Soil/Media Disinfestation for Management of Florists' Crops Diseases

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Abstract

In-ground and pot-based ornamental producers face many challenges related to management of soilborne pests. Ornamental crops are susceptible to a wide range of soilborne pathogens that are capable of surviving for long periods of time on plant debris or on weed hosts. Some of these pathogens have broad host ranges, making it difficult to use crop rotation as a management tool. The number of different species and varieties of ornamentals that may be grown in a small area is often very high, which makes control measures for individual plant pathogens impractical. The availability of commercially desirable varieties that have resistance to specific diseases is limited or unknown for many of the crops grown in pots and in-ground; therefore, broad-spectrum control measures are more feasible, both technically and economically. For many years, both potting soil and field soil were fumigated with methyl bromide, a cost-effective, broad-spectrum biocide, which controlled soilborne fungal and bacterial plant pathogens, plant-parasitic nematodes, and weeds. The loss of this versatile compound, due to its negative impact on the ozone layer, has led to the development of new soil disinfestation approaches as well as renewed interest in improving technologies used in the past. The tools that are currently available for soil

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disinfestation include fumigants, nonfumigant soil applied chemicals, steam, solarization, and anaerobic soil disinfestation.

Keywords
Soilborne plant pathogens • Nematodes • Weeds • Fumigation • Steam • Solarization • Anaerobic soil disinfestation

Contents

1 Introduction

The California floriculture industry is the largest in the USA with a 2014 value of $1.05 billion. Florida follows closely with a 2014 value of $890 million in wholesale value. In both states, the industry consists of bedding and garden plants and potted and in-ground cut flowers (CAS 2013; USDA 2015). In 2014, the covered area used for floriculture production in California was 145 million sq. ft. and open ground was 10,844 acres (USDA 2015). For Florida, in 2014, there were approximately 299 million sq. ft. under cover and 5,200 acres in open ground production (USDA 2015).

The production of cut flowers in open fields in Florida has continued a steady decline, with less than $3 million generated from this industry in 2014. Florida production of potted foliage plants, valued at $420 million, represents 72% of the US total. Florida contributes 79% of the cut greens produced in the USA and this commodity is valued at $58 million (USDA 2015). Florida also produces approximately 95% of the world caladium supply (Fig. 1), tubers from which are used for propagative material for landscape and potted plants (Deng et al. 2005). The California cut flower industry has an annual impact of $10.3 billion on the state's economy contributing nearly $28.2 million on a daily basis to the state (CCFC 2008). California supplies about 76% of the cut flowers sold in the USA at a wholesale value of $261 million in 2012 (USDA 2015). California has 5,000 acres of land used for commercial cut flower production of which 4,000 acres are under open-field production (USDA 2007).

Fig. 1 Florida caladium production accounts for approximately 95% of the world's supply of caladium tubers (E. Rosskopf. USDA.)

2 Pests Controlled by Soil Disinfestation

Both potted ornamentals and open field flowers suffer from soilborne diseases such as Fusarium and Verticillium wilts, damping off and root rots caused by *Pythium* spp., and crown and root rots caused by *Phytophthora* spp. Nematodes such as *Meloidogyne* spp. (Fig. 2) also cause significant reductions in flower yield. Many cut flower varieties of sunflower, for example, are highly susceptible to infection by root-knot and other nematodes and to the diseases southern blight, bacterial wilt, and Fusarium stalk rot. Calla lilies, in particular, have problems with root rots caused by *Pythium* and *Phytophthora* spp. as well as soft rot of rhizomes due to *Erwinia* or *Pectobacterium* spp. (Dreistadt 2001). Similarly, caladium tubers suffer from *Pythium* spp. and root-knot nematodes, which severely limit both yield and quality. It also succumbs to foliar infection by *Xanthomonas axonopodis* pv. *dieffenbachiae* causing bacterial blight (Seijo et al. 2010). These pathogens may all be present in the same production area (Fig. 3). Although there has been progress in terms of breeding for resistance in many crops, it is rare to have a single variety that has desirable horticultural characteristics as well as multiple disease resistance genes (Kokalis-Burelle and Rosskopf 2013; also refer to ▶ Chap. 5, "Breeding for Disease Resistance

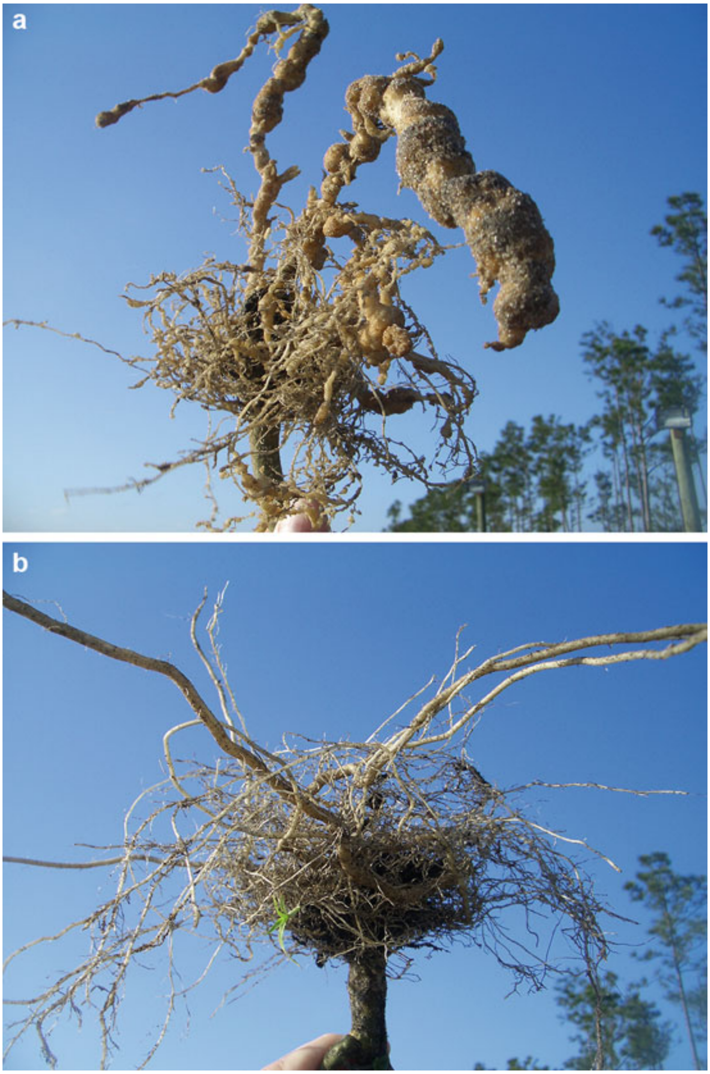

Fig. 2 Roots from an untreated area with significant root galling caused by *Meloidogyne arenaria* (**a**) compared to roots collected from a fumigated field (**b**) (E. Rosskopf. USDA.)

in Florists' Crops"). Weeds, including volunteer bulbs and tubers from previous crops, nutsedge (*Cyperus* spp.), mallow (*Malva* spp.), clover (*Trifolium repens*), geranium (*Geranium carolinianum*), and bluegrass (*Poa* spp.) are major problems in cut flowers (USEPA 2013). If weeds are not effectively controlled in these systems, they can contribute to the survival and reproduction of other pests, such as nematodes (Kokalis-Burelle and Rosskopf 2012; Kokalis-Burelle et al. 2012). These soilborne pests, and many others, have traditionally been controlled using soil

Fig. 3 Impact of the complex of *Pythium* infection and root-knot nematode infestation by *Meloidogyne arenaria* in a caladium field where the fumigant injection was incomplete (E. Rosskopf. USDA.)

disinfestation via chemical fumigation with methyl bromide, which has been phased-out for the majority of agricultural uses in the USA. Without this broad-spectrum biocide, potting media and soil in ornamental production systems must be treated in other ways to minimize the impact of soilborne pests.

3 Nursery Potting Media

3.1 Soilless Media Components

Many large nurseries mix their own potting media or have it custom blended and then delivered by the truckload. Components of substrates include coir, perlite, peat moss, vermiculite, sawdust, sand, biochar, and bark. Gypsum and dolomitic limestone are also frequently added to supply calcium and/or magnesium and to maintain a suitable substrate pH. Compost, either produced on-site or off, is used in some mixes, and more recently, by-products of other agricultural processes such as nut or rice hulls are included in the mix. Recently, the use of composted algae has been investigated as an alternative substrate component that also provides fertilization (Fig. 4) (Albano et al. 2010). Fertilizer, mycorrhizae, or wetting agents may be added, but this is generally done after the media base formula is mixed.

Whether media is custom blended and delivered to the nursery, or blended at the nursery, it is important to test or assay the organic substrates (e.g., coir, peat moss,

Fig. 4 Increased plant vigor resulting from the application of (*left*-to-*right*) composted algae with fertilizer compared to commercial peat-based substrate with fertilizer, composted algae without fertilizer, and commercial peat-based substrate without fertilizer (J. Albano © 2017. All Rights Reserved.)

bark) for pests and disinfest if needed prior to blending. Then the substrates are blended as soon as possible after disinfestation.

After blending, the mix should be placed on concrete pads or other clean areas located away from trash and other piles that are used for holding plant debris. If the media is held for more than 2 weeks, it is helpful to use tarps or other coverings to minimize contamination from windblown weed seeds and fungal spores.

3.2 Soil as a Potting Media Component

In general, soil should be a minor ($<10\%$) component of a potting mix. This is due to the fact that soil physical properties vary depending on where it is from, and these properties affect drainage and root growth. Additionally, mineral soil is heavier than soilless mixes and will increase labor and shipping costs (Hanan 1997). Where soil is used as a component of potting media, it should be disinfested to reduce pathogens, nematodes, and weed seeds and propagules.

3.3 Substrate Disinfestation Methods

3.3.1 Chemical

The primary method of chemical disinfection of potting media substrates is currently the use of dazomet (Agrian 2015c; Fritz and Dimcock 2005). There are important safety restrictions when using this material so the label must be followed carefully. This dry, powder-like formulation is thoroughly mixed into the moist substrate(s) using a cement mixer, front-end loader, or similar equipment. Once distributed, the media can be piled up to 1 m high, preferably on a clean solid surface such as a concrete pad or on polyethylene plastic sheet. The pile is then covered for at least 7 days as the dazomet degrades into the active fumigant, methyl isothiocyanate. The cover is removed and the soil allowed to vent undisturbed for 7 days before using the mix for potting. Because dazomet does not degrade to the active fumigant unless exposed to moisture, it is important the pile be thoroughly irrigated after treatment application. The soil temperature must be above 6 ° C during the entire fumigation period.

An alternative to piles for treatment application to media is the use of 30 cm tall frames. These frames are easily constructed using lumber and wooden or metal stakes. If possible, the frame should be lined with polyethylene plastic sheeting. Dazomet is then uniformly applied to the media surface and mechanically incorporated using a rototiller or similar equipment. The treated media is watered and tarped as above. Although this method requires more space, it more uniformly wets the media, increasing fumigant effectiveness.

3.3.2 Steam

Heating with steam (Fig. 5) is very effective and has the advantage over chemical treatment in that the soil can be used immediately after cooling and is not subject to the regulatory restrictions associated with fumigation. Although pure steam at sea

Fig. 5 Soil cart used for steaming potting mix (S. Fennimore © 2017. All Rights Reserved.)

level is at 100 °C/212 °F, the temperature at which steam is used to treat soil is usually about 82 °C/180 °F because of air that is present in the steam or in the soil being treated. If air is mixed with steam, the temperature of the steam-air mixture can be closely controlled, depending on the ratio of air to steam. Steam may be used to treat stationary and moving soils (Baker and Roistacher 1957).

Many plant pathogens are killed by short exposures to high temperatures; however, experience has shown that the soil temperatures should be maintained for approximately 30 min to ensure the soil is thoroughly disinfested. Most plant pathogens can be killed by temperatures of 60 °C for 30 min; however, some viruses (as well as weed seeds) may survive this treatment (Koike and Wilen 2009). It has been demonstrated that some diseases, such as *Rhizoctonia* damping-off, are much less severe in soil that has been treated at 60 °C/140 °F rather than at 82 °C/180 °F due to mortality of beneficial thermophilic microorganisms at temperatures above 60 °C/140 °F. To maximize control and reduce energy costs, growers or potting media suppliers may need to experiment to find the best temperature and length of time to treat the media. A good starting point is 60 °C/140 °F for 30 min.

Steam from a boiler can be efficiently blended with bulk soil using a cement mixer (see Miller et al. 2014). When this type of system is used it is not necessary to introduce air into the steam because a large amount of air is present in the mixer and the temperature can be controlled by simply regulating the flow of steam.

Stationary systems such as soil vaults or tarp-covered piles require the use of air blowers. If circulating fans can be placed within or external to the vault and the steam can be introduced into the recirculating air, then blowers are not necessary. Nevertheless, it is important to leave space between the vaults and check temperatures throughout the vault to ensure that there is good circulation of steamed air. Another method to ensure that the media is uniformly heated is to combine steam heating with a vacuum system to draw the steam through the media. In this system, perforated pipes are placed 40–45 cm below the media to be treated and attached to vacuum pumps (Hanan 1997).

Steam heating of soil or potting media is also an effective method to kill weed seeds. In this process, steam is mixed with air and injected into tarp covered, wetted soil mix to heat it to 82 °C/180 °F for 30 min (Elmore and Wilen 2000; Baker and Roistacher 1957). Length of time and temperature are critical if weed seeds are to be controlled (Vidotto et al. 2013), and temperature probes must be placed so that the internal temperature is verified. Moist soil conducts heat more readily than dry soil; therefore, the media should be thoroughly moist prior to injecting the steam to facilitate even heat distribution. Also, weed seed are more easily killed when imbibed with moisture.

3.3.3 Double-Tent System for Solarization

A "double-tent" setup can be used to heat media (Fig. 6). This method has been demonstrated to reach at least 60 °C/140 °F for 60 continuous min and 70 °C/158 °F for 30 continuous min (CDFA 2002). In this system, media at or near field water holding capacity is placed in polyethylene planting bags or in small piles (not more than 30 cm high) placed on pallets or wire mesh screen on a layer of polyethylene

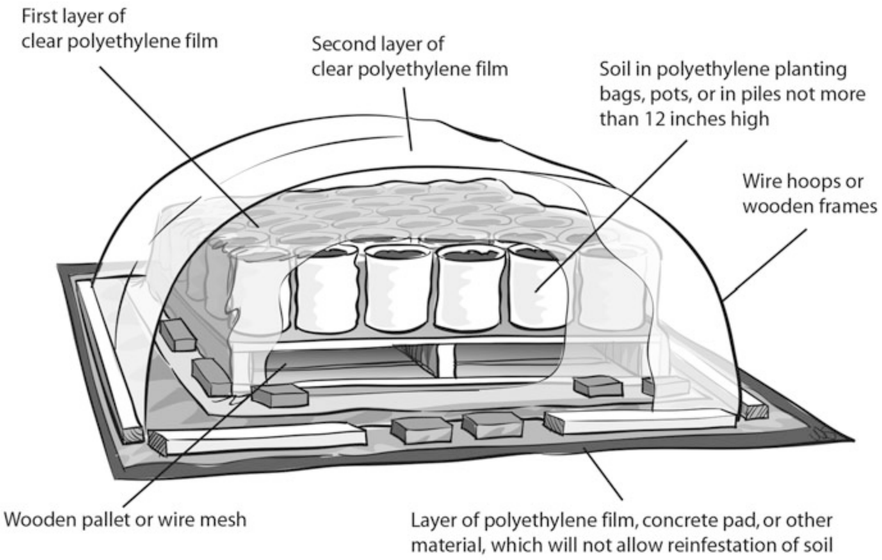

Fig. 6 "Double tent" system for using solarization to disinfest containers and planting mix. Illustration by William Suckow (Reprinted from Stapleton JJ, Wilen CA, Molinar RH. 2008). Pest Notes: Soil Solarization for Gardens & Landscapes. Oakland: Univ. Calif. Div. Agric. Nat. Res. Publ. 74145 (Reprinted with permission from the UC Statewide IPM Program)

film, concrete pad, or other impervious material. An additional layer of clear polyethylene film is then suspended over the first layer to create a still air chamber over the soil to be treated. This approach has been successfully used to treat potting mix for weed control (Prather et al. 2002). This system works best in full sun. Temperature probes should be placed at the bottom center of the pile or bag to monitor that the effective temperatures are reached.

Note that any fertilizer or mycorrhizae should be added after the media has cooled. For many slow-release fertilizer formulations, nutrient release is controlled by temperature and moisture. High temperatures, created by steaming or solarization, will cause the fertilizer to be released immediately. Similarly, mycorrhizae will be killed at high temperatures.

3.3.4 Compost as Disease Suppressive Media

Compost may be a minor component of conventional potting mixes but is commonly used in organic mixes. Organic materials should be thoroughly composted prior to use and should constitute only 20–30% of the mix (Rynk 1992). Composted animal manures and vegetable waste added to peat have resulted in the suppression of several plant diseases (Pugliesi et al. 2015). Disease suppression is highly dependent upon the inputs and chemical composition of the compost. Diseases caused by *Pythium* and *Phytophthora* spp. may be exacerbated when composts have high salinity (Hoitink and Fahy 1986). Colonization of the compost by beneficial organisms, such as *Trichoderma* spp. (Horst et al. 2005), may be the mechanism of disease suppression, and the addition of microbial inoculants could increase disease suppression. Unfortunately, there is a great deal of variability associated with the use of compost for disease suppression and it is not a common practice in the commercial conventional floriculture industry.

An important note on integrated pest management relative to media disinfestation is that reuse of containers is a common practice and disinfesting media without sanitizing used pots will result in the reintroduction of pathogens at planting (Parke et al. 2008).

4 Soil Disinfestation

Soil disinfestation in open-field and shade house production is performed to control multiple pests such as soilborne pathogens and weed seeds but also to kill flower propagules (bulbs, rhizomes, tubers) from the previous crop. Fumigation with methyl bromide was the principal treatment for control of many soilborne plant pathogenic fungi, bacteria, weeds, nematodes, and insects in soil for field-grown cut flowers. Its loss presents a particularly difficult challenge for in-ground ornamental producers (Rosskopf et al. 2005, 2010b; Schneider et al. 2003). Cut flowers are produced using very high-density plantings, which necessitates full-field soil disinfestation in order to sufficiently treat the ground. Materials with low vapor pressure do not move through soil in the manner that methyl bromide does with reduced efficacy as a result. This also limits the efficacy of applications around fixed infrastructure such as shade and glass house posts (Figs. 7 and 8). Buffer zones of up to 400 m or more in sensitive areas near hospitals or schools make use of fumigants combined with chloropicrin for cut flowers challenging as flower production often occurs on small acreages and/or in coastal areas near cities where land rental values are high. Regulatory restrictions on fumigant use create a need for safe fumigants and nonfumigant alternatives to disinfest soils for flower production.

4.1 Soil Fumigants

Fumigants are chemicals that volatilize when applied to the soil, and the vapors diffuse through the soil to contact the target pest. The overall effectiveness of any fumigant is determined by the dosage delivered to the pest and is a function of the concentration and time of exposure. This is referred to as the CT factor (concentration/time factor). Other parameters that are important to the success or failure of fumigation are soil temperature, soil moisture, soil texture, organic-matter content, application method, and surface seal. The objective of a fumigant application is to reach the critical concentration, come in contact with the soil pest, control it, and then the fumigant must degrade to prevent nontarget exposure to people and other plantings in the vicinity of the field and to ensure safety to the crop when it is planted in the days or weeks following fumigation.

Fig. 7 Soil disinfestation is hampered by permanent infrastructure such as posts for shade cloth and glass (E. Rosskopf. USDA.)

Optimum soil temperatures for application of most soil fumigants is between 18° and 24 °C/75 °F at a depth of 15 cm. Cool soil temperature slows volatilization, which results in slow fumigant dispersal and poor pest control. At low soil temperatures, or in excessively wet soil, fumigants break down slowly which may result in persistent fumigant concentrations that can linger and injure the crop if planted before the fumigant concentration falls to safe levels. If soil temperatures are too high, the fumigant may diffuse too rapidly or escape before reaching an adequate concentration for good pest control.

Fumigants present significant hazards to workers and the environment and must be handled carefully. They are classified, with a few exceptions, as restricted use pesticides in the USA and, as such, must be applied only by certified fumigant applicators (Blecker and Thomas 2012; Noling 2013). Most shank applications are conducted using nitrogen pressurization to push the materials through specialized tubing (Fig. 9) that is attached to a shank that runs through the soil (Fig. 10). As the fumigant is injected below the soil surface, a polyethylene tarp is applied over the soil to prevent the fumigant from dissipating too quickly (Fig. 11).

Fumigants can be applied by shank or by chemigation through the drip irrigation system (Fig. 12) (Ajwa et al. 2002). Whether the fumigants are applied by chemigation or shank application, they will benefit from the use of impermeable films such as "totally impermeable film" (TIF) (Fennimore and Ajwa 2011). The TIF

Fig. 8 Areas in which fumigants or disinfestation practices are difficult to use are often treated using many chemical spot-injections, commonly known as “stinging.” This is useful with chemicals that have lower vapor pressure than methyl bromide (E. Rosskopf. USDA.)

blocks fumigant emissions and retains the fumigant in the soil at higher concentrations for longer periods than standard films which results in better pest control. Some fumigant labels only allow for application under high barrier films such as TIF (Agrian 2015d).

The most useful soil fumigant, in the absence of methyl bromide, for field grown flowers in CA, is chloropicrin (Agrian 2015a). Although registered for use, metam sodium and metam potassium (Agrian 2015b) and dazomet are not very effective for controlling many soilborne pathogens, including *Verticillium* and *Fusarium oxysporum*. Two more recently registered fumigants, allyl isothiocyanate (Agrian 2015e) and dimethyl disulfide (Agrian 2015d), are available for use in the USA (FL) and are more feasible for use in floriculture in many cases than are 1,3-dichloropropene and chloropicrin due to fewer regulatory restrictions (Table 1).

4.1.1 Chloropicrin

Chloropicrin must be injected into soil, and it is very effective for controlling many plant pathogenic fungi. Chloropicrin is often combined with 1,3-dicloropropene (1,3-D) in various mixtures such as 56.6% chloropicrin, 37.1% 1,3-D (Table 1) depending upon the target pests in the soil. When chloropicrin is used alone, a water

Fig. 9 Fumigants are injected into soil through a series of specialized tubes that are pressurized using nitrogen gas. Different fumigants are delivered with different sizes of tubing and flow meters in order to achieve precise application amounts and effective distribution of material (E. Rosskopf. USDA.)

seal may be used to confine the gas; however, chloropicrin has a very objectionable smell and is irritating to the eyes (it is commonly known as tear gas) and, if not effectively confined, it may drift to inhabited areas. This is a restricted use material in the USA and requires a permit from the county agricultural commissioner to be purchased and/or applied (Koike and Wilen 2009).

Numerous studies have been conducted in the USA (CA) on the use of chloropicrin and 1,3-D mixed with chloropicrin. In studies using inoculum bags buried at multiple depths, Telone C35 (63.4% 1,3-D, 34.7% chloropicrin) was extremely effective in killing propagules of *Pythium* and *Verticillium* but not very effective for control of *Fusarium* or *Phytophthora* (Cabrera et al. 2015). In a series of calla lily trials aimed at control of Pythium and Phytophthora rots of the rhizomes, drip application of chloropicrin and combinations of 1,3-D and chloropicrin resulted in the greatest yields and reduced incidence of the disease (Gerik et al. 2006). In similar work, drip application of chloropicrin reduced the incidence of *Sclerotinia sclerotiorum* on liatris, although metam sodium provided a greater level of control (Gerik 2005). Combinations of fumigants that include chloropicrin generally provide improved disease control. The use of 1,3-D is heavily regulated, and restrictions on its use may prevent implementation in some areas (Carpenter et al. 2001).

Fig. 10 Green and blue tubing, seen here, runs from the fumigant cylinder, through a series of flow meters, down to the shanks where the gas is injected into the soil. These shanks have small plates on the back of the shanks to close the cut in the soil into which the gas was injected (E. Rosskopf. USDA.)

4.1.2 Dimethyl Disulfide (DMDS)

The volatile sulfur compound dimethyl disulfide (DMDS) has been tested for control of several nematodes including potato cyst (*Globodera* spp.) and root-knot (*Meloidogyne* spp.) nematodes, as well as diseases caused by *Fusarium*, *Pythium*, and *Phytophthora*. Greenhouse experiments were conducted by Coosemans (2005) against potato cyst and root-knot nematodes on potato and tomato. Five rates of DMDS were tested and compared with other nematicides including methyl bromide and aldicarb, reducing both potato cyst and root-knot nematode populations, for increasing plant growth and saprophytic nematode populations.

Although more work has been done with this fumigant in the control of pathogens of vegetables, cut flower field trials were conducted in FL as early as 2004 to assess the efficacy of DMDS for control of the root-knot nematode *M. arenaria* and Pythium root rot on cockscomb (*Celosia argentea*). DMDS and DMDS plus chloropicrin provided excellent nematode and disease control (Church et al. 2004, although it was more effective in eliminating *Pythium* from soil than it was for *Fusarium*. In caladium (*Caladium* x *hortulanum*), DMDS was as effective in controlling *M. arenaria* as methyl bromide. Root condition was better and gall ratings were lower in the DMDS treatment than for several 1,3-D treatments. Control of *Pythium* root rot in caladium by fumigation was highly dependent upon interaction between fumigant and caladium cultivar, with “Sweetheart” combined with DMDS having the lowest pathogen

Fig. 11 After injection of the gas into the soil, the fumigated area is immediately covered by a plastic tarp. Each tarp is glued to the previous one as the gas is injected in each pass. The glue in this photo is *red* and the worker is making sure that it is sealing properly (S. Fennimore © 2017. All Rights Reserved.)

recovery from roots (Fig. 13) (Kokalis-Burelle et al. 2010). In trials conducted in CA cut flowers, DMDS did not provide consistent control of *Pythium* or *Fusarium* (Gerik 2005).

4.1.3 Allyl Isothiocyanate

The use of *Brassica* species as soil-incorporated green manures has been studied extensively for their disease-management effects. In the early 1990s, Kirkegaards et al. (1993) introduced the idea of using *Brassica* species for biofumigation in which the break-down products of brassicas were identified as isothiocyanates. Recently, a formulated biofumigant containing allyl isothiocyanate was registered in the USA. This product is labeled for use in ornamental production in FL, and registration is pending in CA. Several trials have been conducted with this material in cut flowers in FL, and it has provided root-knot nematode control equivalent to methyl bromide in snapdragon, lupin, larkspur, iris, sunflower, celosia, zinnia, and Queen Anne's lace. Control of *Sclerotium rolfsii* was also equivalent to methyl bromide (Rosskopf et al. 2014). Weed control with this compound has been excellent for grass weeds, but it has not provided control of Carolina geranium (*Geranium carolinianum*).

Fig. 12 Fumigants can be applied through drip-irrigation lines, also referred to as “chemigation.” The *lines* are pressurized using nitrogen gas and the fumigant is injected into a port which flows into a static mixer and is pushed out through the drip tape (H. Ajwa © 2017. All Rights Reserved.)

4.2 Steam

Steam has been used for disinfesting soil since the 1800s. This approach was commonly used in cut flower production in the USA prior to the development of fumigants. In many South American countries and the Netherlands, steam continues to be used for soil disinfestation for flower production. The loss of methyl bromide resulted in a resurgence of interest in this approach. Typically, “sheet steaming” was used in which steam is applied to the soil surface, under a heat resistant tarp. The heat moves from the soil surface down (Runia 1984). Injection of steam, either through a fixed drain tile system (Fig. 14), spike application system (Fig. 15), or mobile unit (Figs. 16 and 17), is more efficient. There continues to be significant improvement in the efficiency and, therefore, cost of steam application (Fennimore et al. 2014).

Work on steam to control soilborne pathogens including nematodes was conducted by Van Loenen et al. (2003). They studied the effects of steam on survival structures of several important fungal pathogens, weeds, and the potato cyst nematodes *Globodera rostochiensis* and *G. pallida* in field soil. Using aerated steam at temperatures ranging from 40 °C to 80 °C they found that steaming at 50 °C or 60 °C (122 °F or 140 °F) for 3 min resulted in 100% kill of all pathogens and weeds including nematodes.

Steam has recently been shown to be effective for broad-spectrum nematode and fungal plant pathogen control in field soil (Rosskopf et al. 2010a; Kokalis-Burelle et al. 2014). In cut-flower field trials conducted in Florida, root-knot nematode

Table 1 Fumigants labeled for use in floriculture in the USA and relative effectiveness against soil pests (Modified from Elmore et al. 2007)

Common name	Trade name	Broadcast rates	Nematodes	Fungi	Weeds	Comments
1,3-dicloropropene	Telone II	9–12 gal/A 84–112 L/ha 1 gal = 10.1 lb	Excellent	Poor	Fair	Effective against nematodes and insects
1,3-dicloropropene plus chloropicrin	Pic-Clor 60	0–48.6 gal/A 0–454 L/ha 1 gal = 12.1 lb	Excellent	Very good	Fair	Most effective against nematodes, fungi, and insects
Chloropicrin	Tri-Clor	15–30 gal/A 140–280 L/ha 1 gal = 13.76 lb	Fair	Excellent	Fair	Effective for control of fungi and insects
Dazomet	Basamid G	218–525 lb/A 244–588 kg/ha	Good	Good	Good	Dry powder incorporated into soil or watered into soil
Metam potassium	K-Pam Sectagon K	30–60 gal/A 280–561 L/ha 1 gal = 5.8 lb	Good	Good	Good	Water soluble liquid forms MITC, the active fumigant
Metam sodium	Vapam Sectagon	37.5–75 gal/A 351–702 L/ha 1 gal = 4.26 lb	Good	Good	Good	Same as metam potassium
Allyl isothiocyanate[a]	Dominus	20–40 gal/A 187–374 L/ha 1 gal = 8.5 lb	Excellent	Good	Fair	Not registered in CA
Dimethyl disulfide[a]	Paladin	35–51.3 gal/A 328–480 L/ha 1 gal = 8.85 lb	Excellent	Good	Fair	Not registered in CA

[a] Modified from Elmoredeng

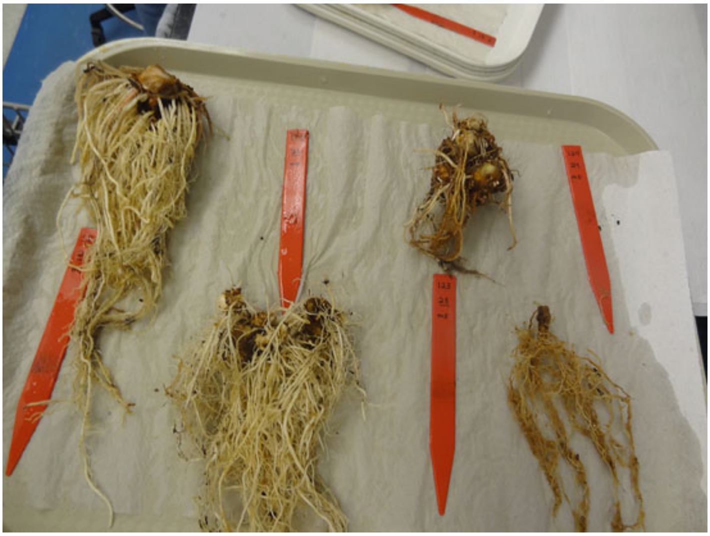

Fig. 13 Cultivars or varieties of the same species often have different levels of susceptibility to pathogens. Some caladium cultivars are resistant to both root-knot and Pythium root rot, caused in this case by *Meloidogyne floridensis* and *Pythium* spp., respectively (N. Kokalis-Burelle. USDA.)

(*M. arenaria*) populations in steam treated soil were equivalent to methyl bromide treatment and lower than those found in solarized soil. Total nematode numbers, including free-living nematodes, were lower after steam treatment compared with solarization and methyl bromide.

In an effort to better understand the dynamic effects of steaming soil on a variety of soil organisms, McSorley et al. (2006) investigated the effects of steam on nematode and microbial populations in sand and muck soils, two important soil types in Florida ornamental crop production. Steamed or nonsteamed soil of each type was inoculated with 2,000 eggs of *M. incognita* per pot. A soil type × steam treatment interaction occurred, with root-knot nematodes suppressed in nontreated sand but not in steamed sand nor in any (steamed or nonsteamed) muck soil. A variety of organisms were monitored in both soils including free-living nematodes (bacterivores, fungivores, omnivores, and predators), enchytraeids, Collembola, mites, nematode-trapping fungi, egg-parasitic fungi, *Pasteuria* spp., rhizosphere fungi including *Fusarium* and *Rhizoctonia*, and a variety of rhizosphere bacteria including Gram positive bacteria, fluorescent pseudomonads, and siderophore producers. Most of these organisms did not show population patterns consistent with the biological suppression of root-knot nematodes observed in the nonsteamed sand. For example, *Pasteuria* and other Gram positive bacteria were more abundant in soils that had been steamed; however, more inoculated root-knot nematodes survived in steamed soils as well.

Fig. 14 Steam can be delivered to the field using a fixed boiler system that is attached to buried drain tile. The drain tile is attached to a manifold (seen here) that is connected to the boiler through heat-resistant hose (S. Fennimore © 2017. All Rights Reserved.)

Population trends of predatory nematodes were most consistent with the suppression of root-knot nematodes observed in nontreated sand.

Finally, steam has some very practical applications in controlling nematode pests for certification requirements in some ornamental crops. Nurseries in Hawaii must follow strict certification requirements to export potted plants. *Rotylenchulus reniformis*, reniform nematode, must be disinfested from mined volcanic cinder, which is utilized as a potting medium by nematode certified nurseries. Cabos et al. (2012) investigated two steam delivery systems for efficacy in disinfesting cinder of *R. reniformis,* a low capacity system consisting of a portable steam generator connected to a cart with a treatment volume of 1.68 m^3 and a large capacity system consisting of a modified dump truck bed with a treatment volume of 24.5 m^3 connected to a boiler. Cinder inoculated with *R. reniformis*-infested roots of *Ipomoea batatas* were buried in various locations and depths in the cinder contained in the two steaming systems. Once the steam was evenly distributed, both systems were successful at eradicating all live *R. reniformis* (Cabos et al. 2012). Many logistical issues remain for steam application and before steam can be adopted on a large scale,

Fig. 15 Steam from a fixed boiler is applied through heat-resistant hose with spikes which are inserted through the plastic into the bed area (S. Fennimore © 2017. All Rights Reserved.)

Fig. 16 Numerous commercial mobile steam units are available that mix soil with steam as it moves through the field (S. Fennimore © 2017. All Rights Reserved.)

Fig. 17 Large-scale application of steaming requires mobile units with access to water and fuel (S. Fennimore © 2017. All Rights Reserved.)

these would need to be resolved. Also the expense of steam application is dependent on energy costs and may limit adoption of steam as an alternative soil treatment in the short term. Nonetheless, this may be a practical approach for the treatment of areas in which chemical fumigant use is restricted.

4.3 Solarization

Soil solarization is a process where sunlight is used to heat moist soil to control various pest organisms (Elmore et al. 1997; Katan et al. 1987). Soil solarization is accomplished by using a clear, thin polyethylene covering on the soil during a period of high radiation, with little wind or cloud cover. This condition is most common during the summer (late May to late August) in the central valley regions of California and may be present in May or more likely in late August or early September, in the coastal regions. Solarization can be used in Florida for the production of fall crops, with solarization conducted from May–October. Similar timing would be expected at similar latitudes.

Some soil-borne pathogens are rather easily controlled when there are enough heat units (temperature and time). The amount of control depends upon the organism and the heat units. Many organisms including weeds, soilborne pathogens, and nematodes are killed by soil temperatures in excess of 50 °C/122 °F. Because soilborne pathogens and nematodes may be found throughout the soil profile, pests below 30 cm will not be controlled as well as pests near the surface where temperatures are hotter. Because weeds mostly emerge from the shallow surface layers, weeds are generally better controlled than nematodes which must be controlled throughout the soil profile. Soil solarization may control nematodes in some cases, particularly in the upper 30 cm of soil in areas of high solar output, light and medium textured soil, soil moisture near field capacity, shallow root depth of previous crop, and limited acreage. Nematodes are also mobile in the soil and thus certain species may escape the thermal killing by movement into cool soils, as do earthworms.

The killing with soil solarization is predominantly by heat induced membrane disruption, though suppression of some organisms may be caused by certain gases formed as the organisms are killed. See Elmore et al. (1997) for details on species of soil pathogens and nematodes controlled with solarization. Keep in mind that these species will not be controlled as well in coastal California under cool foggy conditions as in hot inland valleys.

Most weeds are controlled with 4–6 weeks of solarization in the central valley region of California (Elmore et al. 1997). All winter annual weeds, except some clover species, are controlled. The biennial weed bristly oxtongue (*Picris echioides*) is also controlled. Some perennial weeds can be controlled in the Central Valley area, such as Bermudagrass (*Cynodon dactylon*), Johnsongrass (*Sorghum halepense*), and yellow buttercup (*Ranunculus acris*). Many summer annual weeds are also controlled with the exception of sweet clovers (*Melilotus* spp.). If the treatment is marginal, then common purslane (*Portulaca oleracea*) will not be controlled or will only be partially controlled. Weeds that are only partially controlled include yellow (*Cyperus esculentus*) and purple nutsedge (*C. rotundus*). Field bindweed (*Convolvulus arvensis*) is controlled at the surface (0–10 cm), but it will regrow from deeper rhizomes. In coastal regions of California, the control of weeds is often spotty, depending upon local conditions (Elmore et al. 1997).

The most critical time of high radiation is during the first week of cover. If the weather is warm, sunny, and calm, control is generally good. Fields tarped during cloudy, foggy, or windy conditions will often result in poor control. Common purslane, if present, seems to be a good indicator species. If the conditions are correct, common purslane is controlled and indicates that the solarization procedure has worked.

A great deal of data is available on the effects of soil solarization on nematodes. In general, solarization proves to be more effective for reducing nematode populations when applied during the hottest months in tropical or subtropical growing regions. Early work on solarization using clear or gas-impermeable plastic was conducted in Florida to evaluate combinations of solarization with soil fumigants, herbicide, or cabbage residue (Chellemi et al. 1997). Solarization plastic was applied to vegetable planting beds and left in place for 40–55 days. After the solarization period the plastic was painted white and used for tomato production. At the end of the trial, the density of *Paratrichodorus minor* and *Criconemella* spp. populations were reduced in solarized plots. No differences in populations of *Helicotylenchus* spp. were observed between plots receiving solarization and plots fumigated with methyl bromide + chloropicrin.

In laboratory studies, *Meloidogyne incognita* eggs or J2 were incubated in test tubes containing sand:peat mix and immersed in a water bath heated to 38 °C, 39 °C, 40 °C, 41 °C, 42 °C, 43 °C, 44 °C, and 45 °C for a series of time intervals. Controls were maintained at 22 °C. Nematodes surviving or hatching were collected after 3 weeks of incubation. Regression analyses between percent survival or egg hatch and hours of heat treatment were performed for each temperature. Effect of temperature on nematode survival was not determined by heat units, and oscillating temperature between cool and warm did not interfere with the nematode suppressive effect of the heat treatment. In field studies, solarization for 6 weeks during the summers of 2003 and 2004 in Florida accumulated heat exposure times in the top 15 cm of soil that surpassed levels required to kill *M. incognita* as determined in the water bath experiments. Although near zero *M. incognita* were detected right after solarization, the nematode population densities increased after a cycle of a susceptible pepper crop (Wang and McSorley 2008).

Solarization has also been studied for control of nematodes and pathogens in multiple ornamental species. In a study conducted in west-central FL using 3–4 weeks of solarization implemented in early fall, incidence of Phytophthora blight of Madagascar periwinkle (*Catharanthus roseus*), caused by *P. nicotianae*, was significantly reduced (McGovern et al. 2000). In a similar study, solarization conducted during the fall using a double layer of clear plastic mulch was consistently effective in reducing disease in impatiens (*Impatiens x wallerana*) caused by *Rhizoctonia solani* and *Pythium* spp. (McGovern et al. 2002). The severity of root galling caused by root-knot nematodes was reduced by solarization, as were the populations of several other plant parasitic nematodes. Control of Pythium damping off on snapdragon (*Antirrhinum majus*) was tested in one season using a 4-week solarization period and a 6-week period in the second season (McSorley et al. 2009). The snapdragon plant mortality in the first year was equivalent to the number lost in the untreated control, but after the 6-week period, the incidence was equivalent to that found in methyl bromide-treated plots. Neither of the solarization treatments resulted in an increase in marketable yield over the nontreated control.

One of the advantages of soil solarization is its compatibility with other disease management inputs. In the vegetable study mentioned above, the severity of root galling, caused by *Meloidogyne* spp., was lower when soil solarization was combined with 1,3-dichloropropene + chloropicrin applied under a gas-impermeable film (Chellemi et al. 1997).

In many other countries, an approach referred to as biosolarization is used. For example, a combination of soil solarization and raw or pelletized poultry manure amendments was evaluated for the control of root-knot nematode (*Meloidogyne incognita*) in carnation (*Dianthus caryophyllus*) grown in beds under plastic-covered greenhouse conditions in southern Spain. Soil solarization alone did not provide sufficient control of root-knot nematode, because the carnation growing season in this region only partly coincides with the most effective period for

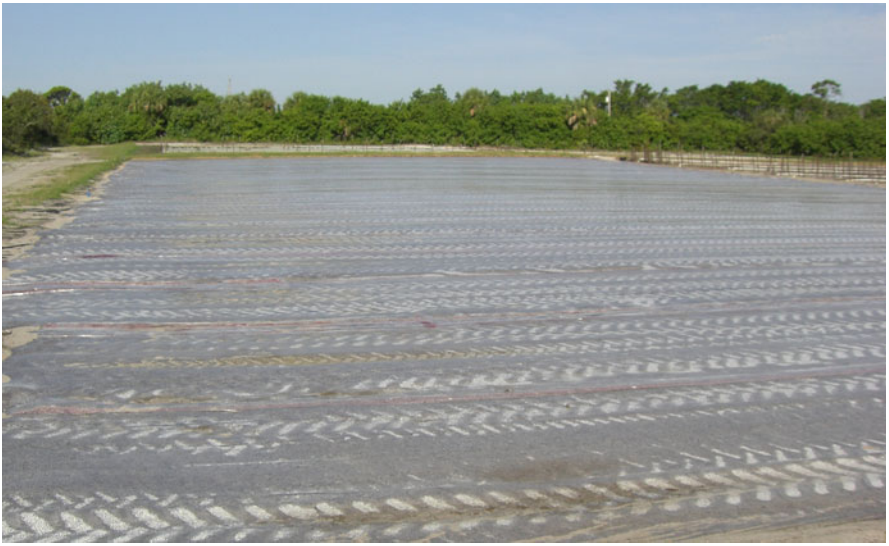

Fig. 18 Full-field solarization using solid tarp requires that tarps are glued together in a manner similar to that used for chemical fumigation (E. Rosskopf. USDA.)

solarization, resulting in an insufficient duration of treatment. The combination of soil solarization and raw or pelletized poultry manure was slightly less effective than chemical fumigation for control of this pathogen but crop yields after 9 months were similar. However, the higher root gall indices observed after 9 months, in comparison with chemically fumigated plots, indicated the need for a reapplication of the organic manure at the start of each successive growing season (Melero-Vara et al. 2012).

The results of this study (Melero-Vara et al. 2012) as well as those reported by Wang and McSorley (2008) indicated above point to one of the weaknesses of the use of solarization that nematode suppression is short-lived under solarization in comparison to fumigation in many cases, and the control does not result in increased crop yields. Solarization in FL is particularly unreliable when there are heavy summer storms (Wang et al. 2004). Full-field tarping for solarization (Fig. 18), which is commonly used in some locations during hot and dry conditions (Katan et al. 1987), is risky in FL due to the potential for loss of the plastic, or for water to pool in wheel ruts (Figs. 19, 20, and 21), or ineffectiveness of solarization at field edges (Grinstein et al. 1995) where inadequate heating can occur, resulting in poor control of weeds and diseases.

One approach to overcoming the expense of steaming and the variability of control associated with solarization is to combine these. In trials conducted in CA on calla lily, steam combined with solarization resulted in greater suppression than either method alone (Rainbolt et al. 2013).

Fig. 19 Utilization of solid-tarp solarization is hampered by the need to treat soil during the rainy season, which can result in water pooling in tractor tire tracks, which reduces soil heating in these areas (E. Rosskopf. USDA.)

Fig. 20 When water pools on *top* of the solarization plastic, the reduction in soil heating can lead to the survival and rapid spread of weeds (E. Rosskopf. USDA.)

Fig. 21 The effects of reduced soil heating from solarization when water pooled in tire tracks under the solarization can be seen in the subsequent crop; in this case, in increased incidence of Pythium damping off in snapdragon (E. Rosskopf. USDA.)

4.4 Anaerobic Soil Disinfestation

Anaerobic soil disinfestation (ASD), a nonchemical alternative to MB, was developed in Japan (Momma 2008) and the Netherlands (Blok et al. 2000) to control soilborne pathogens and nematodes in strawberries and vegetables. ASD integrates principles behind solarization and soil saturation to control nematodes and pathogens in situations where neither is effective or feasible when applied alone (Rosskopf et al. 2015). Anaerobic soil conditions are created during the ASD process when a readily available carbon-source is incorporated into topsoil (Figs. 22 and 23), covered with a plastic tarp and then irrigated to field capacity. The tarp is left in place to maintain soil moisture above field capacity and to sustain anaerobic conditions. Anaerobic decomposers are then able to respire using the added carbon, which results in the build-up of anaerobic by-products that are toxic to pathogens (Katase et al. 2009). These products are degraded rapidly once the tarp is removed or holes are punched through the tarp for planting. Studies were conducted over the past 4 years to optimize ASD for use in California strawberry and Florida vegetable and ornamental production systems. Overall, ASD was effective in suppressing

Fig. 22 Application of rice bran as the carbon source for anaerobic soil disinfestation in California (J. Muramoto © 2017. All Rights Reserved.)

Verticillium dahliae in soils and resulted in 85–100% of the marketable fruit yield observed with fumigated controls in coastal California strawberries when 20 t ha^{-1} of rice bran was pre-plant incorporated and 7.5–10 cm of irrigation was applied in sandy-loam to clay-loam soils (Shennan et al. 2011). In the cooler conditions of the central coast of California, however, ASD may not provide effective control of many weed species (Fennimore et al. 2013). To ensure consistency of pest suppression across varying locations, effects of soil temperatures and treatment length, and the mechanisms of pest suppression by ASD are being further studied. Integration of ASD with other nonfumigant approaches may also have promise. For example, a combination of ASD and mustard seed meal application is currently being tested (Shennan and Muramoto unpublished). Given the fact that much of the flower production in California is near the coast and that ASD does not provide effective weed control in coastal California conditions, control of volunteer flower bulbs and weeds in CA flower fields with ASD will likely be problematic (Fennimore et al. 2013).

In FL, ASD has proven very effective in the field for parasitic nematode control in specialty crops including cut-flowers (Rosskopf et al. 2010b; Butler et al. 2012a, b). The anaerobic conditions are lethal to nematodes and other soilborne pests and pathogens. Experiments were done in Florida to test the use of summer cover crops which could be grown in fields and then incorporated into soil as the organic component of ASD treatments. Several legumes and grasses including pearl millet (*Pennisetum glaucum*), sorghum-sudangrass (*Sorghum bicolor x S. bicolor* var.

Fig. 23 Incorporation of rice bran and bed formation conducted in a single pass in preparation for anaerobic soil disinfestation in CA (J. Muramoto © 2017. All Rights Reserved.)

Fig. 24 On-farm application of molasses as the carbon source for anaerobic soil disinfestation in FL (E. Rosskopf. USDA.)

sudanese), cowpea (*Vigna unguiculata*), and sunn hemp (*Crotalaria juncea*) were grown and then incorporated into soil. These were then compared to molasses, a standard ASD amendment, and a nonamended control. Root galling by the root-knot nematode *M. incognita* was low among all cover crop treatments except pearl millet, which had the highest levels of galling (Butler et al. 2012a). This was most likely due to the other crops tested as amendments (sorghum-sudangrass, cowpea, and sunn hemp) being nonhosts or poor hosts of *M. incognita* compared to pearl millet, which has been reported as a good host (McSorley 1999; McSorley et al. 1994).

Although the generation of organic acids is the most plausible control mechanism for plant-parasitic nematodes during ASD treatment (Katase et al. 2009), the generation of other by-products during amendment decomposition or shifts in microbial populations which favor naturally occurring biocontrol organisms may also play a role (McBride et al. 2000). Further field studies which evaluated ASD combined with soil solarization as an alternative to methyl bromide fumigation for plant parasitic nematode and soil-borne pathogen control defined in more detail the inputs necessary to make the system effective for nematode control (Butler et al. 2012b). In cut flowers in particular, ASD utilizing molasses (Fig. 24) as the labile carbon source, addition of composted broiler litter, soil saturation, and covering with a clear, gas-impermeable film resulted in cut flower yields that were equivalent to or greater than methyl bromide for the first crop (Rosskopf et al. 2010c. Delphinium and *Dianthus* yields under ASD exceeded those produced using steam and were equivalent to methyl bromide, but snapdragons were better yielding with methyl bromide than from any other soil treatment.

5 Summary

A significant amount of progress has been made in the discovery and development of alternatives to methyl bromide for soil disinfestation. Several of the methods discussed here have proven efficacy against a wide range of soilborne pests associated with production of ornamental crops, but the most consistent approaches still include the application of chemical fumigants. For the treatment of potting mixes, there are limited options and the use of steam and dazomet provide the most consistent results. California cut flower growers are likely to continue using chloropicrin in areas where fumigation is allowed, while implementing steam disinfestation in sensitive sites. The FL in-ground industry will continue to depend on the development of new chemical fumigants as the use of 1,3-D and chloropicrin is allowed in limited production areas. Significant advances in steam technology may increase its application on a larger scale in the future, but it is likely that future approaches to soil disinfestation will require the use of integrated approaches such as those used in ASD. Significant advances continue to be made on this and other nonfumigant approaches that will increase feasibility and implementation on a wider scale.

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