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Strategies for Controlling Fusarium Crown and Root Rot in Greenhouse Tomatoes

Fig. 1. Chocolate-brown discoloration of the vascular system 15–30 cm above the soil line is characteristic of Fusarium crown and root rot of tomato.

Fig. 2. Wilting and stunting of mature, fruit-bearing tomato plants are symptoms of Fusarium crown and root rot.

Fig. 3. Pink sporulation of *Fusarium oxysporum* on basal stem of severely diseased tomato plant.

The Ohio greenhouse tomato industry, located primarily in the Cleveland area, is the largest in the United States. In 1974, a new disease of tomato causing extensive root rot and chocolate-brown discoloration of the stem interior was found in four greenhouses. *Fusarium oxysporum* was identified as the causal organism, and the disease was named Fusarium crown and root rot (FCRR) (3). This internal discoloration extends no more than 15–30 cm above the soil line (Fig. 1), unlike that with Fusarium wilt, a similar disease caused by *F. oxysporum* f. sp. *lycopersici*. FCRR-infected plants with heavy fruit loads usually wilt on sunny days (Fig. 2), and severely infected plants are often stunted and may eventually die after repeated wilting.

A 1976 disease survey in the Cleveland area revealed FCRR in 23 greenhouse ranges approximately one-third of the greenhouse area planted to tomatoes. In seven ranges, yield losses were estimated at 20–50% (13). By 1977, nearly every greenhouse in the Cleveland area was infested.

Early Control Efforts Fail

When FCRR was first identified in 1974, every effort was made to limit disease spread. Greenhouses were posted "off limits" to visitors, and interchange of

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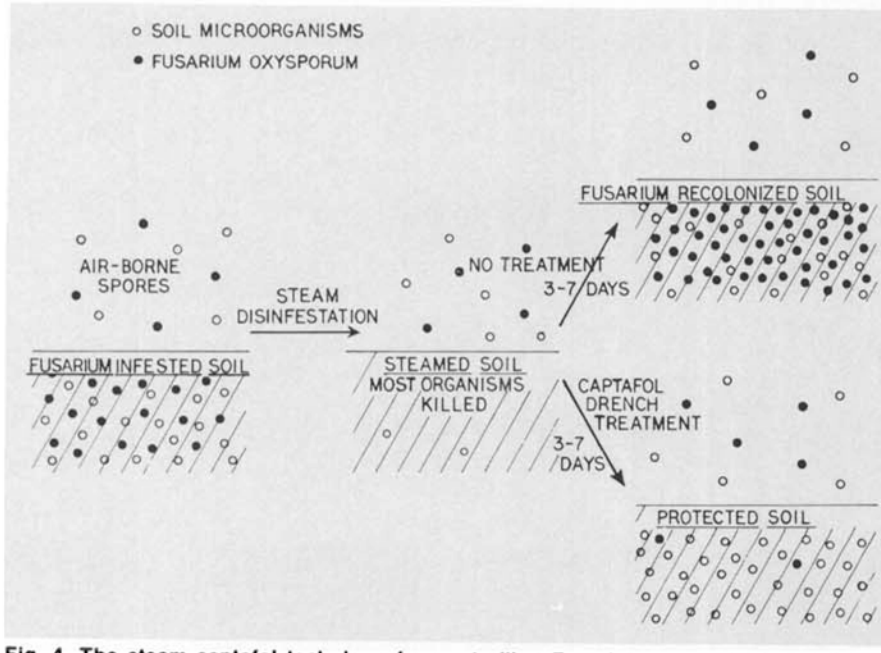

Fig. 4. The steam-captafol technique for controlling Fusarium crown and root rot in tomato greenhouses.

Table 1. Results of treatment with steam alone (1976) and with steam and captafol (1977) for Fusarium crown and root rot of tomato in two commercial greenhouses in north central Ohio[a]

	Location A		Location B	
	1976	1977	1976	1977
Percent wilting plants in May	90	5	85	5
Percent root infection in July[b] (end of season)	99	30	85	40
Total yield (kg/m^2)	6.9	18.2	12.7	15.3

[a] After Rowe and Farley (14).
[b] Every 10th plant in every 10th row uprooted, sectioned, and examined for internal discoloration and decay of root and crown area.

equipment, supplies, and plants among infested and noninfested ranges was stopped. Growers with affected plants began an extensive sanitation program to eliminate the disease or reduce its severity, with unsatisfactory results. Soil steaming, a traditional and generally effective method for controlling soilborne diseases in greenhouses, also failed, even when steaming time was increased and the number of steamings per year was doubled. Control efforts were unsuccessful in all cases, and in some situations the disease was worse in subsequent crops.

Fungicides labeled for use on greenhouse tomatoes, as well as some unregistered compounds, were tested as soil drenches on infected plants. These efforts also failed.

Airborne Spores Are Suspected

The failure of soil steaming to control FCRR led to the suspicion that airborne spores may have been reinfesting the soil after steaming. A similar situation has been reported for Fusarium stub dieback of greenhouse carnations (9). To test the theory, petri plates containing a *Fusarium*-selective agar growth medium (6) were placed at various heights throughout infested greenhouses to catch airborne spores. Monoconidial isolates prepared from colonies of *Fusarium* species arising from caught spores were subjected to pathogenicity tests to positively identify the FCRR pathogen. Results showed that microconidia of *F. oxysporum* capable of causing FCRR symptoms when inoculated to tomato seedlings were common in the air in infested greenhouses (15). The spores were found on stems of infected plants (Fig. 3), on straw mulch between the rows in greenhouses, and on decaying tomato vines in outside dump piles (15).

It is well known that fumigation or steam disinfestation of soil is followed by rapid recolonization of the soil by microorganisms (1,7). Aggressive colonizers, such as some *Fusarium* species, often can reestablish themselves quickly in freshly steamed soil, sometimes at populations higher than those before steaming. In many cases, this has been the reason soil fumigation or steam disinfestation has failed to control soilborne pathogens. This possibility was investigated by inoculating steam-disinfested soil with dilute microconidial suspensions of *F. oxysporum* under controlled conditions. Resulting chlamydospore populations in the soil were monitored daily by soil dilution plating on Komada's medium (6). Chlamydospore concentrations increased by a thousandfold in 3 days and by nearly a millionfold within a week (15).

Soil steaming obviously had failed to control FCRR because soil was recontaminated by airborne microconidia remaining in the greenhouses after steaming. Conidia apparently settled on the freshly steamed soil and developed rapidly, with a large concentration of chlamydospores in the soil serving as inoculum to infect subsequent tomato crops.

Three Approaches to Control

The knowledge that soil reinfestation was the problem prompted investigations of three approaches to control: 1) eliminating spores of *F. oxysporum* within the greenhouse coupled with soil steaming, 2) using poststeaming soil treatments to inhibit recolonization by the pathogen, and 3) developing resistant tomato cultivars suitable for greenhouse production.

Spore elimination, the first approach, was attempted with a formaldehyde disinfestation technique developed in Europe (18,19). Formaldehyde is an excellent surface disinfectant that vaporizes rapidly, facilitating kill of airborne spores, but is extremely hazardous to the applicator and requires rubberized protective clothing and a self-contained breathing apparatus. A tractor-mounted, air-blast orchard sprayer was used to thoroughly cover all interior structural surfaces with 200–250 L/ha of a 1.5% formaldehyde solution both before and after soil steaming. All vents and doors were kept tightly closed for about 16 hours after treatment.

This control measure was the first tested with any degree of success. Treated greenhouses had less disease in subsequent tomato crops, but FCRR control was only partial. A few growers used this procedure for one or two seasons, but the application techniques and equipment required discouraged many others from adopting the method.

Second Approach Succeeds

Because a key to the problem was preventing recontamination of freshly steamed soil, attempts were made to identify fungicides that might bar *F. oxysporum* development in the soil while allowing reestablishment of much of the

soil microflora. While recolonizing, these microorganisms could utilize nutrients released from the soil during the steaming process and, once established, could reduce colonization by the FCRR pathogen.

Flats of steam-disinfested soil were drenched with test fungicides, then inoculated with dilute microconidial suspensions of *F. oxysporum*. Fungus populations in the soil were monitored weekly by dilution plating on Komada's medium. After 3 weeks, seedling tomatoes were transplanted into the flats. Reinfestation of freshly steamed soil by *F. oxysporum* was completely prevented by captafol (*cis*-*N*[1,1,2,2-tetrachloroethyl]thio-4-cyclohexene-1,2-dicarboximide) as Difolatan 4F, a flowable formulation consisting of 480 g a.i./L (14) (Fig. 4).

An emergency state label permitting the use of captafol was obtained, and Ohio growers with severely affected plants were advised to treat their soils before planting the spring crop in December 1976. Six commercial growers in the Cleveland area treated their ranges. Captafol was injected into overhead irrigation lines and the hot soil was drenched with 56 L/ha (6 gal/A) in 6–12 mm of water immediately after steaming tarps were removed. Tomato seedlings were transplanted into the soil 2–3 weeks later. Crops in two greenhouses were monitored throughout the spring 1977 growing season, and control of FCRR was excellent (Table 1). Growers who had lost 30–60% of the crop in 1976 had normal yields in 1977 (Fig. 5).

During the past four seasons, the steam-captafol treatment has been used by virtually every greenhouse tomato grower in Ohio, with minimal losses to FCRR and with no adverse effects. A few mild cases of disease have occurred but probably were associated with nonuniformity in soil steaming or captafol application.

The Steam-Captafol Method

The technique has been easily incorporated into standard soil steaming procedures used by Ohio greenhouse tomato growers. The steaming process generally takes 1–2 weeks to complete. The soil in one range is first rototilled, then covered with a heavy plastic tarp and steamed for 6–10 hours, attaining soil temperatures of 80–85 C. Steam is injected through a permanent system of clay tiles 30–35 cm below the soil surface. The tarp is carefully moved to an adjoining range the next day, and the process is repeated.

While the freshly steamed soil is still hot (> 60 C), captafol is drenched onto the soil through permanent overhead irrigation lines. Most growers have facilities for injecting materials directly into these lines. Once the steaming tarp is moved, the soil is undisturbed during fungicide application and for the next 2 weeks, the period before transplanting. The amount of water used in drenching varies according to soil type and drainage patterns in the greenhouse. Most growers attempt to use enough water to penetrate the soil at least 5–10 cm and provide protection against recolonization in the upper layer.

FCRR Elsewhere

In 1974, FCRR appeared simultaneously in tomato greenhouses in Cleveland (3) and across Lake Erie in Leamington, Ontario, Canada (5). During the past few years, the disease has developed identically in ground-bed greenhouse tomatoes in New Hampshire, New Jersey, and New York (10). In addition, FCRR has been found in tomatoes grown in troughs of peat-vermiculite mix in greenhouses in Pennsylvania and North Carolina; disease in these states has been controlled by the steam-captafol method.

FCRR has been known in Japan for nearly 10 years (16,20). Many of the 3,600 ha of tomatoes grown there under plastic and glass are heavily infested, and losses are severe (Fig. 6). During the spring of 1979, the senior author traveled in southern Japan, observing the disease. In many instances, tomatoes are grown in plastic houses erected in rice paddies after the rice crop is harvested. This double-cropping helps maximize production on a small land area, but FCRR has become a limiting factor in many cases and remains largely uncontrolled because soil steaming is not economically feasible. Some control has been achieved by grafting resistant rootstocks onto horticulturally desirable scions, but labor costs are high. Tomatoes are also produced in Japan in permanent glasshouses in rotation with many other vegetable crops, but even under these conditions soil steaming is not common because of economic constraints (11).

A disease resembling FCRR has been reported on tomatoes field-grown during the winter months in Florida (17) and San Diego County, California (2,8). The disease is not an economic problem in California but has become important in southeastern Florida near Fort Pierce (17), where staked tomatoes are produced during the winter on raised beds that have been fumigated with methyl bromide and covered with black plastic mulch. Presumably, recolonization after soil

Fig. 5. (Left) Commercial greenhouse in spring 1976 with tomato crop uniformly infested with Fusarium crown and root rot. (Right) Same greenhouse in spring 1977 after steam-captafol technique was used; crop yield was normal.

fumigation is part of the problem. In the spring of 1978, the senior author observed symptoms in the fields of southeastern Florida that were very similar to those seen in the Cleveland greenhouses. Similar symptoms were also observed during the spring of 1979 on outdoor staked tomatoes in the Culiacán winter vegetable production area of central Mexico (12).

FCRR seems well established in North America and Japan but has not yet been reported from northern Europe, which also has extensive areas of greenhouse tomato production.

Isolates of *F. oxysporum* from most of the locations mentioned have been used in comparative pathogenicity tests along with isolates of *F. oxysporum* f. sp. *lycopersici* (*F.o.l.*) races 1 and 2. Using a set of four differential tomato lines that allows separation of isolates causing FCRR from isolates of *F.o.l.*, we have shown that incidents of FCRR reported from North America and Japan were all caused by a forma specialis of *F. oxysporum* (designated f. sp. *radicis-lycopersici* by Jarvis and Shoemaker [4]) that is distinct from *F.o.l.* races 1 and 2 (12).

The Third Approach: A Resistant Cultivar

Although the steam-captafol technique has succeeded in Ohio, the method generally has been less satisfactory in other North American greenhouses. Many do not have the overhead irrigation equipment necessary for easy application of soil drenches, and captafol is labeled for this use only in Ohio and a few other states. Furthermore, soil steaming must be adequate before captafol application, and many greenhouses are not equipped with underground steam tiles; injecting steam directly on the soil surface under a plastic tarp does not control FCRR, even when followed by a captafol drench.

Because of the limitations of the steam-captafol technique, research was directed toward developing a commercially acceptable FCRR-resistant tomato cultivar. Initial observations indicated that Ohio greenhouse tomato cultivars differed in susceptibility to FCRR infection. Screening tests in 1974 and 1975 confirmed this, but the level of resistance was consistently low and unsuitable for breeding purposes. All available North American greenhouse and many outdoor tomato cultivars were tested, and none had an acceptable level of resistance.

In 1975, we learned that Kunio Yamakawa, working in Tsu, Japan, had found resistance to FCRR in a line from a cross between an irradiated domestic tomato and a wild species (*Lycopersicon peruvianum* PI 126944). Tests in Ohio in 1976 revealed that this breeding line (IRB 301-31), although susceptible to *F.o.l.* races 1 and 2, was resistant to all known isolates of the FCRR pathogen in our collection (12). With the cooperation of J. W. Scott from the Department of Horticulture at Ohio State University, we initiated an intensive breeding program to incorporate this resistance into commercial greenhouse tomato cultivars with multiple disease resistance and suitable horticultural characteristics. Currently, we are evaluating advanced resistant inbred selections and hybrids in commercial greenhouses for possible release of a FCRR-resistant hybrid cultivar for the spring crop of 1982.

Control Strategies in the Future

The greenhouse ecosystem provides unique opportunities for developing disease control procedures based on precise manipulations of the soil and air environments that are not possible in the field. Possibly, biological control agents could have been used instead of the fungicide captafol. In fact, preliminary

research with incorporating composted hardwood bark into freshly steamed soil showed promise (Fig. 7). The fungicide technique was favored, however, because of efficacy and ease of application with existing equipment and because the situation was urgent.

The financial constraints placed on greenhouse vegetable growers by rising fuel costs may mean the end of soil steaming as a standard procedure. Future disease control strategies for greenhouse crops may have to rely increasingly on cultural and biological mechanisms. In the near future, commercially acceptable FCRR-resistant cultivars may eliminate the need for the steam-captafol treatment.

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Fig. 6. Greenhouse producers in Kochi, Shikoku, Japan, observing tomato crop with severe symptoms of Fusarium crown and root rot.

Fig. 7. Tomato seedlings planted in steam-disinfested soil reinfested with *Fusarium oxysporum* by atomizing a microconidial suspension on the soil surface; the flat on the right was covered with 1 cm of hardwood bark compost before reinfestation. Eight weeks later, the plants in the compost-treated soil are healthy and those in the other flat show severe symptoms of Fusarium crown and root rot.

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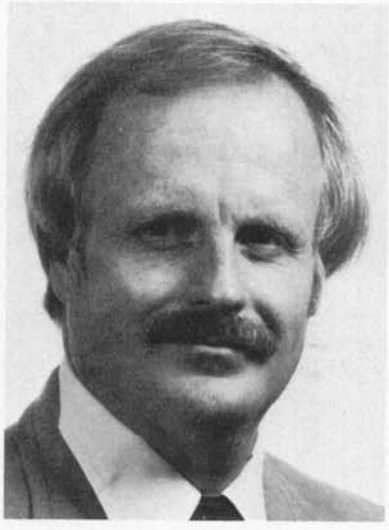

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