, mulching in greenhouses reduces the disease severity, primarily because less moisture is supplied from the soil surface.

All parts of infected plants should be removed and discarded. Weeds of the Cucurbitaceae family such as Trichosanthes cucumeroides surrounding protected horticulture facilities should also be removed because these might serve as reservoirs of the fungus.

For chemical control, it is important to implement appropriate control procedures in the early stages of disease development, usually when only a few spots are evident on a few leaves of one plant. Under favorable conditions, the spores are readily dispersed by air currents; further disease development might occur very rapidly within a few days. Currently registered fungicides for the disease are oxadixyl-copper, metalaxyl, and mancozeb. Moreover, where possible, fungicides should be rotated to reduce the chances of increasing resistance in the fungus against the chemical applied.

**Leaf mold of tomato**

**Pathogen:** Leaf mold, caused by the *Fulvia fulva* fungus, primarily affects tomato leaves in protected horticulture. It produces large spots on leaves, eventually causing them to fall off, and thereby lowering yield. High humidity is necessary for this fungus to grow successfully.

**Symptoms:** In general, lower leaves are affected first, then younger leaves. Pale-green or yellowish areas appear on the upper leaf surface, often becoming distinctly yellow later. The edges are indefinite, and spots might grow together. At the same time, the fungus begins to grow on the undersides of the leaves in areas corresponding to the pale upper surface areas. The grown fungal spots are olive-green to grayish purple and velvety. They are more deeply colored in the respective centers of the areas. As the disease progresses, the spots turn yellowish brown. Then the leaves curl, wither, and drop prematurely.

**Control measures:** For controlling the disease, protected horticulture facilities should be kept warmer than the outside at night. It is effective to space plants adequately and install fans to ensure good air circulation for leaf drying. Ventilation is particularly important when the humidity is greater than 85%. As might be expected, wetting leaves should be avoided, or should be allowed to dry before nightfall. All plant debris should be removed and destroyed after harvest; where possible, solarization or steaming the soil is recommended. Although resistant tomato cultivars are available, it might be difficult to ensure that the plants are resistant to all strains of the fungus, any of which might be present. Current recommendations for chemical control measures are preventive application of registered fungicides such as thiophanate-methyl, triflumizole, and TPN, in combination with the cultural controls explained above.

**Gray mold of ornamentals and vegetables**

**Pathogen:** Gray mold, caused by the fungus *Botrytis cinerea*, is a common disease of nearly all plants. However, this disease is quite prevalent among ornamental and vegetable crops in protected horticulture. Plants with dense or succulent foliage are more heavily damaged, usually becoming more susceptible as they get older. The disease causes a loss of leaf area and fruit quality, including losses during storage and shipment.

![Disease progress of downy mildew (A) and powdery mildew (B) of cucumber under greenhouse conditions.](image)
Symptoms: Light tan or gray spots first appear on leaves or flower petals, which become covered with gray-brown fungal growth. The infected leaves and flowers collapse and wither later. Stems might also be infected, forming elliptical spots where an infected leaf meets the stem. Old flower petals are particularly susceptible, usually starting with light, watery spots. The fruit skin usually breaks over the decayed areas, and a dark grey growth of fungus appears over the spot [11].

Control measures: To prevent the disease from spreading in protected horticulture facilities, relative humidity should be kept less than 90%. Adequate spacing between plants and proper weed control are recommended for good air circulation. In addition, leaves should be kept dry with ventilation and by avoiding overhead watering. Plants should be pruned by breaking petioles close to the stem, and all stubs should be removed from the facilities.

Because few resistant cultivars are available, various measures should be integrated for proper control of the disease. Registered fungicides include azoxystrobin, iprodione, and diethofencarb-thiophanamethy [9]. The fungus is famous for producing mutant strains against chemicals. Therefore, alternating usage of these fungicides is recommended.

Powdery mildew of ornamentals and vegetables

Pathogens: Powdery mildew, a very common disease affecting many ornamental and vegetable crops, is attributable to several fungi including Oidium violae, Oidiopsis sicula, Sphaerotheca fuliginea, and S. humuli (Table 1). Many other fungi can cause powdery mildew on other plant hosts. Although powdery mildew is commonly found in outdoor crops, especially those grown in shady areas with poor air circulation, the disease is more prevalent in protected horticulture.

Symptoms: All powdery mildew fungi cause similar symptoms: old leaves at lower positions are usually affected first. Then a fine white powdery fungal growth appears on the surface of the leaves. Bright white spots, yellowish white in the case of Oidiopsis sicula, approximately 5–10 mm in diameter, develop and might grow together. Whole leaf blades might turn brown and dry up with a severe infection. However, infected leaves seldom drop off from the plant; fruits are unaffected [12].

Control measures: Although the disease prefers dry conditions for developing mycelia and forming conidia on the surface of plants (Table 1), germination of conidia requires moisture. Therefore, the disease development is inconsistent with the humidity condition (Fig. 1B) [10, 21], but good air circulation is generally effective to prevent infection of the pathogen. In addition, excessive nitrogen fertilizer is known to enhance the disease’s development. A variety of resistant ranges exist among commercial cultivars in different crops. Therefore, integration of cultural and chemical methods is practically important if susceptible cultivars are grown. Some registered fungicides include quinomethionate, triflumizole, and wettable sulfur [9].

Anthracnose of strawberry

Pathogen: Whereas “anthracnose” is a general term used to describe diseases of many plants, strawberry anthracnose results mainly from three species of the genus, Colletotrichum: acutatum, fragariae, and gloeosporioides (Table 1, Glomerella cingulata is the teleomorph stage of C. gloeosporioides) in Japan. These pathogens can infect fruits, buds, blossoms, petioles, runners, crowns, and foliage. Although generally regarded as a disease of warmer climates (optimal development temperature is approximately 30°C), anthracnose is not limited to the southern regions of Japan. Anthracnose fruit rot, most often associated with C. acutatum, is a destructive menace worldwide. This disease is especially severe in annual cropping systems in which strawberries are grown on plastic-mulched, raised beds. Fully open flowers and ripening fruits are very susceptible to the infection. Spreading very quickly under humid, warm conditions, the disease might destroy the entire crop [20].

Symptoms: Lesions first appear as small, dark spots on stolons and petioles. They enlarge to become dark, elongated, dry, sunken lesions which often girdle the stem. When petioles or runners become girdled, individual leaves or entire daughter plants might wilt and die. Petiole infections occur at the base of the petiole, causing the leaf to bend sharply at the point of attachment and hang down. Black leaf spots are caused by C. fragariae or C. gloeosporioides, whereas irregular leaf spots are the result of infection by C. acutatum. The former lesions on leaves are small, round, and black to gray, often resembling ink spots, whereas the latter has dark brown to black lesions forming on leaf margins and extending along the margin inward to the mid-vein.

Symptoms in fruits appear as whitish, water soaked lesions up to 3 mm in diameter. As lesions develop, they turn a light tan to dark brown and eventually become sunken and black within a few days. After several days, lesions might be covered with spore masses that are pink to orange. Infected fruits eventually dry down to form hard, black and shriveled mummies. Fruits can be infected at any stage of development; seeds of infected fruits turn black and become slightly sunken [11].

Control measures: Transplants and soil from infested nurseries are the most common primary sources of inocula, especially in annual production systems. In perennial systems, the fungi might survive in infected plants and debris, providing inocula for the subsequent fruiting season. Crown infections often occur in the nursery but do not appear until after planting. Nonetheless, the fungus continues to develop in the plants, which might suddenly die during warm weather in autumn or in early spring of the following year.
Control is extremely difficult when environmental conditions are favorable for the pathogens. Control practices, including usage of antagonistic plants, should therefore start at planting to reduce inoculum levels. Infected fruits during an early season should be culled and removed from the facility. Anthracnose fruit rot might be controlled partly with protective fungicide applications from flower bud emergence to harvest. Currently registered fungicides are propineb, bitertanol, dithianon, and mancozeb [9].

Sclerotinia stem rot of ornamentals and vegetables

Pathogen: Sclerotinia stem rot, also designated as white mold, results from infection by a fungus, Sclerotinia sclerotiorum. Although the pathogen affects a wide range of plants, the disease is particularly common in solanaceous and cucurbit crops in protected horticulture. S. sclerotiorum survives from year to year as hard dark structures, called "sclerotia", which are variously shaped bodies of tightly packed white mycelia covered with a dark, melanized protective coat. Moist soils and a full canopy favor the emergence of apothecia from the sclerotia in protected horticulture facilities. Apothecia are mushroom-like bodies that produce millions of air-borne spores almost daily over a 7–10 day period [6].

Symptoms: Leaves of infected plants start wilting and become gray-green before turning brown and eventually curling and dying. It is important to observe stems for white mycelia and sclerotia to differentiate this disease from other stem and root rot diseases. In a few days diseased stem areas are killed, and become tan and eventually bleached. This bleached stem has a pithy texture and shreds easily. Infected plant parts generally have signs of the fungal pathogen as white, fluffy mycelia, and sclerotia on the surface of or embedded in the stem tissue [11].

Control measures: Sclerotinia stem rot mostly develops under wet, humid conditions with moderate temperatures (15°C–24°C), which are very common in protected horticulture. Row spacing has been shown to influence this disease, with narrow rows resulting in higher disease incidence. Several weeds can also be a host for this fungus. Therefore, it is important to maintain good weed control. The results of foliar fungicide applications vary significantly for this disease. Therefore, chemical treatments are only recommended where severe disease incidences have occurred. Currently, registered chemicals are thiophanate-methyl iprodione, and captan [9].

Fusarium wilts

Pathogens: Fusarium wilts affect and cause severe losses on many ornamental and vegetable crops, especially under the warm soil conditions which commonly occur in protected horticulture. Most of the wilt-causing Fusarium fungi belong to the species Fusarium oxysporum. Different host plants are attacked by special forms or races of the fungus: F. oxysporum f. sp. lycaenopersici attacks only on tomato, F. oxysporum f. sp. cucumerinum on cucumber, F. oxysporum f. sp. melonis on melon, and F. oxysporum f. sp. fragariae on strawberry (Table 1).

Symptoms: Most Fusarium wilts have disease cycles and develop similarly to those of Fusarium wilt of tomato, which begins as a slight vein clearing on outer leaflets and dropping of leaf petioles. Subsequently, the older leaves wilt, turn yellow and necrotic, and the entire plant might be killed, often before the plant reaches maturity. These symptoms in many cases appear on one side of the stem at first and progress upward until all foliage wilts and the stem dies. In a cross section of the stem near the base of the infected plant, a brown ring is evident in the area of the vascular bundles. The upward extent of the discoloration depends on the disease severity. Fruits, which might occasionally become infected, rot and drop off [11].

The fungus F. oxysporum f. sp. lycaenopersici produces asexual spores of three kinds: microconidia, macroconidia, and chlamydospores. Microconidia are the most frequently and abundantly produced spores with one or two cells under all conditions, even inside the vessels of infected plants. Macroconidia, usually three-celled to five-celled, have gradually pointed and curved ends. Chlamydospores are round spores with a thick wall that enables them to survive in the soil for long periods. They are produced within or terminally on older mycelia or in macroconidia.

The pathogen is a soil inhabitant. It survives in infected plant debris in the soil as mycelium and in all its spore forms but most commonly as chlamydospores. It spreads over short distances by water and contaminated equipment, and over long distances primarily in infected transplants or in the soil carried with them. Occasionally, when the soil moisture is high and the temperature is low, infected plants might produce good yields. However, in such cases, the fungus might reach the fruit and penetrate or contaminate the seeds [1].

Control measures: Fusarium wilt is soil-borne. Therefore, the use of resistant cultivars is the most reliable and practical measure for controlling the disease. Several such cultivars, including rootstocks for grafting, are available at present. Use of healthy seeds and transplants is mandatory. If they are suspected of being infected, hot-water treatment of seeds should precede planting. The fungus is so widespread and so persistent in soils that seedbed sterilization and crop rotation are expected to be of limited effect. However, soil fumigation with chloropicrin, dazomet, or methyl-isothiocyanate is currently practiced in some protected horticulture facilities where severe incidences of this disease have occurred.

Verticillium wilts

Similar to Fusarium wilt, Verticillium wilts also occur worldwide but are most important for their effects in temperate regions. Verticillium
attacks more than 200 species of plants including ornamentals and vegetables in protected horticulture.

Symptoms: The symptoms of Verticillium wilts are almost identical to those of Fusarium wilts. In many hosts and most areas, however, Verticillium induces wilt at lower temperatures than Fusarium does. Moreover, the symptoms develop slowly and often appear only on the lower or outer part of the plant or on only a few of its branches. Older plants infected with the fungus are usually stunted, and their vascular tissues show characteristic discoloration [1].

Pathogens: Two species of Verticillium—*V. albo-atrum*, and *V. dahliae*—cause Verticillium wilts in most plants. The latter prefers slightly higher temperatures. Therefore, Verticillium wilts common in protected horticulture are mostly caused by *V. dahliae* in Japan (Table 1). Actually, *V. dahliae* over-winters in the soil as microsclerotia, that can survive for long periods [11]. The fungus is spread by water within a facility; it can be disseminated among facilities by contaminated seeds and seedlings for transplanting. However, *Verticillium* is often found in uncultivated areas, indicating that the fungus is native to the soils and that it can attack susceptible crops as soon as they are planted.

Control measures: Control of Verticillium wilt depends on planting disease-free plants in disease-free soil and using resistant cultivars. Planting of susceptible crops should be avoided, especially where solanaceous crops have been grown repeatedly. Thermal inactivation via soil solarization is useful for controlling this disease in regions with high summer temperatures. In addition, soil fumigation with dazomet and/or methyl-isothiocyanate can be practical in protected horticulture facilities where severe disease has occurred.

Bacterial diseases common in protected horticulture

Bacterial diseases can be extremely serious and destructive, affecting crops in protected horticulture. Plant pathogenic bacteria develop mostly in the host plant as parasites, on plant surfaces, especially buds, as epiphytes, and partly in plant debris or in the soil as saprophytes. However, great differences exist among species in their degrees of development depending on the combination of bacterial virulence, host resistance, and environmental condition.

Some air-borne bacterial pathogens such as *Clavibacter michiganensis* subsp. *michiganensis*, which causes bacterial canker of tomato, and *Pseudomonas syringae* pv. *lachrymans*, which causes bacterial spot or angular leaf spot of cucurbits, produce their populations in the plant host. In the soil, however, their numbers decline rapidly and usually do not contribute to disease propagation from season to season. These pathogens sustain plant-to-plant infection cycles, often via insect vectors and/or vegetative propagating organs or seeds.

Other bacterial plant pathogens are soil-borne, such as *Ralstonia solanacearum*, which causes bacterial wilt of solanaceous crops. Soil-borne bacteria build up their populations within the host plants, but these populations decline only gradually when released into the soil. Sufficiently high quantities of bacteria could be present to cause a net increase of bacterial populations in the soil from season to season if susceptible host crops are grown in such soil in successive years. Plant pathogenic bacteria are usually less competitive as saprophytes. Therefore, they enter the soil in the host tissue and persist there as long as the host tissue remains.

The spread of plant pathogenic bacteria from one plant to another or to other parts of the same plant is conducted primarily by water, insects, or humans in protected horticulture facilities. Even bacteria possessing flagella can move only very limited distances by themselves. Watering by washing or splashing carries and distributes bacteria from one plant to another, from one plant part to another, and from the soil to the lower parts of the plants. Water also separates and carries bacteria on or in the soil to other areas where host plants might be present. Insects not only carry bacteria to plants; they also inoculate the plants with the bacteria by introducing them into particular sites in plants where the disease is almost sure to develop. Humans might inadvertently aid in the spreading of bacteria locally by handling plants, by cultural practices, and by transporting infected transplants or plant parts over long distances. The major bacterial diseases most commonly found in protected horticulture in Japan are bacterial canker of tomato, angular leaf spot of cucurbits, and bacterial wilt of solanaceous crops.

Bacterial canker of tomato

Pathogen: Bacterial canker results from *Clavibacter michiganensis* subsp. *michiganensis*. This is a vascular and parenchymatal disease with a wide array of symptoms. The disease results in loss of photosynthetic area, wilting and premature death, and the production of unmarketable fruit. Although usually sporadic in its occurrence, bacterial canker can be destructive. For that reason, vigilance must be exercised in the selection and handling of seed stocks, and in the preparation and management of greenhouse soil beds or bags. Early recognition of the disease, especially in protected horticulture crops, is necessary if the disease is to be contained. The pathogen can be seed-borne and might survive for short periods in soil, facility structures and equipment and for longer periods in plant debris [23].

Symptoms: Early symptoms of the disease are wilting, curling of leaflets, and browning of leaves, often only on one side of the plant. Because the leaves die, the petioles remain green and firmly attached to the stem. A cut through the stem reveals yellowish brown discoloration of the vascular tissue. Symptoms are classifiable into two types: external symptoms resulting from bacterial colonization of the surface tissues and internal symptoms resulting from bacterial invasion of the
vascular tissue. External symptoms on fruit might be observed at any age, but are usually seen first on green fruit. White spots of 2-3 mm diameter develop on the most-exposed parts of the fruit, and the spots have a dark brown center, which becomes raised, surrounded by a distinct white halo. Therefore, they are often called ‘bird’-eye spots.’

Control measures: Bacterial canker is an extremely difficult tomato disease to control. The problem of detecting infected plants presents difficulty because of the wide variation of symptoms. In addition, the highly infectious nature of the pathogen, the number of sources of inocula, and the absence of highly effective chemicals for treatment must also be considered. Therefore, it is strongly recommended to use only certificated, disease-free seeds from canker-free plants, and to transplant only certified disease-free seedlings that have been produced under a vigorous inspection program. It is usually not possible to distinguish between infected and healthy seedlings at the time of transplanting.

Once the disease is suspected or confirmed in a facility, aids to pollination and high-volume, high-pressure pesticide spraying should stop. These restrictions will decrease the risk of spread, especially when external symptoms are present. Diseased plants should be removed with surrounding healthy plants by cutting the plants off at the ground line immediately after they are detected. Sanitation is important by disinfecting hands, shoes, tools, and crop-supporting wires. Soils and seedbeds must be sterilized to destroy the bacteria with steam or chloropicrin fumigation. Infested facilities should be rotated out of tomatoes for at least 3 years. Weeds belonging to the Solanaceae family should also be destroyed. Registered chemicals such as Kasugamycin and fixed copper sprays might help in protecting healthy plants, particularly if only external symptoms are present.

Angular leaf spot bacterial spot of cucurbit crops

Pathogen: Angular leaf spot (sometimes designated as bacterial spot) of cucurbits is caused by the bacterium Pseudomonas syringae pv. lachrymans. Although the bacterium can attack widely various cucurbits, the disease is mainly important for cucumbers in Japan. The pathogen attacks the leaves, stems and fruits, and survives in seed and diseased plant debris over winter in protected horticulture facilities. Seed-borne bacteria spread to the cotyledons when the seed germinates, and by splashing water in the facilities from the soil to plant parts and from plant to plant. Angular leaf spot is most active between 24–28°C and favors high humidity.

Symptoms: On leaves, the bacterium causes small, angular, water-soaked areas which later turn brown or straw-colored. Leaf lesions are delimited by the veins, causing the angular appearance of the lesions. Under humid conditions, white, milky exudates, consisting of bacteria, form on the lesion, which becomes a thin, white crust when dried. Affected leaf tissue often dries and drops out, leaving irregularly shaped holes in the leaves. Lesions might also occur on petioles and stems. On fruit, the pathogen causes circular spots, which often crack open and turn white. Rot might extend internally and predispose infected fruit to secondary bacterial soft rot [11].

Control measures: To control the disease, in addition to resistant cultivars and preventive chemicals, cultural practices are strongly recommended including the use of pathogen-free seeds, crop-rotation out of cucurbits for at least 2 years, and restriction of overhead watering. Regarding chemical sprays, fixed copper with amendment of maneb can be applied at the first sign of disease [8].

Bacterial wilt of solanaceous crops

Pathogen: Bacterial wilt, caused by the bacterium Ralstonia (Pseudomonas) solanacearum, has a wide host range of 200 plant species of 33 plant families. However, crops of the Solanaceae family, such as tomato, potato, eggplant, and tobacco, are among the most susceptible plants. This disease is quite common in Japan, especially in areas of humid and warm climates.

The pathogen enters the roots through wounds made at planting, through cultivation, or by nematodes or insects. Natural wounds made by root emergence might also be points of entry. The bacteria multiply in the vascular system, eventually clogging the water-conducting vessels with bacterial cells and their slimy exudates. An easy procedure to diagnose this disease is to cut the stem at the base of the plant, suspend the stem in a glass of water, and let it stand for 3-5 min. A whitish substance consisting of bacterial cells and slime will flow from the xylem into the water if infected.

Symptoms: The first symptom is wilting of a few leaves, which often goes un-noticed, but soon thereafter, the entire plant suddenly wilts and dies. Such dramatic symptoms occur when the soil temperature is high (> 30°C), and soil moisture is abundant. Under less conducive conditions, wilt and decline are slower, and numerous adventitious roots often form on the lower stems. In both cases, however, a brownish discoloration is present, first in the vascular system, and in advanced cases, spreading into the pith and cortex [14].

Control measures: To control bacterial wilt, soil fumigation using chloropicrin is an effective measure in protected horticulture, although it is difficult to eliminate the bacteria thoroughly from the soil. The bacterial cells are released into the soil from decaying roots and stems after plants die. For that reason, infected roots should be removed immediately. To prevent secondary infection, sanitation is important for keeping tools and facilities clean and disinfested. Kasugamycin and fixed copper sprays are effective for this purpose.

Because the bacterium can survive for long periods in the soil, even in the absence of host plants, crop-rotation excluding solanaceous crops usually must be done for 3 years at least. Soil drainage also influences
the degrees of the disease. For that reason, it is recommended to improve the soil physical structure and to use raised beds. Various resistant cultivars are available for tomatoes and eggplants including root-stocks for grafting. However, care must be taken because none shows true resistance and they must match with their pathogen types.

**Viral diseases common in protected horticulture**

Viruses are ultra-microscopic particles that infect plant cells and alter the growth and development of host plants. They consist of nucleic acids surrounded by a protein coat. Viral diseases cause severe damage and large economic loss in protected horticulture worldwide. The amount of such losses can vary depending on the virus strain, the host species, the age of the plant at infection time, the presence of other diseases, and the extent to which viruses have spread through planting.

*Virus ecology:* Viruses usually begin infection through a wound, very often from insect feeding. Once a plant is infected, the virus spreads systemically within the plant. More than 80% of plant viruses can be transmitted by insects, primarily aphids, leaffoppers, thrips, and whiteflies, and secondarily by mites, fungi, and nematodes. In addition, viruses are often spread by propagation of infected plant parts (cuttings, bulbs, and sometimes seeds); some can also be spread by mechanical means including contact (rubbing, abrasion, or by handling). With the exception of TMV, most viruses problematic in protected horticulture can survive only in living plants or briefly in insects.

*Symptoms:* Symptoms of viral diseases may be confused easily with nutritional disorders, chemical spray injury, and fungal or bacterial diseases. For that reason, it is important to identify the virus accurately. Serological techniques such as enzyme-linked immunosorbent assay (ELISA) are available to identify viruses of many types. Symptoms might vary depending on virus strains, host plants, duration of infection, and environmental conditions. Mosaic (a variable pattern of chlorotic and healthy tissues on the same leaf), distortion of leaves or flowers, yellow or chlorotic streaking, yellow veins, ring spots, dead brown areas (necrosis), and unusual line patterns might be commonly observed with viral infections. Infected plants might also show only mild symptoms or symptoms might be latent. Moreover, symptom expression can be temperature-sensitive: some viruses are expressed only at high temperatures whereas others at lower temperatures. Viral symptoms might also be masked when the plants are growing vigorously [15].

*Control measures:* Viral diseases are very difficult to control once they become established. Prevention is the first line of defense against viral infection. It is possible to present a potential virus on other host plants, including weeds, in the absence of a host crop. It is therefore highly recommended that a collective management approach be used, i.e., a combination of cultural practices, sanitation with disinfection practices, and insect-vector controls. Such measures should be adopted to reduce the impact of viral diseases.

**Tobacco mosaic virus (TMV)**

TMV is a common viral disease in protected horticulture. This exceptionally strong virus is able to survive for many months outside a living plant or insect, on tools, facility frames, and in the soil. In dried leaves such as in cigarettes it can survive for many years. It is rarely transmitted by insects, although it is easily spread by touching diseased plants or from contaminated objects. Although TMV can be seedborne, the probability of seeds with virus in contaminated lots is very small, usually less than a few percent. In greenhouses, hard surfaces such as doorknobs or flats can become contaminated after handling virus-infected plants. They remain a common source of infection [7].

**Cucumber mosaic virus (CMV)**

Cucumber mosaic virus has a wide host range of more than 400 plant species. Infected plants might show mild mosaic patterns and mottling, flower color breaking, flecking, and leaf distortion. CMV is primarily spread by aphids, which can acquire the virus in as little as 5-10 seconds. Aphids then move the virus from plant to plant over a few hours. In addition, CMV is spread mechanically in the plant sap when cuttings are taken from infected stock plants. CMV is also both seed and pollen transmitted in plants in which symptoms develop in very young plants. It is important to discard diseased plants, and to control aphids and weeds properly, which might be reservoirs of CMV [15].

**Tomato yellow leaf curl virus (TYLCV)**

TYLCV is known to infect many vegetable crops including tomato, pepper and bean as well as many ornamental plants such as poinsettia. TYLCV can cause severe economic losses of tomato production, even up to 100% in some protected horticulture facilities. TYLCV spreads systemically in the host plant and is limited to phloem tissue. Visible symptoms of this disease are apparent on tomato plants 2-3 weeks after initial infection. Symptoms can vary slightly depending on the tomato cultivar and amount of virus infection. Generally, infected plants have smaller leaves that are cupped upward, thick and rubbery with chlorotic margins. Young infected plants become severely stunted, whereas infected plants drop up to 90% of their flowers, resulting in major yield losses.

Adult silverleaf whiteflies, *Bemisia argentifolii*, previously known as *Bemisia tabaci* biotype B transmit TYLCV. They are small, phloem-feeding insects which pick up the virus while feeding on infected host
Tomato spotted wilt virus (TSWV)

Tomato spotted wilt virus (TSWV) has a very wide host range of more than 600 hosts. Infected plants might show stunting, necrotic and chlorotic spotting, stem cankers, line patterns, and ringspots. Thrips spread TSWV: winged adults are primarily responsible for transmission. This virus is also spread in the sap when cuttings are taken from infected plants.

The best way to control TSWV is to keep the virus out of production areas. It is therefore mandatory that clean, virus-free seeds, seedlings and rootstocks must be used, and that infected plants must be discarded. Control of thrips in protected horticulture facilities is an important and effective measure. Yellow sticky cards are useful to monitor for thrips and to enable prompt initiation of strict thrip-control programs. Weeds should also be removed because they can be reservoirs of both the virus and the thrips. In addition, this virus might be spread mechanically in sap, contaminating hands or cutting tools. Therefore, the virus should be eliminated from tools with disinfectants [17].

Concluding remarks and prospects

Over the past 50 years, standard control measures have evolved routinely, and they have been practiced regularly in intensive greenhouse cropping. However, modern technology has provided more powerful management tools for crop production and for disease control in protected horticulture systems. Precise environment and nutrition controls that optimize the photosynthates toward flowers and fruits are pushing plants to new limits of growth and productivity. This set of circumstances might put plants under stressful conditions that are difficult to qualify and quantify. These phenomena are apparently conducive to some diseases that are not common in out-field cultivation conditions [10].

Nonetheless, reduction in fungicide applications has been a trend in recent years in protected horticulture as the industry leads the way in environmentally responsible, intensive crop production. For example, the controlled environment of the system offers a unique niche for the biological control of plant diseases. In fact, a large share of biocontrol products have been developed specifically or especially for use with greenhouse crops [13]. For that reason, protected horticulture systems have a well established reputation for using biological control agents more than other crop production mode. The primary strategy of biological control for plant diseases is to introduce antagonists to control populations of disease causing microorganisms in the systems so that they are unable to infect the crops, or at least have a diminished capability of doing so. Some promising biological control agents include Trichoderma spp., which are strong competitors of diseases-causing fungi such as Botrytis cinerea, and which are useful to protect wound sites and prevent pathogens from colonizing the wound site [2]. In the future, biological control of diseases in protected horticulture might become more widely practiced than the use of chemical pesticides in the same way that biological control of greenhouse insects predominates in some areas.

Climate change is another factor that is likely to affect protected horticulture in the future. In fact, it is becoming increasingly recognized that increased frequency of drought and flooding, as well as other unusual events of local climates will pose a substantial challenge to food security. Although such events might be less damaging to protected horticulture systems than to extensive cultivation in non-controlled environments, the potential risk posed by climate change should not be minimized unduly, particularly in light of its likely long-term effects on plant pathosystems [3]. Moreover, even modest increases in temperature are expected to raise costs for controlling humidity instead. Much research should be conducted on the potential effects of climate change on semi-natural and protected environments.

Overall, successful crop production demands that crop diseases and pests be managed so that the effects of these biotic factors on the plants are minimized. Managing the environment for disease control has brought success in recent years through the use of environmental control facilities and a better understanding of the ecology of plant pathogens, as described in this review. However, to improve disease control effectiveness in protected horticulture, these new developments should be integrated further into specialized plant husbandry systems with a holistic approach of both disease and pest control in the future.

References

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