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Fusarium Crown and Root Rot of Tomato and Control Methods

[1]Nusret Ozbay and [2]Steven E. Newman
[1]Kahramanmaras Sutcu imam University, Ziraat Fakultesi,
Bahce Bitkileri Bolumu, 46100 Kahramanmaras, Turkey
[2]Department of Horticulture and Landscape Architecture, Colorado State University,
105 Shepardson Building, Fort Collins, CO 80523-1173, USA

Abstract: *F. oxysporum* is a widespread soilborne plant pathogen, which causes diseases such as vascular wilt and crown and root rot. The species delimitation has been defined according to morphological and physiological characteristics; with strains of F. *oxysporum* classified into *formae speciales* on the basis of pathogenicity on a particular host plant and races based on differences in virulence to given host cultivars. There are over 120 described *formae speciales* and races. One of these *formae speciales* is *Fusarium oxysporum* Schlect f. sp. *radicis-lycopersici* Jarvis and Shoemaker, which causes Fusarium crown and root rot (FCRR) of tomato. FCRR is one of the most damaging soil-borne diseases of tomato and becoming more common in greenhouse and field tomato production. The disease occurs in both the greenhouse and the field on tomato worldwide and causes significant losses in tomato production. In closed systems, with recirculation of nutrient solution and rock wool as a growing medium, crown and root rot of tomato can cause serious problems. This review discussed biology, ecology and epidemiology of the fungus and management options; cultural control, chemical control, biological control and integrated control in managing FCRR.

Key words: *Fusarium oxysorum* f. sp. *radicis-lycopersici, Fusarium* crown and root rot, tomato, biological control

INTRODUCTION

Fusarium crown and root rot (FCRR) caused by *Fusarium oxysporum* Schlect f. sp. *radicis-lycopersici* Jarvis and Shoemaker (FORL) is one of the most damaging soil-borne diseases of tomato and becoming more common in greenhouse tomato production[1]. The disease was initially reported in 1974 in Japan[2] and soon afterwards was identified in North America[3]. FCRR also has been reported in Canada, Mexico, Israel, Japan, many countries in Europe[4] and other states in the U.S. including California, New Jersey, New York, New Hampshire, Ohio, Pennsylvania and Texas[1]. The disease was identified in Colorado in 1998. The disease occurs in both the greenhouse and the field on tomato worldwide and causes significant losses in tomato production[5,6]. In closed systems, with recirculation of nutrient solution and rock wool as a growing medium, crown and root rot of tomato can cause serious problems[7,8]. It is reported that FCRR affects 40% of the surveyed acreage in Florida[3]. Commercial yields have been reported to be reduced 15-65%[9,10,3].

Symptoms: Wide ranges of symptoms are associated with FORL. The fungus invades susceptible plants through wounds and natural openings created by newly emerging roots[1]. Early symptoms caused by FORL in tomato seedlings include stunting, yellowing and premature abscission of cotyledons and lower leaves. A pronounced brown lesion that girdles the hypocotyls, root rot, wilting and seedling death are advanced symptoms[11]. Typically, the first symptom in the mature plants is a yellowing along the margins of the oldest leaves when the first fruit is at or near maturity. Yellowing is soon followed by necrosis and collapse of the leaf petiole. Symptom development progresses slowly upward on successively younger leaves. Some plants may be stunted and wilt quickly and wither. Older plants may wilt slowly and still be alive at the end of the harvest[6]. Wilting first occurs during the warmest part of the day and plants appear to recover at night. Infected plants may be stunted, totally wilt and die, or persist in a weakened state, producing reduced numbers of inferior fruit[1].

As disease progresses dry brown lesions develop in the cortex of the tap or main lateral roots and taproot often

Corresponding Author: Dr. Nusrat Ozbay, Kahramanmaras Sutcu Iman University, Ziraat Fakultesi, Bahce Bitkileri Bolumu, 46100 Kahramanmaraas, Turkey
Tel: +90-344-223 76666 ext: 414 Fax: +90-344-223 0048

rots away[1]. Chocolate brown lesions develop at or near the soil line and extend into the vascular system. When diseased plants are sectioned lengthwise, extensive brown discoloration and rot are evident in the cortex of the crown and roots. This brown vascular discoloration typically does not extend more than 25-30 cm above the soil line, which helps to distinguish this disease from Fusarium wilt, where discoloration may extend 1 meter high. Stem cankers may develop at or above the soil line. Following rains and during fogs, the pink sporulation of the pathogen can be profuse on exposed necrotic lesions[12,13,6]. The fungus produces masses of white mycelium and yellow to orange spores in necrotic stem lesions on dead and dying plants[1].

Biology, ecology and epidemiology: The causal fungus produces three types of spores: macroconidia, micro conidia and chlamydospores. Two of these spore types figure prominently in the survival and spread of FORL. Microconidia form in great abundance in necrotic tissue and have been implicated in the recolonization of sterilized soil in greenhouses through aerial dispersal[12,14]. They readily reinfest soil sterilized by heat or broad-spectrum biocides such as fumigants. Chlamydospores have thicker walls and enable the fungus to survive in the soil and wooden stakes for long periods in the soil[15,1].

FCRR severity varies widely by site and season and is favored by cool temperatures[16]. The pathogen grows best from 10 to 20°C, which is lower than the optimum for the fungus that causes Fusarium wilt on tomato[17,1]. The disease affects the plants in early crops and those located in the cooler areas of the greenhouse. The optimum temperature for disease development is 21°C. Low soil pH, ammoniacal nitrogen and waterlogged soil also exacerbate the disease[17,1].

FORL is a polycyclic soilborne pathogen[18]. Lateral spread of the pathogen from plant to plant during a growing season is via root-to-root contact[1]. Large numbers of FORL macroconidia are produced on stem surface of diseased plants and aerially disseminated in fields and greenhouses. Infection occurs either via soil infestation and subsequent root infection or by a direct infection of the foliage[18-20]. Movement of the fungus in the soil in the absence of roots is minimal (< 2.5 cm)[1]. Long-range dissemination of FORL can occur through infected transplants and perhaps via chlamydospores in soil particles on contaminated shoes, plant stakes, farm machinery, transplant trays and other equipment[12,1].

The host range of the pathogen includes some non-solanaceous plants, including spinach (*Spinacia oleracea* L.), beets (*Beta procumbens* L.), legumes, cucurbits and other solanaceous plants, such as pepper and eggplant (*Solanum melongena* L.), but not potatoes[12,1]. The fungus also has been isolated either naturally or experimentally from the roots of a number of weeds, including Brazilian pepper (*Schinus terebinthifolius*), carpet weed (*Mollugo verticillata*), hickweed (*Stellaria media*), corn spurry (*Spergula arvense*), cudweed (*Gnaphatium sp.*), curly dock (*Rumex crispus*), narrow leaved plantain (*Plantago lanceolata*), redroot pigweed (*Amaranthus retroflexus*), *Scoparia* sp., Shepard's purse (*Capsella bursa-pastoris*) and wild buckwheat (*Polygonum convolvulus*)[1] and saltcedar (*Tamarisk nilotica*)[21]. Monocots, such as corn (Zea *mays* L.) are not susceptible.

MATERIALS AND METHODS

Management options: Several control procedures have been attempted for managing FCRR in the greenhouse and field, including use of resistant varieties[9,22,79], cultural practices[5,23,24], pesticides[25,26], fumigants[27,10], etc. but losses are still substantial. Control programs should be put in place before planting, because there are no rescue treatments. Once the disease is present, avoiding stress is an important part of minimizing losses[23]. Four management options; cultural control, chemical control, biological control and integrated control will be discussed in the following sections for managing FCRR in a greenhouse.

Cultural control: Aggressive sanitation programs are very important, starting with a very clean house and cleaning or disinfecting. The worse cases of this disease have been associated with attempts to reuse items without sanitizing them, especially items that come in direct contact with the soil mix[23]. Crown rot is likely to occur with a higher frequency where direct seeding is used, instead of healthy transplants and where the soil contains high levels of chloride salts[17]. The utmost sanitation production scheme for transplants in greenhouses should be used so that individuals or equipment used within or around the transplant site do not become contaminated with disease-causing orgamisms from the field. Finally, transplants should be transported, pulled and set without tissue damage, as damaged tissues are likely to be sites for infection[17]. Transplanting should be done when soil or media is 20°C or above[28]. The selection and application of fertilizers can significantly influence disease development. For example, increasing soil pH and minimizing use of ammoniacal nitrogen help controlling FCRR[17]. Dead tomato plants need to be completely removed[5].

One of the most important components in an integrated disease control program is the selection and planting of cultivars that are resistant to pathogens. The term *resistance* usually describes the plant host's ability to suppress or retard the activity and progress of a pathogenic agent, which results in the absence or reduction of symptoms[29]. Some resistant varieties are available for FCRR for mostly greenhouse production. The use of crown rot resistant cultivars is increasing, but is currently not widely accepted due to horticultural characteristics that make these varieties less competitive than standard varieties[9]. The following are some cultivars with resistance: Trend, Trust, Medallion, Match, Switch and Blitz for greenhouse production; Charleston and Conquest for field production[28,30]. Fusarium crown and root rot resistance is conferred by a single dominant gene and already has been incorporated into commercially available cultivars[22].

Crop rotation is a historical method of crop production that reduces soil pest problems by removing susceptible plants from an infested area for a period of time long enough to reduce pest populations to tolerable levels[31]. Rotation away from tomatoes may be necessary on fields with a recurring crown rot problem. Avoid rotation with susceptible crops, such as eggplant or peppers; use non-hosts, such as lettuce instead[5,24]. Crop rotation as a control strategy may be limited in controlling FCRR because the fungus can survive in soil for many years. Capital field improvements such as irrigation systems and the availability of suitable land also limit adoption of crop rotation as a pest control strategy. Once a grower has invested in an irrigation system for a piece of land, the grower is less likely to rotate to a lower value crop[5].

Another cultural method in controlling FCRR is soil solarization. Solarization is a non-chemical soil disinfestation method, first developed for soilborne disease control in Israel and California during the 1970s[76,33]. Soil solarization, is defined as heating the soil by solar energy resulting in both physical and biological processes to control pathogens and other soil pests[32,77] . Solarization depends on solar energy to heat the soil to temperatures that are lethal to pathogenic organisms. This is accomplished by covering moist soil with a clear plastic film or mulch during a 2 to 8 week period with plentiful solar radiation. Most soilborne pests and plant pathogens are mesophilic and are killed at temperatures between 40 and 60°C. At these elevated temperature, disfunction of membranes and increased respiration are responsible for death. However, death depends on the thermal dose, a product of temperature and exposure time[34]. Exposure to long periods of sub-lethal temperatures may effectively control diseases by reducing the ability of propagules to geminate, increasing the susceptibility to biological control organisms and decreasing the ability to infect the host[34].

Soil solarization has been demonstrated to control FCRR. In stydies with different solarization methods, soil solarization reduced populations of *Fusarium oxysporum* f.sp. *radicis-lycopersici* down to a depth of 5 cm[35].

Crown rot incidence was significantly reduced by Metam Sodium (29%), solarization + Metam Sodium (51%) and by Methyl bromide+chloropicrin (50%), while disease severity was significantly reduced (74%) by both the latter two treatments. No significant differences in marketable yield were observed among the treatments[36]. Preliminary studies carried out in the open field showed that 12 days of soil solarization reduced survival of FORL propagules significantly. The effectiveness of pathogen control was improved by combing solarization with manure, or extending the solarization treatment to 27 days. In a closed greenhouse, solarization and biofumigation with bovine manure proved effective in reducing the viability of FORL chlamydospores, reducing disease incidence and in increasing commercial yield[37].

Grafting also is used in control of crown and root rot of tomato. Resistant rootstocks provide excellent control of many tomato soilborne pathogens and particularly *Fusarium oxysporum* f. sp. *lycopersic*i., *F. oxysporum* f. sp. *radicis-lycopersic*i, *P. lycopersici* and *Meloidogyne* spp.[38]. This technique, which initially was considered too expensive, is now widely used at a commercial level in many Mediterranean countries and North America[38]. In general, without grafting, the tomato plant density per hectare is about 18,000 plants. When grafted plants are used, the same yield could be obtained with half plant population (9,000 plants ha^{-1})[38]. In addition to controlling some soilborne pathogens, tomato grafting promotes growth, increases yield, increases plant tolerance to low temperature, extends the growth period and improves fruit quality[38]. Susceptible tomato plants grafted on FCRR-tolerant hybrid rootstock (He-man), even cropped in a severe FORL infested soil, remained healthy during the growing season and gave a profitable yield[39].

Chemical control: Chemical control of FCRR in steam sterilized soil by using a captafol drench proved effective in preventing reinfestation by airborne FORL conidia[40]. Mihuta-Grimm[26] reported that the application of benomyl at 0.090 g a.i./L on a 21-day schedule to plants growing on rockwool productions slabs resulted in optimum FCRR control. Yield from infected transplants treated with benomyl, however, was not significantly different from that of control plants. Other candidate fungicides proved to be phytotoxic at levels needed to control FCRR[41]. Although fungicides such as benomyl or captafol have been demonstrated[25] to be effective, they have some drawbacks. They are expensive, cause environmental pollution and may induce pathogen resistance. Fungicides added to seeds can also cause stunting and chlorosis of young seedlings and results may vary as fungicides are absorbed or inactivated by components of the soil or planting medium[41]. Captafol is no longer labeled for usage, thus it can not be used commercially.

Fumigation with methyl bromide (MBr)+chloropicrin formulations have been the most commonly used pre-plant practice for control of Fusarium crown and root rot in tomatoes[36,10]. Application of MBr+chloropicrin significantly reduces the incidence and severity of the disease[10]. Mbr: chloropicrin (67:33, by volume) reduced populations of FORL to a depth of 35 cm[35]. However, Fusarium crown and root rot incidence is still very high[22]. Even with the use of methyl bromide as a preplant fumigant, epidemics of Fusarium crown and root rot have occurred in commercial production fields[35]. MBr is a powerful soil fumigant providing effective control of a wide range of soil-borne pathogens and pests, including fungi, bacteria, nematodes, insects, mites, weeds and parasitic plants[42]. Despite these major advantages, the use of MBr has been associated with major problems, including the depletion of the ozone layer[43]. Because of this, its production and use will be phased out on a worldwide scale, by 2005 in the U.S. and E.U. and other developed countries and by 2015 in the developing countries[44]. An estimated 22.2 million kilograms of methyl bromide are applied annually for preplant soil fumigation in the United States[45]. Many strawberry and tomato growers have depended on MBr for control of nematodes, weeds and fungal pathogens[46]. The elimination of MBr in accordance with the U.S. Clean Air Act poses a critical challenge to these growers, whose crops are valued at more than $2.5 billion annually[46].

The ban on MBr production and use has prompted the study of new chemical alternatives for the control of soil-borne pests. However, these materials tend to provide a narrower spectrum of control than MBr, have less predictable efficacy and may have their own problems with environmental pollution and safety[47]. Five soil fumigants (1,3-dichloropropene, chloropicrin, dozamet, fosthiazate and sodium methyldithiocarbamat, a contact nematicide and several combinations with pebulate herbicide were compared to MBr/chloropicrin (98 and 2%, respectively) for control of nutsedge, Fusarium wilt and crown rot and nematodes in tomato[48]. Fusarium crown rot was reduced by methyl bromide and 1,3 dichloropropene + chloropicrin in the spring, but in the fall all chemical treatments, except those containing SMDC, provided better crown rot control than MBr[48]. McGovern *et al.*[38] reported that Crown rot incidence (defined as percentage number of plants infected by the pathogen) was significantly reduced by Metam Sodium (29%), solarization + Metam Sodium (51%) and by MBr + chloropicrin (50%), while disease severity (defined as percentage crown discoloration) was significantly reduced (74%) by both the latter two treatments. No significant differences in marketable yield were observed among the treatments.

A fresh market tomato study comparing metam sodium and MBr fumigation to an untreated control reported that yields and fruit quality obtained with metam sodium were equivalent to those achieved with methyl bromide fumigation[49]. Metam sodium has been demonstrated to significantly reduce crown rot incidence and when combined with solarization, control was equivalent to MBr+chloropicrin[36]. Metam sodium could reduce Fusarium crown rot only when thoroughly incorporated in the planting bed, such as through application to the soil prior to bed formation[36].

Plantpro45™, a new "low risk" iodine-based compound, was investigated as a potential alternative in controlling FCRR[50]. Plantpro45 ™ provided significant control of Fusarium crown rot of tomato in naturally infested fields. Under greenhouse conditions, soil drench with Plantpro 45™ at 80 ppm a.i. followed by planting 21 days later and a foliar application at 80 ppm one week after planting increased root and shoot weight and improved root condition of tomato when grown in field soil naturally infested with FORL. Final disease incidence ratings revealed that plots pretreated with Plantpro45 were comparable to MBr for control of FCRR[50,51].

Biological control: Research has demonstrated that biological control of FCRR has been successful in some instances under greenhouse and field conditions. The fungus *Trichoderma,* a natural soil-inhabiting genus, has been used successfully to control Fusarium crown rot and root rot of tomatoes[27,52]. The potential of *T. harzianum, Aspergillus ochraceus* Wilhelm and *Penicillium funiculosum* Thom in controlling FCRR of field grown tomatoes was shown[53]. Sivan and Chet[54] used *T. harzianum* in combination with soil sterilization and reduced rates of MBr to obtained significant control of tomato crown and root rot in the field with transplants colonized by *T. harzianum* during greenhouse propagation.

Datnoff *et al.*[27] conducted field experiments in Florida to evaluate commercial formulation of two fungi, *T. harzianum* and *Glomus intraradices* Schenck & Smith, for control of FCRR of tomato. Compared to untreated controls, significant reduction in disease incidence was obtained with treatment by biocontrol agents. The interaction between *G. intradices* and FORL and effect of *G. intradices* on tomato plants were investigated. Caron *et al.*[55,56] reported that tomato crown and root rot was decreased with *G. intradices*. However, there was no growth response of tomato plants to inoculation with the biocontrol agent. *T. harzianum* applied, as a peat-bran preparation to the rooting medium at the time tomatoes were transplanted. Such an application resulted in significant decrease in Fusarium crown rot through the growing season in field conditions. Yield increased as much as 26.2% over the controls in response to the treatment[52]. Nemec *et al.*[57] evaluated some biocontrol agents; *T. harzianum, G. intraradices* and *Streptomyces griseverdis*, for controlling root diseases of vegetable crops and citrus. At the end of the study, they found that all biological control agents reduced FCRR of tomato in the field. *T. harzianum* and *B.subtilis* were the most effective biocontrol agents. *Paenibacillus macerans* and *T. harzianum* were evaluated for promoting plant growth and suppressing FCRR under fumigated and non-fumigated field conditions[58]. *Trichoderma harzianum* and *P. macerans* significantly reduced severity of FCRR. *Trichoderma harzianum* reduced the severity of FCRR by 12% and *P. macerans* 9% in comparison to the untreated control in the nonfumigated treatments. No differences were observed between the biologicals and the untreated control in the MBr treated plots[58]. Datnoff and Pernezny[58] also reported that *T. harzianum* and *P. macerans* alone or in combination significantly increased the growth of tomato transplants in the greenhouse and after outplanting into the field 30 days later.

The potential of *T. harzianum* as a biocontrol agent in a soilless culture system was investigated with tomato plants infected with FORL. The application of *Trichoderma* reduced the incidence and spread of FCRR in tomatoes on an artificial growing medium[59]. Marois and Mitchell[25] reported that in greenhouse and growth chamber experiments, the fungal biocontrol amendment significantly reduced the mean lesion length and the incidence of FCRR. Under greenhouse conditions, the incidence of crown rot of tomato was reduced by up to 80% 75 days after sowing when *T. harzianum* T35 was applied as either a seed coating or a wheat bran-peat preparation applied to soil[52].

Much research has been done on the potential of nonpathogenic *F. oxysporum* for control of FCRR. Louter and Edgington[60] and Brammall and Higgens[61] used isolates of avirulent *F. oxysporum* and isolates of *F. solani,* respectively, to reduce the effects of FORL on tomato plants. It was suggested that the fungi acted through either cross protection (Louter and Edmington, 1985) or competition for infection court sites[61].

Alabouvette and Couteadier[62] studied the efficacy of nonpathogenic *F. oxysporum* strain Fo47 and the fungicide himexazol for of control the root diseases of tomato in the greenhouse. Both treatments gave a good control of FCRR; the yield was slightly higher with the biological treatment and the cost of the biocontrol treatment was less than the cost of the chemical product. Under greenhouse conditions, control of FCRR of tomato can be achieved by introduction of either strain Fo47, or fluorescent *Pseudomonas* strain C7, or by the association of both into the growing medium[63]. Four nonpathogenic isolates of *F. oxysporum* (26B, 43A, 43AN1 and 43AN2) and an isolate of *T. harzianum* (Th2) were found to be effective in protecting tomato seedlings from FCRR. However, the *T. harzianum* isolate was less effective than the *F. oxysporum* isolate at reducing disease[7].

There are also some bacteria, especially *Pseudomonas* spp., that have been shown to be effective in controlling FCRR[64]. *Pseudomonas fluorescens* strain CHA0 suppressed crown and root rot of tomato[64,65]. M'Piga *et al.*[66] reported that *P. fluorescens* colonizes and grows in the outer root tissues of whole tomato plants and sensitizes them to respond rapidly and efficiently to FORL attack in addition to exhibiting an antimicrobial activity *in planta*[65].

Streptomyces griseoviridis strain K61 (Mycostop™) has been tested against *F. oxysporum*-induced crown rot in Israel and in the UK[67]. A clear reduction of the disease was observed, but complete control was not achieved by using Mycostop™. Mycostop™ is a live formulated strain of the bacterium *S. griseoviridis* that was discovered in Finnish peat[67]. It is labeled for use on greenhouse tomato and is available from at least two suppliers in the U.S.[67]. *Streptomyces* sp. Di-944, a rhizobacterium from tomato, suppressed Rhizoctonia damping-off and Fusarium root rot in plug transplants when applied to seeds or added to potting medium. Antibiosis was suspected as a key mechanism of biocontrol[68].

Among the most promising bioactive oligosaccharides is chitosan (poly-N-glucosamine), a mostly deacetylated derivative of chitin occurring in the cell walls of several fungi, which is readily extracted from the chitin of crustacean shell wastes[78]. Oligomers of chitosan, which are likely to be released by the action of plant encoded-chitinase from walls of invading fungi, can protect tomato roots against *F. oxysporum* f.sp. *radicis-*

lycopersici when applied to the seed or roots[69,70]. Chitosan, derived from crab-shell chitin, was applied as seed coating and substrate amendment prior to infection with the fungus *F. oxysporum* f. sp. *radicis-lycopersici*. Experiments were performed either on a mixture of peat, perlite and vermiculite or on bacto-agar in petri dishes. In both cases, a combination of seed coating and substrate amendment was found to significantly reduce disease incidence.

The potential of *Bacillus pumilus* strain SE 34, either alone or in combination with chitosan, for inducing defense reactions in tomato plants inoculated with the vascular fungus, FORL, was studied by light and transmission electron microscopy[71]. Treatment of the roots with *B. pumilus* alone or in combination with chitosan prior to inoculation with FORL, substantially reduced symptom severity of FCRR as compared with untreated controls. Although some small, brownish lesions could be occasionally seen on the lateral roots, their frequency and severity never reached levels similar to those observed in control plants[71].

Chitosan, oligandrin and crude glucan, isolated from the mycoparasite *P. oligandrum*, were applied to decapitated tomato plants and evaluated for their potential to induce defence mechanisms in root tissues infected by *Fusarium oxysporum* f. sp. *radicis-lycopersici*[72]. A significant decrease in disease incidence was monitored in oligandrin- and chitosan-treated plants as compared to water-treated plants whereas glucans from *P. oligandrum* cell walls failed to induce a resistance response. In root tissues from oligandrin-treated plants, restriction of fungal growth to the outer root tissues, decrease in pathogen viability and formation of aggregated deposits, which often accumulated at the surface of invading hyphae, were the most striking features of the reaction. In chitosan-treated plants, the main response was the formation of enlarged wall appositions at sites of attempted penetration of the reaction.

Lettuce residue soil amendments and lettuce intercropping were considered for biological control[73,74]. Co-planted lettuce and *T. harzianum* strain Th2 provided protection from naturally occurring FCRR in a commercial tomato crop[7].

Integrated management: At present, Fusarium crown and root rot is difficult to control in field-grown tomatoes because the pathogen rapidly colonizes sterilized soil and persists for long periods. However, an integration of the following management procedures may help to reduce the impact of crown and root rot[1]:

1. Use disease-free transplants. Transplant houses should not be located near tomato production fields. Avoid over watering, which makes the transplants more susceptible to crown and root rot. Disinfect transplant trays by steaming before reuse.
2. Use a pre-plant fumigant. The soil should be of good tilth and adequately moist for at least two weeks prior to fumigation. Use an appropriate chisel spacing and depth and immediately cover the bed with plastic mulch following fumigation.
3. Optimize cultural practices in the field. Avoid injuring transplants when they are set in the field. Physical damage and injury from excessive soluble salts may make young plants more susceptible to crown and root rot. The use of water drawn from wells rather than ditches for watering-in transplants may help to prevent recontamination of fumigated soil. Avoid ammoniacal nitrogen and maintain the soil pH at 6 to 7. Rapidly plow in crop debris following final harvest. Disinfest tomato stakes before reuse, or use new stakes.
4. Rotate with a non-susceptible crop. Incomplete knowledge of the host range of FORL makes precise recommendations in this area difficult. Current research data suggests that leguminous crops should be avoided in favor of corn and similar crops. Rotation and intercropping with lettuce had reduced FORL in greenhouse-grown tomatoes.
5. Significant progress has been made in breeding for resistance to Fusarium crown and root rot in field-grown tomatoes. Although the commonly used commercial cultivars do not have resistance, some resistant cultivars, such as Conquest, are available for field use and Trust for greenhouse use.
6. Additional management strategies under investigation include the use of biological control, cover crops and soil solarization alone or in combination with fumigants.

Integration of different management methods has been shown to be effective in controlling FCRR. McGovern[30] indicated that Fusarium crown and root rot of tomato can be effectively managed by integrating the use of pathogen-free transplants and stakes, resistant cultivars and pre-plant fumigation. A commercial tomato field in southwest Florida, naturally infested with FORL was used to compare the effectiveness of methyl bromide: chloropicrin, 67%:33% (Terr-O-Gas 67, 336 kg ha^{-1}), metam sodium (Vapam, 935 l ha^{-1}), composted sewage sludge (Florida Organix, 5.5 MT ha^{-1}), soil solarization and combinations of solarization and Vapam or Florida

Organix in reducing FCRR. Fusarium crown rot incidence was significantly reduced by Vapam (-29%), solarization plus Vapam (-51%) and by Terr-O-Gas (-50%), while disease severity was significantly reduced (-74%) by both the latter two treatments[36].

Minuto *et al.*[75] reported that the combination of soil solarization with reduced dosage of Dazomet and of MB controls Fusarium and Verticillium wilts and Fusarium crown rot on tomato. Preliminary studies carried out in the open field showed at 12 days of soil solarization reduced survival of FORL propagules significantly. The effectiveness of pathogen control was improved by combing solarization with manure, or extending the solarization treatment to 27 days. In a closed greenhouse, solarization and biofumigation with bovine manure proved effective in reducing the viability of FORL chlamydospores, disease incidence and in increasing commercial yield[37].

Under field conditions, the combination of *T. harzianum* with soil solarization or with a reduced dose of methyl bromide resulted in significant disease control of FCRR of tomato induced by FORL[54]. Combination of the biocontrol agent *Pseudomonas fluorescens* with the mineral element zinc significantly reduced disease severity of FCRR of tomato, however, *P. fluorescens* strain CHA0 alone was only moderately effective[64].

Diseases caused by *Fusarium* spp. are important limiting factors in the production of tomato. Several types of diseases associated with these pathogenic fungi have been identified, including Fusarium wilt, foot rot and crown and root rot disease. One of the most damaging soilborne pathogens of tomato is *Fusarium oxysporum* f. sp. *radicis-lycopersici,* which causes Fusarium crown and root rot. Several control procedures have been attempted for managing FCRR in the greenhouse and field. Possibilities to manage fusarium wilt, rot by using fungicides or resistant cultivars, are limited. The use of *Fusarium*-resistant tomato cultivars can provide some degree of control of this disease, but the occurrence and development of new pathogenic races is a continuing problem and currently there are no commercially acceptable cultivars with adequate resistance to *F. oxysporum* f. sp. *radicis-lycopersici.* Although fungicides such as benomyl or captafol have been demonstrated to be effective, captafol is no longer labeled for usage and there is an imminent possibility of fungicide resistance.

Fumigation with methyl bromide (MBr) + chloropicrin formulations have been the most commonly used pre-plant practice for control of FCRR. Application of MBr + chloropicrin significantly reduces the incidence and severity of the disease. However, disease incidence is still very high. Even with the use of MBr as a pre-plant fumigant, epidemics of fusarium crown and root have occurred in commercial production fields.

Research has demonstrated that biological control of FCRR has been successful in some instances under greenhouse and field conditions. Biocontrol of FCRR with antagonistic microbes such as the fungus *Trichoderma* or non-pathogenic strains of *F. oxysporum* are areas of research. There are also some bacteria, especially *Pseudomonas* spp., that have been shown to be effective in controlling FCRR. More research needs to be done on biological and integrated management of FCRR.

REFERENCES

1. Roberts, P.D., R.J. McGovern and L.E. Datnoff, 2001. Fusarium crown and root rot of tomato in Florida. Florida Cooperative Extension Service/ Institute of Food and Agricultural Sciences/ University of Florida. Plant Pathology Fact Sheet, pp: 52.
2. Yamamoto, I., H. Komada, K. Kuniyasu, M. Satio and A. Ezuka, 1974. A new race of *Fusarium oxysporum* f. sp. *lycopersici* inducing root rot of tomato. Proc.Kansai Plant Protect. Soc., 16: 17-29.
3. Sonoda, R.M., 1976. The occurrence of Fusarium root rot of tomatoes in South Florida. Plant Dis. Rep., 60: 221-274.
4. Jarvis, W.R., 1988. Fusarium crown and root rot of tomatoes. Phytoprotection, 69: 49-64.
5. Blankard, D., 1994. A Colour Atlas of Tomato Disease: Observation, Identification and Control. Manson Publishing, London.
6. Jones, J.B., J.P. Jones, R.E. Stall and T.A. Zitter, 1991. Compendium of Tomato Diseases. American Phytopathological Society, St. Paul, MN.
7. Hartman, J.R. and J.T. Fletcher, 1991. Fusarium crown and root rot of tomatoes in the UK. Plant Pathol., 40: 85-92.
8. Rattink, H., 1992. Targets for pathology research in protected crops. Pesticide Sci., 36: 385-388.
9. Anonymous, 1999. Crop Profile for South Florida Tomatoes. Glades Crop Care, Inc., Jupiter, Florida.
10. McGovern, R.J., C.S. Vavrina, J.W. Noling, L.E. Datnoff and H.D. Yonce, 1998. Evaluation of different application methods of metam sodium for management of Fusarium crown and root rot in tomato in southwest Florida. Plant Dis., 82: 919-923.
11. McGovern, R.J., C.S. Vavrina and L.A. Mckay, 1993a. Fffect of transplant tray type and tomato cultivar on the incidence of fusarium crown and root rot in tomato transplants. Proc. Fla. State Hort. Soc., 106: 173-175.
12. Davis, M., 2002. Fusarium Diseases of Tomato: An Overview. University of California Cooperative Extension, Vegetable Research and Information Service. Vegetable Notes-Special Edition.

13. Gabor, B. and W. Wiebe, 1997. Tomato Diseases. Seminis Vegetable Seeds, Inc. Saticoy, California.
14. Rowe, R.C., J.D. Farley and D.L. Coplin, 1977. Airborne spore dispersal and recolonization of steamed soil by *Fusarium oxysporum* in tomato greenhouses. Phytopathol., 67: 1513-1517.
15. McGovern, R.J. and L.E. Datnoff, 1992. Fusarium crown and root rot: Reevaluation of management strategies. In 'Proceedings of Florida Tomato Institute'. (Ed. C.S. Vavrina). Vegetable Crops Special Series SS-HOS-1, Vegetable Crops Department, University of Florida-IFAS, Gainesville, FL., pp: 75-86.
16. McGovern, R.J., C.S. Vavrina, T.A. Obreza and J.C. Capece, 1995. Reduction of fusarium crown and root rot of tomato by combining soil solarization and metam sodium. 1995 Annual Research Conference on Methyl Bromide Alternatives and Emission Reductions. San Diego, California.
17. Kucharek, T., J.P. Jones, D. Hopkins and J. Strandberg, 2000. Some diseases of vegetable and agronomic crops caused by Fusarium in Florida. Florida Cooperative Extension Service/ Institute of Food and Agricultural Sciences/ University of Florida. Circular 1025.
18. Rekah, Y., D. Shtienberg and J. Katan, 1999. Spatial distribution and temporal development of fusarium crown and root rot of tomato and pathogen dissemination in field soil. Phytopathol., 89: 831-839.
19. Rekah, Y., D. Shtienberg and J. Katan, 2000. Disease development following infection of tomato and basil foliage by airborne conidia of the soilborne pathogens *Fusarium oxysporum* f. sp. *radicis-lycopersici* and *Fusarium oxysporum* f. sp. *basilica*. Phytopathol, 90: 1322-1329.
20. Rekah, Y., D. Shtienberg and J. Katan, 2001b. Means of dissemination of *Fusarium oxysporum* f. sp. *radicis-lycopersici*, the causal agent of Fusarium crown and root rot in tomatoes. 2001 APS/MSA/SON Joint Meeting. Phytopathol., 91: S76.
21. Rekah, Y., D. Shtienberg and J. Katan, 2001a. Role of the Shrub *Tamarix nilotica* in Dissemination of *Fusarium oxysporum* f. sp. *radicis-lycopersici*. Plant Dis., 85: 735-739.
22. Chellemi, D.O., 1997. Alternatives to methyl bromide for the management of soilborne diseases. In: 'Proceedings of the Florida Tomato Institute'. University of Floridia, IFAS, Cooperative Extension Pub. PRO110, pp: 32-33.
23. Nesmith, W., 1998. Fusarium crown and root rot of greenhouse tomatoes. University of Kentucky, College of Agriculture, Kentucky Pest News, 831: 2-3.
24. Pernezny, K., 1997. Tomato production guide for Florida: Disease control. Commercial Vegetable Guide Series, Florida Cooperative Extension Service, Institute of Food and AgriculturalSciences, University of Florida. Circular 98 C. SP 214.
25. Marois, J.J. and D.J. Mitchell, 1981. Effects of fumigations and fungal antagonists on the relationships of inoculum density to infection incidence and disease severity in Fusarium crown rot of tomato. Phytopathol., 71: 167-170.
26. Mihuta-Grimm, L., 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.
27. Datnoff, L.E., S. Nemec and K.L. Pernezny, 1995. Biological control of Fusarium crown and root rot of tomato in Florida using *Trichoderma harzianum* and *Glomus intraradices*. Biological Control, 5: 427-431.
28. Dodson, M., J. Bachmann and P. Williams, 2002. Organic greenhouse tomato production, Horticulture Production Guide. Appropriate Technology Transfer for Rural Areas. (ATTRA), the University of Arkansas in Fayetteville, AR.
29. Koike, S.T., M. Gaskell, C. Fouche and J. Mitchell, 2000. Plant disease management for organic crops. University of California's Division of Agriculture and Natural Resources Publication 7252.
30. McGovern, R.J., 1994. Integrated management of fusarium crown and root rot of tomato in Florida. Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions. Kissimmee, Florida.
31. Cook, R.J. and R.J. Veseth, 1991. Wheat health management. Plant health management series. APS Press. St. Paul, MN.
32. DeVay, J.E. and J. Katan, 1991. Mechanisms of pathogen control in solarized soils. In: 'Soil Solarization'. (Eds. J. Katan and J.E. Devay). CRC Press, Boca Raton, FL. pp: 97-101
33. Katan, J., 1981. Solar heating (solarization) of soil for control of soilborne pests. Ann. Rev. Phytopathol., 19: 211-236.
34. Pinkerton, J., 1998. Soil Solarization: A perspective from a northern temperate region. 1998 Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions. Orlando, Florida.
35. Chellemi, D.O., S.M. Olson, R. McSorley, D.J. Mitchell, W.M. Stall and J.W. Scott, 1994. Integrated Pest Management For Soilborne Pests Of Tomato. In: 'Annnal International Research Conference on Methyl Bromide Alternatives and Emissions Reductions'. Kissimmee, Florida. http://mbao.org/mbrpro94.html.
36. McGovern, R.J., C.S. Vavrina, T.A. Obreza and J.C. Capece, 1996. Reduction of fusarium crown and root rot of tomato by combining soil solarization and metam sodium. Methyl Bromide Alternatives. U.S. Department of Agriculture Agricultural Research Service, Beltsville, Maryland, 2: 8.

37. Cartia, G., 2002. Alternatives to Methyl Bromide for Tomatoes and Vegetables. In: 'Proceedings of International Conference on Alternatives to Methyl Bromide'. (Eds. T.A. Batchelor and J.M. Bolivar). Sevilla, Spain.
38. Besri, M., 2000. Tomatoes in Morocco: Integrated pest management and grafted plants. In: 'Case studies on alternatives to methyl bromide'. Technologies with low enviroument impact". UNEP, Division of technology, industry and economics, Ozone Action Programme, pp: 14-17.
39. Di Primo, P. and G. Cartia, 2001. Solarizzazione e biofumigazione del terreno per il contenimento di *Fusarium oxysporum* f.sp. *melonis* su melone nel sud-Italia. Atti del Convegno ioTecniche alternative alla fumigazione dei terreni con bromuro di metile in fragola e ortiveli. Metaponto, 30 ottobre, 2001. *L'Informatore Agrari*o, pp: 3-6.
40. Rowe, R.C. and J.D. Fraley, 1978. Control of Fusarium crown and root rot of tomatoes by inhibiting recolonization of steam-disinfested soil with a captafol drench. Phytopathology, 68: 1221-1224.
41. Lumsden, R.D. and J.C Locke, 1989. Biological control of damping-off caused by *Pythium ultimum* and *Rhizoctonia solani* with *Gliocladium virens* in soilless mix. Phytopathology, 79: 361–66.
42. Maw, G.A. and R.J. Kempton, 1973. Methyl bromide as a soil fumigant. Soil Fertility, 36: 41-47.
43. Anonymous, 1997. Stratospheric Ozone Protection: Alternatives to Methyl Bromide. U.S. Goverument Printing Office, Washington DC, USA.
44. Rowlands, I.H., 1993. The fourth meeting of the parties to the Montreal Protocol: Report and reflection. Enviroument, 35: 25-34.
45. Ferguson, W. and A. Padula, 1994. Economic effects of banning methyl bromide for soil resources. Technology Division. Economic Research Service, U.S. Department of Agriculture. Agricultural Economic Report Number 677.
46. Anonymous, 1996. Statistical Abstract of the United States 1996. The National Date Book. 116th Ed.
47. Stapleton, J.J., C.L. Elmore and J.E. DeVay, 2000. Solarization and biofumigation help disinfest soil. California Agriculture, 54: 42-45.
48. Gilreath, J.Z., J.P. Jones and A.J. Overman, 1994. Soil-borne Pest Control in Mulched Tomato with Alternatives to Methyl Bromide. Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions. Kissimmee, Florida.
49. Cook, R. and A.P. Keinath, 1994. Metam sodium as an alternative soil fumigant to methyl bromide in fresh market tomatoes, 1993. F&N Tests, 49:160.
50. Adams, P.D., N. Kokalis-Burelle, P. Fuentes-Bórquez and W. Basinger, 2000. Plantpro45™: A potential low risk alternative for control of soil-borne plant pathogens. 2000 Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions. Orlando, Florida. http://mbao.org/altmet00/60adams.pdf.
51. Adams, P.D., N. Kokalis-Burelle, P. Fuentes-Bórquez and W. Basinger, 2001. Plantpro 45: An overview on soilborne pathogen and weed control. 2001 Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions. November 5-9, 2001. San Diego, California. http://mbao. org/2001proc/ 026%20Adams% 20PD%20 MeBrSummary2001. pdf.
52. Sivan, A., O. Ucko and I. Chet, 1987. Biological control of Fusarium rot of tomato by *Trichoderma harzianum* under field conditions. Plant Dis., 71: 587-592.
53. Marois, J.J., D.J. Mitchelland and R.M. Sonoda, 1981. Biological control of Fusarium crown rot of tomato under field conditions. Phytopathology, 71: 1257-1260.
54. Sivan, A. and I. Chet, 1993. Integrated control of fusarium crown and root rot of tomato with *Trichoderma harzianum* in combination with methyl bromide or soil sterilization. Crop Protection, 12: 380-386.
55. Caron, M., J.A. Fortin and C. Richard, 1985. Influence of substrate on the interaction of *Glomus intraradices* and *Fusarium oxysporum* f. sp. *radicis-lycopersici* on tomatoes. Plant and Soil, 87: 233-239.
56. Caron, M., J.A. Fortin and C. Richard, 1986. Effect of *Glomus intradices* on infection by *Fusarium oxysporum* f. sp. *radicis-lycopersici* on tomatoes over a twelve-week period. Can. J. Bot., 64: 552-556.
57. Nemec, S., L.E. Datnoff and J. Strandberg, 1996. Efficacy of biocontrol agents in planting mixes to colonize plant roots and control root diseases of vegetables and citrus. Crop Protectection, 15: 735-742.
58. Datnoff, L.E. and K.L. Pernezny, 2001. *Paenibacillus macerans* and *Trichoderma harzianum* enhance transplant growth and suppress fusarium crown and root rot in Florida tomato production. 2001 Caribbean Division Meeting Abstracts, La Habana, Cuba. Publication no. P-2002-0025-CRA.
59. Van Steekelenburg, N.A.M., 1991. Effect of *Trichoderma harzianum* on incidence of Fusarium crown and root rot in rockwool-grown tomatoes. In: Biotic interactions and soil-borne diseases. (Eds. A.B.R. Beemster, G.J. Bollen, M. Gerlagh, M.A. Ruissen, B. Schipper and A.Tempel). Elsevier, Amsterdam, pp: 199-205.
60. Louter, J.H. and L.V. Edgington, 1985. Cross protection of greenhouse tomato against fusarium crown and root rot. Can. J. Plant Pathol., 7: 445-446.

61. Brammall, R.A. and V.J. Higgens, 1987. The control of Fusarium crown and root rot disease of tomato by root inoculation with alien pathogenic fungi. Can. J. Plant Pathol., 9: 274-280.
62. Alabouvette, C. and Y. Couteadier, 1992. Biological Control of Plant Diseases: Progress and Challenges for the Future. In: 'Biological control of Plant Diseases'. (Eds. E.C. Tjamos, G.C. Papavizas and R.J. Cook) Plenum Press, New York, pp: 415-426.
63. Lemanceau, P. and C. Alabouvette, 1991. Biological control of fusarium diseases by fluorescent *Pseudomonas* and non-pathogenic *Fusarium*. Crop protection, 4: 279–286.
64. Duffy, B.K. and G. Défago, 1997. Zinc improves biocontrol of Fusarium crown and root rot of tomato by *Pseudomonas fluorescens* and represses the production of pathogen metabolites inhibitory to bacterial antibiotic biosynthesis. Phytopathology, 87: 1250–57.
65. Thomas, F.C. Chin-A-Woeng, Daan van den Broek, Gert de Voer, Koen M. G. M. van der Drift, Sietske Tuiuman, Jane E. Thomas-Oates, Ben J.J. Lugtenberg and G.V. Bloemberg, 2001. Phenazine-1-carboxamide production in the biocontrol strain *Pseudomonas chlororaphis* PCL1391 is regulated by multiple factors secreted into the growth medium. Mol. Plant Microbe Interact, 14: 969-979.
66. M'piga, P., R. Bélanger, T.C. Paulitz and N. Benhamou, 1997. Increased resistance to *Fusarium oxysporum* f. sp. *radicis-lycopersici* in tomato plants treated with the endophytic bacterium *Pseudomonas fluorescens* strain 63-28. Physiol. Mol. Plant Pathol., 50: 301-320.
67. Lahdenperä, M.L., 2000. Mycostop® in the control of *Fusarium oxysporum* on vegetables. Biocontrol Infoletter. Kemira Agro Oy, Espoo Research Centre, Espoo, Finland.
68. Sabaratnam, S., A.N. Starratt and J.A. Traquair, 2001. Antifungal biocontrol activity of a streptomycetous rhizobacterium from tomato. 2001 APS/MSA/SON Joint Meeting Phytopathology, 91: S78.
69. Benhamou, N. and G. Theriault, 1992. Treatment with chitosan enhances resistance of tomato plants to the crown and root rot pathogen *Fusarium oxysporum* f. sp. *radicis-lycopersici*. Physiol. Mol. Plant Pathol., 41: 33–52.
70. Benhamou, N., P.J. Lafontaine and M. Nicole, 1994. Induction of systemic resistance of *Fusarium* crown and root rot in tomato plants by seed treatment with chitosan. Phytopathology, 84: 1432-44.
71. Benhamou, N., J.W. Kloepper and S. Tuzun, 1998. Induction of resistance against Fusarium wilt of tomato by combination of chitosan with an endophytic bacterial strain: ultrastructure and cytochemistry of the host response. Planta, 204: 153-168.
72. Benhamou, N., R. Richard, P.R. Bélanger and Y. Tirilly, 2001. Oligandrin, the elicitin-like protein produced by the mycoparasite *Pythium oligandrum*, induces systemic resistance to Fusarium crown and root rot in tomato plants. Plant Physiol. Biochem, 39: 681-696.
73. Jarvis, W.R. and H.J. Thorpe, 1981. Control of Fusarium foot and root rot by soil amendment with lettuce residues. Can. J. Plant Pathol., 3: 159-162.
74. Jarvis, W.R. and H.J. Thorpe, 1983. The control of Fusarium foot and root rot by lettuce intercropping. Proceedings of the 10th International Congress 797.
75. Minuto, A., G. Gilardi, M.L. Gullino and A. Garibaldi, 2000. Combination of soil solarization and Dazomet against soil borne pathogens of glasshouse-grown basil, tomato and lettuce. Acta Hort., 532: 165-170.
76. DeVay, J.E. and J.J. Stapleton, 1997. Soil solarization: past, present and future. In: 'Soil Solarization and Integrated Management of Soil-borne Pests'. (J.J. Stapleton, J.E. DeVay and C.L. Elmore). Plant production and protection paper 147, FAO, Rome, Italy, pp: 1-5.
77. Katan, J., 1987. Soil solarization. In: Innovative approaches to plant disease control. (Ed. I. Chet). John Wiley and Sons, New York, pp: 77-105.
78. Hadwiger, L.A., C. Chiang, S. Victory and D. Horovitz, 1988. The molecular biology of chitosan in plant-pathogen interactions and its application to agriculture. In: 'Chitin and chitosan: sources, chemistry, biochemistry, physical properties and applications'. (Eds. B. Anthonsen and P. Sandford). Elsevier Applied Sciences, Amsterdam, pp: 119-138.
79. McGovern, R.J., L.E. Datnoff and C.S. Vavrina, 1993b. Evaluation of seven tomato genotypes for resistance to *Fusarium oxysporum* f. sp. *radicis-lycopersici*. Phytopathology, 83: 1395.