**M. E. Stanghellini and S. L. Rasmussen**
University of Arizona

# Hydroponics
# A Solution for Zoosporic Pathogens

Hydroponics is the technology of growing plants in nutrient solution, either with or without the use of a substrate (which is usually inert) to provide mechanical support to the root system (23). Systems lacking an inert substrate are called liquid hydroponic systems, while systems employing various substrates (e.g., sand, gravel, peat, perlite, vermiculite, rock wool, etc.) are called aggregate hydroponic systems. Hydroponic systems are also classified as either open or closed. In a closed system, the nutrient solution is recovered, replenished, and recycled following its direct delivery to the root system. In an open system, the nutrient solution is not replenished or recycled, although it may be recovered. Various types of hydroponic systems are shown in Figure 1. Among the more common closed hydroponic systems are the nutrient film technique (NFT) (Fig. 1A–C) and the deep flow technique (Fig. 1D). Common open hydroponic systems include trough culture (Fig. 1E), rock wool culture (Fig. 1F), sand culture (Fig. 1G), and bag culture (Fig. 1H). Rock wool is currently the most widely used aggregate substrate and is used in open as well as closed hydroponic systems.

Although the history of hydroponics can be traced to the seventeenth century, commercial use began in the early 1940s (23) and is currently employed worldwide to grow flower, foliage, and bedding plants, in addition to high cash value vegetable crops. This article will focus on vegetable crops: in particular, root diseases of hydroponically grown vegetable crops. Although worldwide figures are not available, Eparvier et al (8) estimated that in 1991 there were about 4,000 ha of hydroponic vegetable production in northern Europe alone. In the United States, total greenhouse vegetable production (both soil and hydroponic) has been estimated (1994) at about 220 ha, 75% of which is grown under hydroponic conditions (Michael Dowgert, AgroDynamics, *personal communication*). The size of individual commercial facilities ranges from 232 $m^2$ to 16 ha. Major vegetable crops grown in hydroponic systems include tomato, cucumber, spinach, lettuce, and pepper. Minor crops include watercress, corn-salad, and various herbs and spices.

Dr. Stanghellini's address is: Plant Pathology Department, University of Arizona, Tucson 85721.



Avoidance of root diseases was one of the motivating forces underlying the development of hydroponics. Although cultivation in hydroponics has resulted in a decrease in the diversity of root-infecting microorganisms compared with conventional culture in soil, root diseases still occur, and disease losses are occasionally greater than in soil. In open-field agriculture, the rapid development of a plant disease is generally regarded as a unique feature of foliar or above-ground infectious agents. However, the use of hydroponics (particularly the closed systems) now imparts these same characteristics to root or below-ground infectious agents. Infectious agents, once introduced into the system, are favored as a result of 1) the abundance of a genetically uniform host, 2) a physical environment with a more constant temperature and moisture regime, and 3) a mechanism for the rapid and uniform dispersal of a root-infecting agent throughout the cultural system. Thus, knowledge of the avenues of pathogen introduction is requisite for maintaining a pathogen-free environment. Additionally, accurate identification of the specific pathogen involved is essential to the selection or development of an appropriate strategy for control, because no single method is applicable to all root-infecting pathogens.

## Root-Infecting Agents

Compared to the numerous and diverse types–genera of root- infecting pathogens associated with field-grown vegetable crops, relatively few have been reported as pathogens of crops grown under hydroponic conditions. To date, four viral, two bacterial, and 20 fungal pathogens have been associated with root diseases of hydroponically grown vegetable crops (Table 1). Although this list, at first glance, appears ominous, relatively few of these pathogens have been associated with either major or widespread economic losses in the industry.

With the exception of *Fusarium oxysporum* f. sp. *radicis-lycopersici* (a root and crown pathogen of tomato), most of the destructive root diseases in hydroponics have been attributed, either directly or indirectly, to the fungal genera *Pythium, Phytophthora, Plasmopara,* and *Olpidium*. These fungi, which are capable of infecting seedlings as well as mature, fruit-bearing plants (Fig. 2), all produce a motile spore known as a zoospore and are favored by an aquatic environment. Additionally, all of these zoosporic fungi (Table 1), as opposed to nonzoosporic fungi, have been demonstrated experimentally to spread within a system via recirculation of zoospore-infested nutrient solution. A zoospore is a motile, unicellular, propagative body measuring 3–12 μm in diameter. Zoospores are formed inside a sporangium (or vesicle) on infected roots (Fig. 3) and are eventually released. During the motile period, which can last up to 24 hr, the zoospore, through a chemotactic mechanism, locates a root, encysts, and penetrates and infects the plant root. Under optimum environmental conditions, these events can occur within 5 minutes. Subsequent to root infection, completion of the asexual life cycle (e.g., zoospore to zoospore) can occur (depending on the particular zoosporic fungus) within 12 hours. The reproductive capabilities of these zoosporic fungi are enormous. For example, we have determined that about 40 sporangia of *Plasmopara lactucae-radicis* (Fig. 4) are produced on a 1-cm-long segment of an infected lettuce root. Each sporangium produces approximately 100 zoospores. Thus, 4,000 zoospores are produced per


**Fig. 1. Types of commercial hydroponic cultural systems. (A–C) Nutrient film technique. (D) Deep flow technique. (E) Trough culture. (F) Rock wool culture. (G) Sand culture. (H) Bag culture.**

centimeter of infected root. The uniform infection of a single mature lettuce plant, which has about 2,000 cm of roots, can result in the production and release of about 8 million zoospores.

Most of the zoosporic fungi listed in Table 1 are recognized as root pathogens of the same crops grown in the field. The most common root pathogens are *Pythium aphanidermatum, Pythium myriotylum, Phytophthora cryptogea,* and *Phytophthora nicotianae*. However, cultivation in hydroponics may select for "new" pathogens. For example, *Phytophthora cryptogea* attacks a crop (e.g., lettuce) in hydroponics that it is not reported to attack in the field (29) (Fig. 5). We also recently identified a new root-infecting pathogen on hydroponically grown lettuce. This fungus, an obligate root-infecting downy mildew, was named *Plasmopara lactucae-radicis* (42,43) and has not been reported from any field-grown crop (Fig. 3B). Additionally, some root pathogens that are of little or unrecognized importance under field conditions can be of major economic importance in hydroponic culture. This is particularly true of *Pythium dissotocum*. This fungus was first identified as the cause of a destructive root rot of hydroponically grown spinach (1). Since then, this fungus has been identified as a major pathogen of hydroponically grown lettuce (44). To date, we have isolated this pathogen from the roots of hydroponically grown lettuce submitted for diagnosis from commercial greenhouses in California, Illinois, New York, Florida, Virginia, North Carolina, New Jersey, Canada, and Finland. It appears to be almost ubiquitous in nature. On lettuce, this root pathogen is particularly insidious, because infected plants do not exhibit any root rot symptoms. The only indication of the presence of this fungus, other than its isolation from roots, is a general retardation in the maturation rate of the plant (Fig. 6). However, since all plants in a hydroponic system are uniformly infected, there is no reference point for diagnosis.

## Source of Greenhouse Pathogens

Maintenance of a pathogen-free cultivation system is dependent on identification and elimination of the source(s) responsible for introduction of the pathogen. Potential and documented sources of pathogen introduction include the following: air, sand, soil, peat, water, and insects.

**Air.** In general, soilborne root-infecting pathogens are seldom airborne. An exception, however, is *F. o. radicis-lycopersici*, the most destructive nonzoosporic fungus in hydroponic culture (2,4,19,28,37). This particular fungus attacks both roots and crowns of tomato plants. Airborne spores of this fungus have been identified as a major source of introduction into and within greenhouses (37).

**Seed.** Only two of the pathogens listed in Table 1 are known to be seedborne: *Clavibacter michiganense* (24) and melon necrotic spot virus (32). Melon necrotic spot virus is also transmitted by *Olpidium radicale* (56). Thus, once introduced on seed or seedlings, the virus may spread rapidly via its zoosporic fungal vector.

**Soil.** Soil, although an obvious source of introduction for many plant pathogens, is seldom used in commercial hydroponic facilities. However, soil is still a source of inoculum. Soil is constantly being introduced into most facilities on the shoes of greenhouse personnel, and many greenhouse facilities have nutrient solution reservoirs located at ground level. Often, these reservoirs have no covers or barriers to prevent accidental introduction of the soil into the nutrient solution. Additionally, all soil within the greenhouse should be covered to prevent splash dispersal or the generation of dust, which may harbor soilborne pathogens.

**Sand.** Washed river sand has occasionally been used in greenhouses as an aggregate substrate or as a ground cover–pathway between production areas. Washed river sand can be infested with many plant pathogens and has been identified as the source of introduction of *Pythium aphanidermatum* and *P. dissotocum* into a hydroponic system (1).

**Table 1.** Infectious agents isolated from roots of hydroponically grown vegetable crops

| Pathogen | Spread by infested nutrient solution | Reference |
|---|---|---|
| Bacteria | | |
| *Clavibacter michiganense* | Inconsistent | 6,17,52,53 |
| *Pseudomonas solanacearum* | Yes | 22 |
| Fungi | | |
| Nonzoosporic | | |
| *Colletotrichum coccodes* | Inconsistent | 5,22,53 |
| *Fusarium oxysporum* f. sp. *lycopersici* | Inconsistent | 4,9,52 |
| *F. o. radicis-lycopersici* | Inconsistent | 2,19,22,30 |
| *F. o. cucumerinum* | No | 22 |
| *Pythium ultimum* | Inconsistent | 9,22,57 |
| *Verticillium dahliae* | No | 9 |
| *V. tricorpus* | No | 10 |
| *Thielaviopsis basicola* | Not tested | 46 |
| Zoosporic | | |
| *Phytophthora cryptogea* | Yes | 20,29,34,35 |
| *Phytophthora nicotianae* | Yes | 9,20,41,52,57,59 |
| *Plasmopara lactucae-radicis* | Yes | 42,43 |
| *Pythium aphanidermatum* | Yes | 1,11,22,31,41,45,48 |
| *Pythium debaryanum* | Yes | 22,57 |
| *Pythium dissotocum* | Yes | 1,13,44 |
| *Pythium intermedium* | Yes | 51 |
| *Pythium irregulare* | Not tested | 11,40 |
| *Pythium myriotylum* | Yes | 22,40 |
| *Pythium sylvaticum* | Not tested | 57 |
| *Olpidium brassicae* | Yes | 54,55 |
| *O. radicale* | Yes | 56 |
| Viruses | | |
| Lettuce big vein virus[a] | Yes | 32,54,55 |
| Melon necrotic spot virus[b] | Yes | 56 |
| Tomato mosaic virus | Yes | 32,33 |
| Cucumber green mottle mosaic virus | Yes | 32 |

[a]Transmitted by *Olpidium brassicae*.
[b]Transmitted by *Olpidium radicale*.

**Fig. 2. Death of a mature, fruit-bearing cucumber plant caused by *Pythium aphanidermatum*.**

**Peat.** Commercial peat and peat mixtures are major sources for the introduction of plant pathogens. A survey conducted in 1975 (27) showed that 15 out of 52 randomly selected peat products contained *Pythium*, and all 52 contained *Fusarium*. More recently, Favrin et al (11) reported that eight out of 10 peat or peat-based propagation mixes used in Canada were infested with *Pythium*. Peat has also been implicated as the source of introduction of *Olpidium brassicae* and *Thielaviopsis basicola* into greenhouses in England (55) and Florida (16), respectively.

**Water.** Reservoir and surface water, such as rivers and streams, are known to be infested with many potential plant pathogens and should be avoided. Well water, however, is commonly regarded as pathogen free. In 1988, we suspected river water as the source of *Pythium dissotocum* in a commercial lettuce hydroponic facility in Finland and recommended that the grower might try, if available, deep-well water. In October 1989, we received a letter from the grower indicating that he drilled a well 140 m deep. Since he began to use the well water, *Pythium* has not been a problem, and the well paid for itself in a very short time.

**Insects.** Fungus gnats (*Bradysia* spp.) and shore flies (*Scatella stagnalis*) are common insect pests in greenhouses and have been regarded merely as a nuisance. Recently, however, both larva and adult life stages of these two insects were implicated as vectors of some of the root pathogens listed in Table 1. A summary of the current status regarding transmission by these insects is presented in Table 2. Although larvae of both of these two insects have been shown to ingest, excrete, and transmit some of the root pathogens, their significance to spread within a greenhouse is probably minimal. They are slow moving and, for all practical purposes, confined to the moist surface–subsurface of aggregate substrates supporting individual plants.

Adult stages of these two insects are, however, very mobile and are capable of aerial transmission of some root-infecting pathogens. Adult shore flies have been documented to aerially transmit *Pythium aphanidermatum* (14) and *T. basicola* (47). *T. basicola* (18) and *F. o. radicis-lycopersici* (12), but not *Pythium aphanidermatum* (21), are vectored by adult fungus gnats. The method of pathogen acquisition by the adult stages of these two insects is, however, quite different. In adult fungus gnats, acquisition is either not known (12) or by external contamination (18). In contrast, adult shore flies are internally infested with the root-infecting pathogen and excrete viable fungal propagules.

Acquisition of the root pathogens by adult shore flies can occur by two

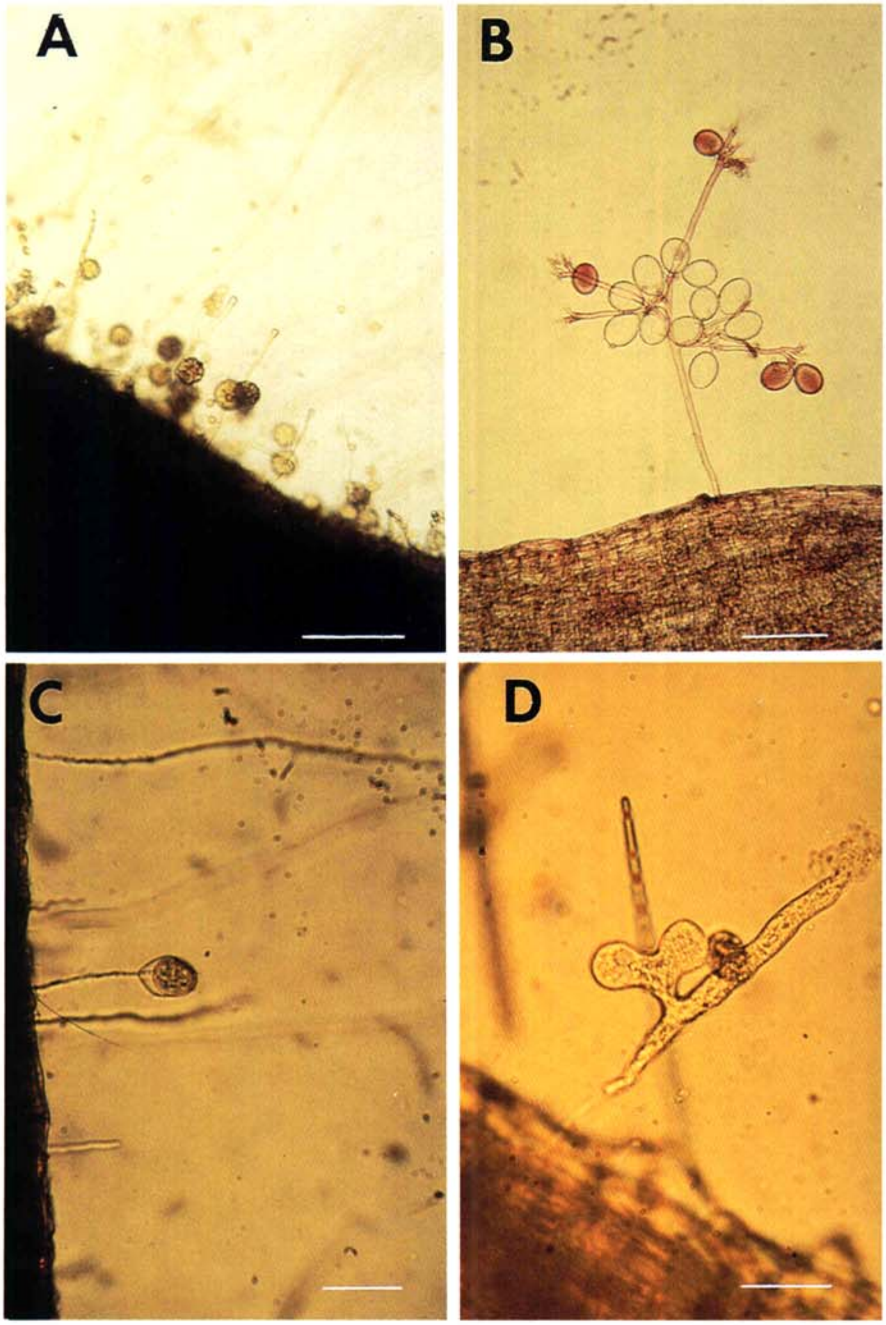



**Fig. 3. Sporangia of zoosporic fungi on roots of their respective hosts. (A) *Pythium dissotocum*. Bar = 150 μm. (B) *Plasmopara lactucae-radicis*. Bar = 160 μm. (C) *Phytophthora cryptogea*. Bar = 150 μm. (D) *Pythium aphanidermatum*. Bar = 100 μm.**

**Fig. 4. Extensive sporulation of *Plasmopara lactucae-radicis* on a naturally infected lettuce root. Bar = 1 cm.**

methods. First, fungal propagules ingested by larvae are retained through pupation. For example, oospores of *Pythium aphanidermatum* were observed in the gut of larvae, pupae, and adult shore flies; and viable oospores were excreted in frass deposited by larvae and adults (Fig. 7). Larvae that fed on infected cucumber roots laden with oospores acquired the fungus. Because adult shore flies do not have access to or feed on infected roots, the oospores observed in the guts of adult flies reflect residual oospore populations retained through pupation. Although only a small percentage (10%) of adult shore flies were internally infested with this root pathogen, these populations were highly efficient in transmission of the pathogen. All cucumber plants frequented by naturally infested adult shore flies were killed (14). Second, the adult shore fly can ingest the pathogen. Chlamydospores and endoconidia of *T. basicola,* a crown and root pathogen of hydroponically grown corn-salad, were microscopically observed in frass deposited by larvae and adult shore flies collected in the immediate vicinity of naturally infected plants (Fig. 8). Approximately 95% of the adult flies and 85% of the larvae were internally infested with this root pathogen, but only 14% of the pupae were internally infested. The high percentage of internally infested adult shore flies and the low percentage of internally infested pupae suggested that adult shore flies were acquiring the fungus by direct feeding. Extensive sporulation of *T. basicola* was observed on above-ground portions (i.e., the crown and lower stems) of infected plants, tissue that would allow adult shore flies access to the fungus.

We subsequently demonstrated that adult shore flies (93%) caged with plants infected with this fungus actually ingest the fungus and excrete viable endoconidia and chlamydospores. The flies can transmit the pathogen, via infested frass, to healthy plants (Fig. 9), which subsequently become infected (47). A similar situation may exist for tomato plants infected with *F. o. radicis-lycopersici.* The latter fungus, like *T. basicola,* sporulates profusely on the lower stem and crown of infected plants. Adult shore fly acquisition by direct feeding is thus highly likely and, along with documented transmission by adult fungus gnats (12) and airborne spores (37), may account for the high incidence of the disease in tomato greenhouses. The above scenario is supported by the fact that this fungus has not been demonstrated to spread from plant to plant via recirculation of the nutrient solution (22,30).

In addition to transmission of pathogenic fungi, adult shore flies have also been demonstrated to transmit certain plant pathogenic bacteria (M. E. Stanghellini and S. L. Rasmussen, *unpublished*). Larvae of adult shore flies, feeding in the root zone of plants artificially infested with a population of rifampicin-resistant strains of *Erwinia carotovora* and *Pseudomonas cichori,* ingested the bacteria. These two bacteria were retained through pupation, and colonies of both were detected in frass excreted by newly emerged adult shore flies (Fig. 10) when the latter were caged on petri dishes containing agar amended with rifampicin. The bacteria were also detected in frass deposits on lower leaves of plants frequented by internally infested adult shore flies (Fig. 11). Insect transmission may account for the occa-

**Fig. 5. Root rot of lettuce caused by *Phytophthora cryptogea* (left). Healthy plant of the same age (right).**

**Fig. 6. Uniform retardation in the maturation rate of lettuce plants infected with *Pythium dissotocum* (left A frame) and healthy plants of the same age (right A frame).**

sional occurrence of stem rot of hydroponically grown tomato caused by *E. carotovora* (22).

The cumulative results of the above investigations indicate that insects must now be added to the list of documented mechanisms for the introduction and spread of pathogens in greenhouses. Insect control must be included in strategies for maintenance of a pathogen-free system.

**Table 2.** Transmission of root-infecting fungi by shore flies and fungus gnats

| | Shore flies | | | Fungus gnats | | |
|---|---|---|---|---|---|---|
| Pathogens[a] | Larvae | Adult | Ref[b] | Larvae | Adult | Ref |
| *Pythium* | Yes[c] | Yes[d] | 14 | Yes[c] | No | 21 |
| *Thielaviopsis* | NT[e] | Yes[c] | 47 | Yes[c] | Yes[f] | 18 |
| *Fusarium* | NT | NT | ... | Yes[f] | Yes[f] | 12 |

[a] *Pythium aphanidermatum, Thielaviopsis basicola, Fusarium oxysporum* f. sp. *radicis-lycopersici*.
[b] References in text.
[c] Internally infested: Acquisition by ingestion.
[d] Internally infested: Acquisition from internally infested pupae.
[e] Not tested.
[f] Method of acquisition not reported or externally contaminated.

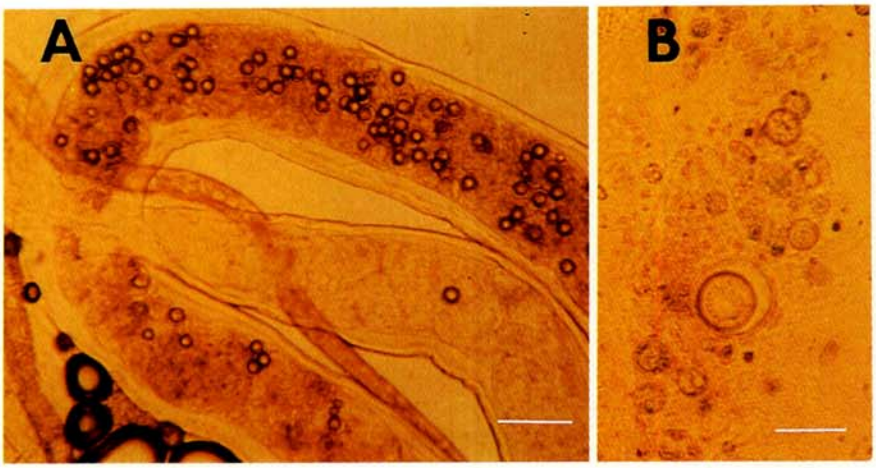



**Fig. 7.** Oospores of ***Pythium aphanidermatum*** in (A) gut of larvae (Bar = 100 μm) and (B) frass excreted by adult shore flies (Bar = 25 μm).

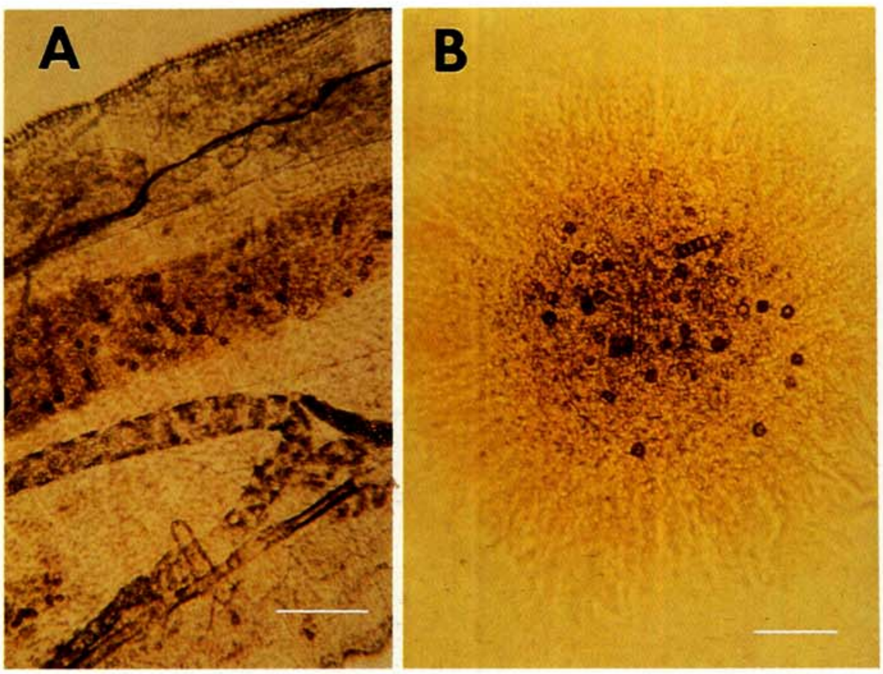



**Fig. 8.** Chlamydospores of ***Thielaviopsis basicola*** in (A) gut of larvae (Bar = 180 μm) and (B) frass excreted by adult shore flies (Bar = 90 μm).

## Environmental Factors

Under field conditions, two of the more important environmental factors that govern the onset or occurrence of root disease are soil temperature and soil moisture. These two factors fluctuate dramatically over a cropping season and are generally favorable for root infection by soilborne pathogens for relatively short periods of time. Additionally, the prevalence of disease (i.e., the number of infected individuals) under field conditions is primarily dependent on the inoculum density of the pathogen per unit volume of soil. Pathogen reproduction on infected roots (i.e., secondary inoculum) generally plays little or no role in current-season disease prevalence. In contrast, both temperature and moisture are relatively constant over the entire cropping season in hydroponic culture. Moisture in the root zone is never lacking, and nutrient solution temperatures can be relatively constant over long periods of time. This constancy, if coincident with the moisture and temperature requirements of the pathogen, provides a near-optimum environment for sustained root infection. Additionally, disease prevalence in hydroponics, in contrast to that in open-field agriculture, is dependent on the production and dispersal of secondary inoculum.

The abundance of free water in hydroponic systems favors all of the zoosporic pathogens. Nutrient solution temperatures, however, appear to be the most important environmental factor governing both the onset and the prevalence of root diseases caused by specific zoosporic pathogens. For example, *Pythium aphanidermatum,* which attacks cucumbers, tomatoes, and spinach, is most destructive at nutrient solution temperatures above 25 C and is not of economic concern at temperatures below 20 C (1,13). Similarly, *Plasmopara lactucae-radicis,* which attacks lettuce roots, is favored by warm temperatures and is inhibited at nutrient solution temperatures below 20 C (42). In contrast, *Phytophthora cryptogea,* a zoosporic pathogen of tomatoes, is most destructive at 15 C and causes little or no damage at 25 C (25,26,34). In all of the above cases, lack of disease at specific temperatures has been associated with an inhibition of, or reduction in, production of zoospores (i.e., secondary inoculum) by the pathogen.

## Pathogen Spread in Hydroponic Culture

Any infectious propagule, upon entry into the nutrient solution, will eventually make contact with a root, or vice versa. The probability of encounter is very high when one takes into consideration the density and confinement of roots in a hydroponic system, particularly those employing the nutrient film technique. Once a zoosporic, root-infecting fungus has been introduced into a production facility, it will multiply and spread rapidly throughout the system. Methods of pathogen dispersal include the following: self-dispersal (i.e., via zoospore motility), dispersal resulting from recirculation of the nutrient solution, and root-to-root contact. Zoospores readily pass through sand filters (49) and the impellers of centrifugal pumps (20,49) in a viable condition (most probably as encysted zoospores). Additionally, many root pathogens are capable of growing, via hyphae, from an infected to a healthy root.

## Methods of Control

Once a root-infecting pathogen has established itself in a production facility, control is often difficult but can sometimes be achieved. The choice of a particular control strategy depends on accurate identification of the root-infecting pathogen. Various methods of control are listed below.

A. Biological methods
  1. Use of resistant cultivars
  2. Use of antagonistic microorganisms
B. Cultural and physical methods
  1. Sanitation
  2. Treatment of infested nutrient solution
  3. Manipulation of the physical environment
C. Chemical methods
  1. Fungicides
  2. Other biocides

**Biological methods.** *Resistant cultivars.* The first line of defense against a plant pathogen is the use of resistant cultivars. Accurate identification of the pathogen, to the species level, is mandatory for the selection of appropriate cultivars. Unfortunately, few cultivars are resistant to most of the pathogens listed in Table 1. Tomato cultivars resistant to *Fusarium* spp. and lettuce cultivars resistant to *Plasmopara lactucae-radicis* are available.

*Antagonistic microorganisms.* The use of antagonistic microorganisms, particularly in rock wool culture, has been the subject of recent investigations (8,28,36, 58), and the results of these investigations appear promising. However, most of the antagonists are not registered for use in commercial hydroponic systems. The only antagonist registered for such a use is *Streptomyces griseoviridis* (Mycostop, Kemira Biotech, Finland). This antagonist is most effective against *Fusarium.*

**Cultural and physical methods.** *Sanitation.* The removal of all infested or infected plant debris, as well as disinfestation of equipment and recycled aggregate substrates, is mandatory for the maintenance of a pathogen-free system. This is particularly true in the nursery. Pathogen-free nursery stock is of the utmost importance. The nursery should be housed in a facility physically separated from the production facility and should not use the same nutrient solution employed in the production facility.

*Treatment of infested nutrient solution.* Numerous methods have been proposed for the elimination of pathogens from infested nutrient solutions. Such methods include filtration, sonication, ozonation, ultraviolet irradiation, and thermal inactivation (10,15,38,39,49). Although some of these methods are experimentally demonstrated to be effective, successful application to large com-

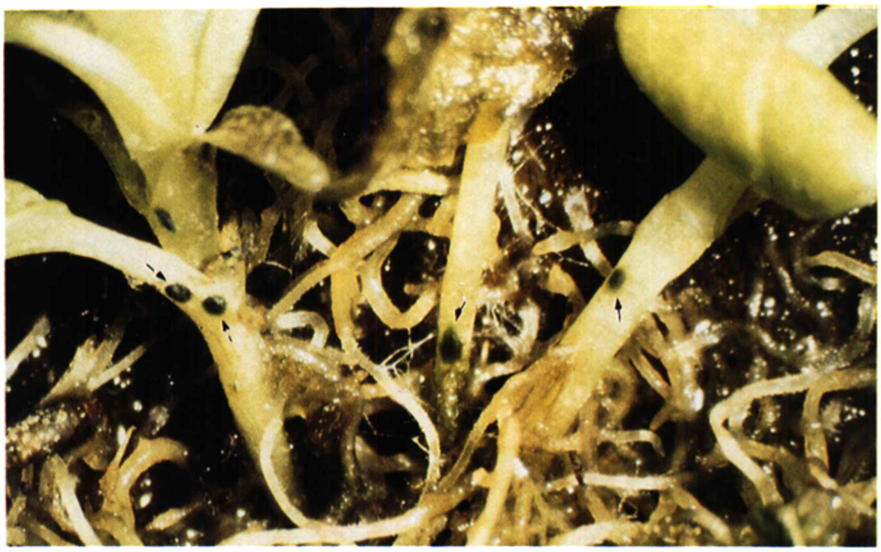


**Fig. 9. Adult shore fly frass deposits (arrows) on the hypocotyl of corn-salad seedlings.**

mercial systems is often cost prohibitive. Large commercial systems require nutrient solution flow rates often exceeding 1,000 L/minute. Sterilization of such large volumes of nutrient solution, particularly in closed systems where there is no down time, is virtually impossible.

*Manipulation of the physical environment.* As previously mentioned, two of the more important environmental factors known to govern the life cycle of root-infecting pathogens and disease cycles are temperature and moisture. Hydroponics provides for a nearly constant saturated environment. Thus, management of the moisture in the root zone will have minimal impact on the pathogens listed in Table 1. However, the temperature of the nutrient solution can be manipulated. If the temperature requirements of the root pathogen are known, nutrient solution temperatures can be raised or lowered to retard development of the pathogen. For example, spinach, cucumbers, and tomatoes are attacked by *Pythium aphanidermatum.* This fungus is most destructive at temperatures above 25 C. Similarly, *Plasmopara lactucae-radicis,* a pathogen of lettuce roots, is favored by temperatures above 20 C. Thus, lowering the temperature of the nutrient solution will result in economic control of these two root pathogens. In contrast, *Phytophthora cryptogea,* a root pathogen of tomato, is favored by cool temperatures and can be controlled by elevating root zone temperatures to 25 C (25,26). The above examples illustrate the necessity for accurate identification of the causal agent of a particular disease.

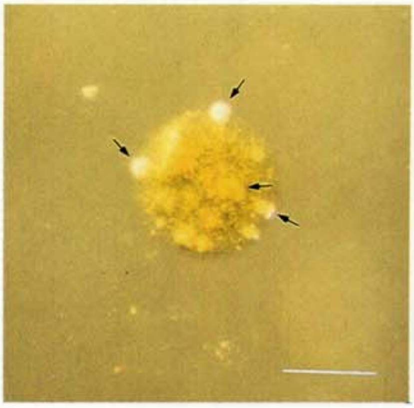


**Fig. 10. Colonies of a rifampicin-resistant strain of *Erwinia carotovora* developing in a frass deposit excreted by an adult shore fly. Bar = 0.75 mm.**

**Fig. 11. Frass deposits excreted by adult shore fly on lower leaf of a poinsettia plant. Frass deposits were infested with *Erwinia carotovora.***

**Chemical methods.** *Fungicides.* The addition of fungicides to the recirculating nutrient solution is obviously an effective method of disease control. However, no fungicides are registered for use in hydroponic systems in the United States. The reasons for the lack of registered products are numerous. First, most fungicides have a lag period between application and harvest, and most commercial hydroponic facilities harvest every day. Second, the limited acreage of hydroponics in the United States does not warrant the cost of registration. Third, the probability that chemically resistant strains of the pathogen would develop is very high.

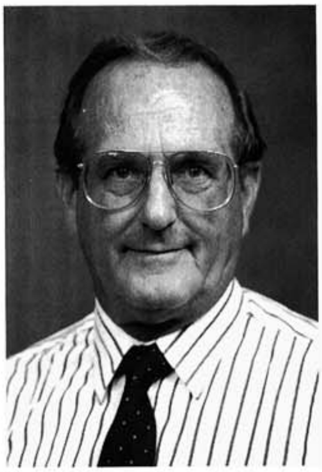
*Other biocides.* Amending the nutrient solution with potassium silicate (3) and chitosan (7) have recently been reported to control certain root-infecting pathogens in hydroponics. The results of these preliminary studies look promising, but neither is currently registered for commercial use. In addition to the above two chemicals, surfactants also exhibit promise in the control of root diseases caused by zoosporic fungi. In 1980, Tomlinson and Faithfull (54,55) demonstrated effective commercial control of lettuce big vein disease, which is caused by a virus vectored by *O. brassicae.* Zoospores of *O. brassicae,* in addition to zoospores of *Pythium* and *Phytophthora* (50), are rapidly killed (via dissolution of the unit membrane encasing the zoospore) when exposed to surfactants. Evaluations of the efficacy of surfactants for the control of root rot of cucumbers and tomatoes caused by *Pythium aphanidermatum* and two species of *Phytophthora,* respectively, are currently in progress (M. E. Stanghellini and S. L. Rasmussen, *unpublished*). Preliminary results indicate complete suppression of zoospore spread in a recirculating rock wool system.

## Summary

Root diseases are one of the constraints on the maximum yield potential of any crop. The accidental introduction of a pathogen into a recirculating hydroponic system essentially guarantees a rapid and uniform infestation of the entire crop. Thus, knowledge of the avenues of pathogen introduction is requisite for maintaining a pathogen-free environment. Once a pathogen becomes established, disease control is often difficult. Accurate identification of the pathogen is essential to the selection or development of an appropriate strategy for control, because no one method is applicable to all root-infecting pathogens. Undoubtedly, new diseases will be encountered as the hydroponic industry expands, and research on effective methods of control will be needed.

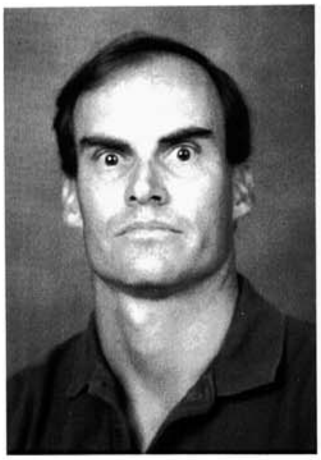
## Literature Cited

1. Bates, M. L., and Stanghellini, M. E. 1984. Root rot of hydroponically grown spinach caused by *Pythium aphanidermatum* and *Pythium dissotocum.* Plant Dis. 68:989-991.
2. Brammall, R., and Lynch, K. 1990. Occurrence of *Fusarium* crown and root rot of tomato in New Brunswick, Canada. Plant Dis. 74:1037.
3. Chérif, M., and Bélanger, R. R. 1992. Use of potassium silicate amendments in recirculating nutrient solutions to suppress *Pythium ultimum* on long English cucumber. Plant Dis. 76:1008-1011.
4. Couteaudier, Y., and Alabouvette, C. 1981. Fusarium wilt diseases in soilless cultures. Acta Hortic. 126:153-158.
5. Daughtrey, M. L., and Schippers, P. A. 1980. Root death and associated problems. Acta Hortic. 98:283-291.
6. Davies, J. M. L. 1980. Diseases in NFT. Acta Hortic. 98:299-305.
7. El Ghaouth, A., Arul, J., Grenier, J., Benhamou, N., Asselin, A., and Belanger, R. 1994. Effect of chitosan on cucumber plants: Suppression of *Pythium aphanidermatum* and induction of defense reactions. Phytopathology 84:313-320.
8. Eparvier, A., Lemanceau, P., and Alabouvette, C. 1991. Population dynamics of non-pathogenic *Fusarium* and fluorescent *Pseudomonas* strains in rockwool, a substratum for soilless culture. FEMS Microbiol. Ecol. 86:177-184.
9. Evans, S. G. 1979. Susceptibility of plants to fungal pathogens when grown by the nutrient-film technique (NFT). Plant Pathol. 28:45-48.
10. Ewart, J. M., and Chrimes, R. J. 1980. Effects of chlorine and ultra-violet light in disease control in NFT. Acta Hortic. 98:317-323.
11. Favrin, R. J., Rahe, J. E., and Mauza, B. 1988. *Pythium* spp. associated with crown rot of cucumbers in British Columbia greenhouses. Plant Dis. 72:683-687.
12. Gillespie, D. R., and Menzies, J. G. 1993. Fungus gnats vector *Fusarium oxysporum* f. sp. *radicis-lycopersici.* Ann. Appl. Biol. 123:539-544.
13. Gold, S. E., and Stanghellini, M. E. 1985. Effects of temperature on Pythium root rot of spinach grown under hydroponic conditions. Phytopathology 75:333-337.
14. Goldberg, N. P., and Stanghellini, M. E. 1990. Ingestion-egestion and aerial transmission of *Pythium aphanidermatum* by shore flies (Ephydrinae: *Scatella stagnalis*). Phytopathology 80:1244-1246.
15. Goldberg, N. P., Stanghellini, M. E., and Rasmussen, S. L. 1992. Filtration as a method for controlling Pythium root rot of hydroponically grown cucumbers. Plant Dis. 76:777-779.
16. Graham, J. H., and Timmer, N. H. 1991. Peat-based media as a source of *Thielaviopsis basicola* causing black root rot on citrus seedlings. Plant Dis. 75:1246-1249.
17. Griesback, E., and Naumann, K. 1984. Uber das auftreten der bakteriellen welke in NFT-tomatenanlagen. Nachrichtenbl. Pflanzenschutz DDR 38:164-168.
18. Harris, M. A., Oetting, R. D., and Moody, E. 1994. Transmission of *Thielaviopsis basicola* and *Fusarium proliferatum* by fungus gnats. (Abstr.) Phytopathology 84:1066.
19. Hartman, J. R., and Fletcher, J. T. 1991. Fusarium crown and root rot of tomatoes in the UK. Plant Pathol. 40:85-92.
20. Holderness, M., and Pegg, G. F. 1986. Interaction of host stress and pathogen ecology on *Phytophthora* infection and symptom expression in nutrient film-grown tomatoes. Pages 189-205 in: Water, Fungi and Plants. P. G. Ayres and L. Boddy, eds. British Mycological Society.
21. Jarvis, W. R., Shipp, J. L., and Gardiner, R. B. 1993. Transmission of *Pythium aphanidermatum* to greenhouse cucumber by the fungus gnat *Bradysia impatiens* (Diptera: Sciaridae). Ann. Appl. Biol.



**Michael E. Stanghellini**

Dr. Stangellini is a professor of plant pathology at the University of Arizona. He received his B.A. degree in biological sciences from the University of California, Davis, in 1963, an M.S. in plant pathology from the University of Hawaii in 1965, and his Ph.D. in plant pathology from the University of California, Berkeley, in 1969. He joined the faculty of the Department of Plant Pathology at the University of Arizona in 1969. His research interests focus primarily on the ecology, epidemiology, and control of root diseases of field and hydroponically grown vegetable crops. Pathogens of particular interest include *Pythium, Erwinia,* and most recently *Monosporascus cannonballus.* He teaches the introductory course in plant pathology and a graduate course on the rhizosphere biology of root-infecting plant pathogenic fungi.



**Scott L. Rasmussen**

Mr. Rasmussen is a senior research specialist in the Department of Plant Pathology at the University of Arizona. He received his B.S. degree in agronomy from the University of Arizona in 1983 and his M.S. degree in plant pathology from the same institution in 1986. In 1986, he accepted the position of laboratory manager in Dr. Stanghellini's laboratory.

122:23-29.
22. Jenkins, S. F., Jr., and Averre, C. W. 1983. Root diseases of vegetables in hydroponic culture systems in North Carolina greenhouses. Plant Dis. 67:968-970.
23. Jensen, M. H., and Collins, W. L. 1985. Hydroponic vegetable production. Hortic. Rev. 7:483-558.
24. Jones, J. B., Jones, J. P., Stall, R. E., and Zitter, T. A. 1991. Compendium of Tomato Diseases. American Phytopathological Society, St. Paul, MN.
25. Kennedy, R., and Pegg, G. F. 1990. *Phytophthora cryptogea* root rot of tomato in rockwool nutrient culture. II. Effect of root zone temperature on infection, sporulation and symptom development. Ann. Appl. Biol. 117:537-551.
26. Kennedy, R., Pegg, G. F., and Welham, S. J. 1993. *Phytophthora cryptogea* root rot of tomato in rockwool nutrient culture: III. Effect of root zone temperature on growth and yield of winter-grown plants. Ann. Appl. Biol. 123:563-578.
27. Kim, S. H., Faorer, L. B., and Longenecker, J. L. 1975. Recovery of plant pathogens from commercial peat-products. Proc. Am. Phytopathol. Soc. 2:124.
28. Lemanceau, P., and Alabouvette, C. 1991. Biological control of fusarium diseases by fluorescent *Pseudomonas* and non-pathogenic *Fusarium*. Crop Prot. 10:279-286.
29. Linde, A. R., Stanghellini, M. E., and Matheron, M. E. 1990. Root rot of hydroponically grown lettuce caused by *Phytophthora cryptogea*. Plant Dis. 74:1037.
30. Mihuta-Grimm, L., Erb, W. A., and Rowe, R. C. 1990. Fusarium crown and root rot of tomato in greenhouse rock wool systems: Sources of inoculum and disease management with benomyl. Plant Dis. 74:996-1002.
31. Nowicki, B. 1985. *Pythium aphanidermatum* (Edson) Fitzp., a pathogen of glasshouse cucumber. Acta Agrobot. 35:107-112.
32. Paludan, N. 1985. Spread of viruses by recirculated nutrient solutions in soilless cultures. Tidsskr. Planteavl. 89:467-474.
33. Pategas, K. G., Schuerger, A. C., and Wetter, C. 1989. Management of tomato mosaic virus in hydroponically grown pepper (*Capsicum annuum*). Plant Dis. 73:570-573.
34. Pegg, G. F., and Jordan, M. M. 1991. *Phytophthora cryptogea* root rot of tomato in rockwool nutrient culture. I. Analysis of root infection. Ann. Appl. Biol. 117:525-535.
35. Price, T. V., and Fox, P. 1986. Studies on the behavior of furalaxyl on pythiaceous fungi and cucumbers in recirculating hydroponic systems. Aust. J. Agric. Res. 37:65-77.
36. Rankin, L., and Paulitz, T. C. 1994. Evaluation of rhizosphere bacteria for biological control of Pythium root rot of greenhouse cucumbers in hydroponic culture. Plant Dis. 78:447-451.
37. Rowe, R. C, Farley, J. D., and Coplin, D. L. 1977. Airborne spore dispersal and recolonization of steamed soil by *Fusarium oxysporum* in tomato greenhouses. Phytopathology 67:1513-1517.
38. Runia, W. Th. 1988. Elimination of plant pathogens in drainwater from soilless cultures. Pages 429-443 in: ISOS Proc.
39. Runia, W. Th., van Os, E. A., and Bollen, G. J. 1988. Disinfection of drainwater from soilless cultures by heat treatment. Neth. J. Agric. 36:231-238.
40. Schuerger, A. C., and Pategas, K. G. 1984. Management of two *Pythium* spp. in hydroponic lettuce production. (Abstr.) Phytopathology 74:796.
41. Skadow, K., Schaffrath, J., Gohler, F., Drews, M., and Lanckow, H. J. 1984. *Phytophthora nicotianae* and *Pythium aphanidermatum* causing damage in NFT culture. Nachrichtenbl. Planzenschultz DDR 38:169-172.
42. Stanghellini, M. E., Adaskaveg, J. E., and Rasmussen, S. L. 1990. Pathogenesis of *Plasmopara lactucae-radicis,* a systemic root pathogen of cultivated lettuce. Plant Dis. 74:173-178.
43. Stanghellini, M. E., and Gilbertson, R. L. 1988. *Plasmopara lactucae-radicis,* a new species on roots of hydroponically-grown lettuce. Mycotaxon 31:395-400.
44. Stanghellini, M. E., and Kronland, W. C. 1986. Yield loss in hydroponically grown lettuce attributed to subclinical infection of feeder rootlets by *Pythium dissotocum*. Plant Dis. 70:1053-1056.
45. Stanghellini, M. E., and Phillips, J. M. 1975. *Pythium aphanidermatum*: Its occurrence and control with pyroxychlor in the Arabian desert at Abu Dhabi. Plant Dis. Rep. 59:559-563.
46. Stanghellini, M. E., Rasmussen, S. L., and Barta, D. J. 1990. Thielaviopsis root rot of corn-salad. Plant Dis. 74:81.
47. Stanghellini, M. E., Rasmussen, S. L., and Kim, D. H. 1994. Ingestion-egestion and aerial transmission of *Thielaviopsis basicola,* a root and stem pathogen of corn-salad, by adult shore flies. (Abstr.) Phytopathology 84:1066.
48. Stanghellini, M. E., and Russell, J. D. 1971. Damping-off of tomato seedlings in commercial hydroponic culture. Prog. Agric. Ariz. 23(5):15-16.
49. Stanghellini, M. E., Stowell, L. J., and Bates, M. L. 1984. Control of root rot of spinach caused by *Pythium aphanidermatum* in a recirculating hydroponic system by ultraviolet irradiation. Plant Dis. 68:1075-1076.
50. Stanghellini, M. E., and Tomlinson, J. A. 1987. Inhibitory and lytic effects of a nonionic surfactant on various asexual stages in the life cycle of *Pythium* and *Phytophthora* species. Phytopathology 77:112-114.
51. Stanghellini, M. E., White, J. G., Tomlinson, J. A., and Clay, C. 1988. Root rot of hydroponically grown cucumbers caused by zoospore-producing isolates of *Pythium intermedium.* Plant Dis. 72:358-359.
52. Staunton, W. P., and Cormican, T. P. 1978. The behavior of tomato pathogens in a hydroponic system. Acta Hortic. 82:133-135.
53. Staunton, W. P., and Cormican, T. P. 1980. The effects of pathogens and fungicides on tomatoes in a hydroponic system. Acta Hortic. 98:293-297.
54. Tomlinson, J. A., and Faithfull, E. M. 1980. Effects of fungicides and surfactants on the zoospores of *Olpidium brassicae*. Ann. Appl. Biol. 93:13-19.
55. Tomlinson, J. A., and Faithfull, E. M. 1980. Studies on the control of lettuce big-vein disease in recirculated nutrient solutions. Acta Hortic. 98:325-331.
56. Tomlinson, J. A., and Thomas, B. J. 1986. Studies on melon necrotic spot virus disease of cucumber and on the control of the fungus vector (*Olpidium radicale*). Ann. Appl. Biol. 108:71-80.
57. Vanachter, A., Van Wambeke, E., and Van Assche, C. 1983. Potential danger for infection and spread of root diseases of tomatoes in hydroponics. Acta Hortic. 133:119-128.
58. Van Steekelenburg, N. A. M. 1991. Effect of *Trichoderma harzianum* on incidence of Fusarium crown and root rot in rockwool-grown tomatoes. Pages 199-205 in: Biotic Interactions and Soil-borne Diseases. A. B. R. Beemster, ed. Elsevier, Amsterdam.
59. Van Voorst, G., Van Os, E. A., and Zadoks, J. C. 1987. Dispersal of *Phytophthora nicotianae* on tomatoes grown by nutrient film technique in a greenhouse. Neth. J. Plant Pathol. 93:195-199.