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# Life after Methyl Bromide: Research on 1,3-Dichloropropene plus Chloropicrin in Florida [1]

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## Introduction

The most important vegetable crops in Florida from the standpoint of gross sales are tomato (*Lycopersicon esculentum*), bell pepper (*Capsicum annuum*), strawberry (*Fragaria x ananassa*), cucumber (*Cucumis sativus*), summer squash (*Cucurbita pepo*), watermelon (*Citrullus lanatus*), and muskmelon (*Cucumis melo*) (USDA, 2005). Establishment of these crops mostly relies on production on polyethylene-mulched raised beds fumigated with methyl bromide plus chloropicrin (MBr + Pic) for soilborne disease, nematode, and weed control. However, MBr for agricultural use is being phased out in compliance with the Montreal Protocol, which classifies this fumigant as ozone-depleting (Albritton et al., 1998; EPA, 1999).

Considerable research has been conducted during the last 15 years to identify alternatives to MBr in Florida. Soilborne pests thrive under the subtropical climate most of the year there, allowing pest populations to multiply quickly during spring, summer, and fall, and to preserve reproductive structures in mild winters. Many research reports are available on diverse MBr alternatives. Perhaps the most commonly tested is the combination of the fumigants 1,3-dichloropropene (1,3-D) and Pic, which is sold under the trade names of Telone® and Inline®. In many instances, the combination of 1,3-D + Pic with herbicides also has been examined to determine its potential to enhance weed control, and to study the influence of application methods and mulches on fumigant activity, retention, and performance. Since the early 1990s, extensive research has been conducted with 1,3-D + Pic to compare it to MBr and to identify fumigation programs that could be used in vegetable production systems. This article summarizes the most important findings on 1,3-D + Pic research in Florida. We used scientific papers, research reports, and extension/outreach articles as references.

## Soilborne Disease, Nematode, and Weed Management

In the U.S., 1,3-D + Pic is sold in the 83:17 and 65:35 (v/v) ratios, which merges the nematicidal activity of 1,3-D with the fungicide Pic. This material is commercially formulated as a liquid under pressure, which vaporizes upon application, and as an emulsifiable concentrate for water dilution. Because

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of these two formulations, different application procedures are used under varying field conditions. The gas formulation of 1,3-D + Pic is applied in the soil with the same injection equipment as for MBr, which would facilitate adoption by growers. On the other hand, the liquid formulation has the advantage of reducing application costs, since it is applied through the drip-irrigation lines used for fertigation, and reduces the risks of human exposure to the fumigant.

1,3-D provides a relatively inexpensive means for nematode control, with similar efficacy as MBr. In fresh-market tomato, previous studies have shown that populations of stunt (*Tylenchorhynchus*), sting (*Belonolaimus*), stubby-root (*Trichodorus*), and root-knot (*Meloidogyne*) nematodes and the damages they cause are reduced with in-bed soil injections of 1,3-D + Pic to the same control level obtained with MBr + Pic (Gilreath et al., 2004a, 2004b, 2005a, 2006a). Dickson et al. (1998) and Mirusso et al. (2002) determined that there were no differences between the root gall ratings caused by root-knot nematode in plots applied with 1,3-D + Pic and MBr + Pic. Similar results were reported in tomato by Eger (2002), Locascio and Dickson (2000), and Locascio et al. (2001).

Investigations in other vegetable crops have revealed effective nematode control under mulched beds with preplant applications of 1,3-D + Pic. For example, bell pepper studies during multiple years and in different locations suggested that 1,3-D + Pic provided equal control of root-knot, sting, and stubby-root nematodes, as with MBr + Pic (Mirusso et al., 2002), whereas in pepper-cucumber rotations, 1,3-D + Pic reduced nematode root galling compared with the non-treated control (Gilreath et al., 2004c). In strawberry, fumigation with 1,3-D + Pic improved root-knot and ring (*Criconema*) nematode control and total fruit weight to the same levels as in the MBr + Pic plots (Eger, 2000; Gilreath et al., 2006b).

With regard to soilborne diseases, most of the research on alternatives to MBr has been conducted in fresh-market tomato, although several reports in bell pepper and strawberry exist. In fresh-market tomato, Gilreath et al. (2004a)**,** Eger (2000), and Gilreath and Santos (2004d) indicated that application of 1,3-D + Pic at the labeled rate is equally effective against fusarium wilt (*Fusarium oxysporum* f.sp. *lycopersici*) as MBr + Pic. Chellemi et al. (2001), using fields with low to moderate incidence of fusarium wilt and fusarium crown rot (*F. oxysporum* f.sp. *radicis-lycopersici*), determined that deep placement into the soil of 1,3-D + Pic provides similar control as MBr + Pic.

In bell pepper, vascular wilting caused by the fungi (*Phytophthora*, *Pythium*, and *Sclerotinia*) have been regularly controlled with 1,3-D + Pic. However, in certain cases where the disease pressure is very high, additional injections of Pic during bedding might be necessary to improve inoculum control (Chellimi et al., 2001; Mirusso et al., 2002). In spite of all the success with 1,3-D + Pic application for soilborne disease control, Locascio et al. (1999) reported poor strawberry plant growth in plots fumigated with several treatments, including 1,3-D + Pic. Likewise, control inconsistencies of soilborne fungi and the bacterial wilt (*Ralstonia solanacearum*) with 1,3-D + Pic were found in tomato, causing up to 40% yield losses as compared to soil fumigated with MBr + Pic (Dickson, 1997; Locascio et al., 1997).

Despite these results, weed management remains a challenge in Florida, where warm temperatures ($\geq$20° C)are the norm between March and November, when most polyethylene-mulched vegetables are grown. Weed species regularly occurring in Florida vegetables include the grasses crabgrass (*Digitaria*), bermudagrass (*Cynodon*), barnyardgrass (*Echinochloa*), goosegrass (*Eleusine*), and fall panicum (*Panicum*), and the broadleaves pigweed (*Amaranthus*), common purslane (*Portulaca*), common lambsquarters (*Chenopodium*), nightshade (*Solanum*), Florida pusley (*Richardia*) eclipta (*Eclipta*), sida (*Sida*), evening primrose (*Oenothera*), and beggarweed (*Desmodium*). These weeds usually grow in row-middles and through planting holes. In contrast, the sedges purple nutsedge (*Cyperus rotundus*) and yellow nutsedge (*C. esculentus*) penetrate the polyethylene mulch, making these species especially problematic to control. Extensive research has been conducted to determine the efficacy of the combination of 1,3-D + Pic and preemergence herbicides. The herbicides flazasulfuron, lactofen, halosulfuron, metolachlor, metribuzin, napropamide, and pebulate have been the focus of previous studies. However, varying success rates been found with these herbicides.

In particular, the herbicide pebulate was widely used in preliminary research to improve nutsedge control in tomato. Gilreath and Santos (2005b) found that in-bed injections of 1,3-D + Pic combined with broadcast applications of pebulate were more effective in controlling nutsedge than the fumigant alone in fresh-market tomato fields. At the same time, applying either napropamide, metolachlor, lactofen, or flazasulfuron with 1,3-D + Pic failed to reduce densities of this weed to the levels observed with the fumigant and pebulate. Similar findings have been reported elsewhere (Gilreath and Santos, 2004d and 2004e; Gilreath et al., 2004b; Locascio and Dickson, 2000; Locascio et al., 2001). Unfortunately, this herbicide is no longer registered in Florida. The herbicide halosulfuron has been recommended as a pretransplant treatment to reduce nutsedge populations in tomato (Stall and Gilreath, 2006).

Other herbicides have been tested in other vegetable crops. For example, in bell pepper-cucumber rotations, Gilreath et al. (2004c) suggested that the application of the herbicides napropamide and metolachlor in addition to in-row injections of 1,3-D + Pic during the bell pepper season had a excellent control of goosegrass, crabgrass and pigweed, but only poor to fair control of nutsedge during the following cucumber season. After evaluating results of five and eight bell pepper and strawberry trials, respectively, Eger (2000) concluded that the addition of the herbicide napropamide to fumigation with 1,3-D + Pic resulted 90% of the times in nutsedge control similar to that for MBr + Pic. Similarly, Gilreath et al. (2006b) reported that fumigation with 1,3-D + Pic and napropamide improved weed control and early and total strawberry yield in relation to the non-fumigated control.

## Application Methods and Mulches

One of the advantages of MBr is that when applied under a wide range of soil textures, moisture levels, temperatures, and depths, it keeps its relatively high efficacy on soilborne pests. However, MBr alternatives, such as 1,3-D + Pic, are less flexible with regard to application methods and conditions needed to enhance efficacy. Most commercial applicators use gas knives, chisel plows, large sweeps, and S-shape tine harrows, or combinations of these, that deliver the fumigants in-bed before mulching. For this application, much hand labor is required and personnel must wear personal protective equipment to avoid fumigant exposure. This protective equipment is uncomfortable and cumbersome, especially in Florida's warm weather. This situation encouraged researchers to study closely the possibility of broadcast fumigants, because it would reduce worker exposure to these products.

Another important aspect that could develop from broadcast fumigant applications is increased pest exposure to lethal gases. An effective dosage of a fumigant results from the combination of a relatively high fumigant concentration over an extended duration of exposure. Based on this principle, research was conducted to study the effect of incorporation depths and application methods on 1,3-D + Pic performance against soilborne pests. Gilreath et al. (2004a) compared the efficacy of in-bed and broadcast applications of 1,3-D + Pic in combination with the herbicides pebulate and napropamide in fresh-market tomato and determined that both application methods were equally effective to reduce populations of nutsedge, stunt, sting and root-knot nematodes, and fusarium wilt. Other research has indicated that there were no significant differences between the broadcast application of 1,3-D + Pic and MBr + Pic for fresh-market tomato plant vigor, height, and yields, as well as nutsedge, stubby-root and root-knot nematode control (Gilreath et al., 2005a and 2006a). Other studies have revealed similar findings in fresh-market tomato, bell pepper, and strawberry (Chellimi et al., 2001; Eger, 2000; Locascio and Dickson, 2000; Mirusso et al., 2002).

One of the advantages of drip-application of 1,3-D + Pic is that it reduces production costs by relying on the same drip irrigation lines that are used for fertigation. Most vegetable crops are grown with drip irrigation on beds covered with high-density polyethylene (HDPE) mulch. In Florida sandy soils, the emusifiable formulation of 1,3-D + Pic is usually applied at rates between 15 and 30 gal/acre, and typical dilution rates are between 500 and 1500 ppm (Dow AgroSciences, 2006). Previous studies have demonstrated that this formulation is as effective as MBr + Pic to reduce nematode populations (Gilreath et al., 2005c).

Previous studies proposed that fumigant activity against soilborne pests can be enhanced by using highly retentive mulches, such as virtually impermeable films (VIF) and metalized mulch. These could increase duration of relatively high fumigant concentrations of vapors under the mulch to allow more exposure of soilborne pests to lethal concentrations and for better lateral distribution into the soil (Gilreath et al., 2005d; Minuto et al., 1999; santos et al., 2005a). Desaeger et al. (2004) showed that 1,3-D + Pic vapors enhance significant soilborne pest control beyond wetted fronts. Soil texture plays a significant role in fumigant distribution throughout planting beds. However, fumigant lateral movement is limited in Florida spodosols, resulting in both leaching and volatilization through the mulch and hence poor nutsedge control on bed shoulders (Desaeger et al., 2004; Gilreath et al., 2003). With regard to lateral movement of 1,3-D + Pic in sandy soils, Gilreath et al. (2003) tested the effects of soil moisture status on lateral movement by applying the fumigant in both saturated soil (20% moisture) and at field capacity (7% moisture), obtaining the highest cross section coverage (90 and 94% at 8 and 10 hours after application) with saturated soil. In soils at field capacity, the maximum cross section coverage was 82%, with nearly no fumigant coverage on bed shoulders.

Most of the mulch research has focused on fumigant retention and field performance against soilborne pests. For instance, a study showed that paper mulch appeared to be a valuable alternative to control *C. rotundus* with no fumigants (Gilreath et al., 2004f). However, with high-volatility fumigants, such as 1,3-D + Pic, it was ineffective. One aspect consistently proven by research has been the lack of homogeneity among VIF, partly because there is not an international standard to classify these mulches according to their fumigant retention and handling properties. Although there is general agreement on the improved fumigant retention of VIF and metalized mulches, reports might have slightly different conclusions depending on film manufacturers. For both MBr + Pic and 1,3-D + Pic, the addition of VIF and metalized mulches reduced field rates and improved fumigant retention, therefore increasing the chances for exposing soilborne diseases, nematodes, and weeds to lethal doses (Gilreath et al., 2005e, 2005f, 2006c; Santos et al., 2005b and 2006).

## Summary

The last decade of MBr-alternative research in Florida has demonstrated that there is no definitive one-to-one replacement for this fumigant for controlling soilborne disease, nematodes, and weeds. Because of the intense pest diversity and pressure in Florida's subtropical climate, combining the activity of several active ingredients and improving fumigant retention in the soil with mulches appears to be the best approach. Noling et al. (2006) recommended using 1,3-D + Pic in tomato, bell pepper, eggplant, and strawberry in combination with herbicides and high-retention mulches to control soilborne pests. Although significant progress has been made since the beginning of the 1990s, growers should continue testing these MBr alternatives in their own conditions to determine the best fumigation programs for their farms.

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