Alternatives to methyl bromide in strawberry production in the United States of America and the Mediterranean region

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Summary. Methyl bromide (MB) is a broad-spectrum soil fumigant, which has been critical in strawberry production for forty years. Strawberry and other high-value cash crops benefit from pre-plant soil fumigation with MB and chloropicrin (Pic). Mixtures of these two fumigants work synergistically in controlling a wide range of plant pathogens and pests, including fungi, nematodes, insects, mites, rodents, weeds, and some bacteria. Methyl bromide was listed in 1993 by the Parties of the Montreal Protocol as an ozone-depleting compound. According to the Montreal Protocol, the import and manufacture of MB in the United States of America (USA) and other developed countries will be banned by 2005, after stepwise reductions in 1999, 2001, and 2003. Currently, there is no single registered alternative fumigant for all of the MB uses and there is a need for environmentally sound and economically feasible alternatives. The fumigants 1,3-dichloropropene (1,3-D) and Pic in combination with methyl isothiocyanate (MITC) generators have shown to be the most promising alternatives to methyl bromide for strawberry production. Studies with the experimental fumigants methyl iodide and propargyl bromide suggested that these compounds have higher reactivity than MB as stand-alone fumigants. This review evaluates the commercially available and experimental alternatives to MB soil fumigation for strawberry production based on relevant scientific publications, proceedings, and personal communications.

Key words: chloropicrin, 1,3-dichloropropene, methyl isothiocyanate, iodomethane, soil solarization.

Introduction

Within several areas in the United States of America (USA) and many Mediterranean countries, intensive cropping systems have been developed where high-value crops, such as strawberry (*Fragaria*×*ananassa* Duch.), are replanted at a high plant density on the same ground. These continuous cropping systems caused a frequent build-up of detrimental biological factors in the soil that can substantially reduce yield and crop quality. Subsequently, growers have widely used methyl bromide (MB) as a pre-plant soil fumigant because it effectively and economically controls weeds, pests, and soilborne pathogens (Tacconi *et al*., 1989).

In 1992, MB was included in the list of ozone-depleting substances by the parties of the Montreal Protocol (Table 1). In 1993, the U. S. Environmen-

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tal Protection Agency (EPA) classified MB as a Class I Stratospheric Ozone Depleting Substance (USEPA, 1993; Ristaino and Thomas, 1997). In 1998, the USA passed federal legislation to alter the Clean Air Act which required the phase-out of MB on the same schedule as the signatory countries of the Montreal Protocol (USEPA, 2002).

The European Community (EC, now EU, European Union) regulations that were signed by all 15 Member States (i.e., 3094/94/EC and 2037/00/EC) and that came into force on October 1, 2000 are more stringent than those in the original Montreal Protocol (Table 2). The EU regulations required an earlier and greater reduction in MB consumption than the Montreal Protocol. Further, the EU treaties mandate minimum qualifications for the fumigators, ban the sale of MB in disposable containers, limit the amount of MB that can be applied for quarantine and pre-shipment, strictly control any further uses of MB (so-called "critical

Table 1. Control measures on methyl bromide production and consumption adopted by the meetings of the parties to the Montreal Protocol (Gullino *et al*., 2003).

Meetings of parties	Developed countries (baseline, 1991)	Developing countries (Baseline, avg. 1995–1998)
4th (Copenhagen, 1992)	Freeze by 1995[a]	——
7th (Vienna, 1995)	25% reduction by 2001 50% reduction by 2005 100% reduction by 2010	Freeze by 2002[b]
9th (Montreal, 1997)	50% reduction by 2001 70% reduction by 2003 100% reduction by 2005[a,b]	20% reduction by 2005 100% reduction by 2015[a,b]

[a] Quarantine and preshipment uses of MB exempted.
[b] Possible exemption for critical uses.

Table 2. Methyl bromide production and use phaseout schedules under the EU Regulations 3093/1994 and 2037/2000 (Gullino *et al*., 2003).

EU regulation	Control measure[a]	
	Nonquarantine and preshipment	Quarantine and preshipment
3093/1994	Freeze on production and consumption by 1995 25% reduction by 1998	Exempted
2037/2000	25% reduction on production and consumption by 1999 60% reduction by 2001 75% reduction by 2003 100% reduction by 2005[c] Mandatory application of VIF when MB is used for soil fumigation	Freeze on consumption by 2001[b]

[a] Baseline: production and consumption levels of 1991.
[b] Baseline: average consumption levels of 1996–1998.
[c] Possible exemption for critical uses.

uses") after phase-out, and require annual progress reports on the development of MB alternatives for all uses (Batchelor, 2001, 2002).

Although the total phase-out of MB consumption in developing countries is scheduled for the year 2015, the EU MB consumption for all major uses is scheduled to be phased-out on January 1, 2005, at the same final phase-out date as that targeted in the Montreal Protocol (Table 2). The EU regulations require a 25% reduction of MB use in 1998 (one year earlier than under the Montreal treaty), a 60% reduction by January 1, 2001 (10% more than under the Montreal treaty), and a 75% reduction by January 1, 2003 (5% more than the Montreal treaty). After December 31, 2004, no further consumption of MB is allowed in the EU excluding critical and essential uses. Any stocks of MB have to be used by December 31, 2005, whereas the Montreal Protocol permits their use for a longer time period (as authorized by local authorities).

Approximately 20,000 metric tons of MB are applied annually to soils in the United States, making it one of the most used pre-plant pesticide in the country. In 1997, MB use in two states (California, 42%; Florida, 36%) accounted for about 80% of the total USA consumption. In California and Florida, most of the MB (83%) was applied as a pre-plant soil fumigant, of which 69% was used for high-value crops such as strawberries, tomatoes, peppers, melons, grapes, ornamentals, and nurseries (Ristaino and Thomas, 1997). These figures do not take into consideration the amount of MB consumed for post-harvest and quarantine.

In the USA, the importation of MB was frozen at 25,528 metric tons, the 1991 production and importation level. A 32% reduction to 17,425 metric tons MB occurred by 1999 (USEPA, 2002) and a 70% reduction was required in 2003. In California alone, the MB use decreased from the 1995 level of 7,786,310 kg to 3,000,881 kg in 2001, of which 57% was attributed to strawberry nursery and fruit production.

In 2001, about 8,514 metric tons of MB were consumed in the EU, mainly by Italy, Spain, Greece, France, Belgium, Portugal and the United Kingdom (Batchelor, 2002). Italy was ranked first in Europe and second in the world after the USA for the consumption of MB (Gullino and Clini, 1997). About 60% of the applied MB in the EU is consumed by strawberry, tomato and cucurbit production. The remaining 40% of the MB is consumed by peppers, eggplants, cut-flowers, and tobacco (Anonymous, 2002). Strawberry production consumes the largest amounts of MB in Spain using 800 and 237 metric tons for fruit and runner plant production, respectively (López-Aranda *et al*., 2002a, b). A survey conducted in 2000 on the implementation of MB alternatives found that 86% of the agricultural MB uses in Spain had potential alternatives, with the exception of strawberry nurseries (Batchelor, 2002). France reported a reduction in MB use in quarantine and preshipment uses to 750 metric tons. These reductions were due to a ban of MB in sensitive crops such as lettuce, and increasing percentage of soilless production methods (i.e., on substrate materials such as peat, coconut fiber, grape bagasse compost or compost cork) (Batchelor, 2002). Italy consumed 3,700 metric tons of MB in 2001, over 50% less than the amounts (more than 7,600 metric tons) applied in 1995 (Gullino *et al*., 2003). About 94% of MB currently consumed in Italy is used for preplant soil fumigation (Gullino *et al*., 2003). The largest use is in southern Italy (89%) including 56% in Sicily where horticultural production is more intensive. More than 75% of the MB used for soil fumigation in Italy is consumed by tomatoes (43%), strawberries (17%), and between 7 and 8% each by melon, eggplant and ornamentals (Gullino *et al*., 2003). Nonetheless, it is expected that more than 96% of the MB consumption in agriculture will be replaced by an alternative by 2005 (Batchelor, 2002). The survey further reported that in 2000, about 30% of the MB users in Italy were applying alternatives. In Portugal, about 220 metric tons of MB were applied in 2000, 45% of it to strawberries (Batchelor, 2002). By the end of 2005, it is expected that more than 90% of the current MB users in Portugal will be employing alternatives. Although more than 90% of users in the United Kingdom are expected to apply MB alternatives, only 3% of them were using alternatives in 2000 (Batchelor, 2002). The slow response of users in the UK is mainly related to a lack of registration of alternative chemicals, especially for food facilities and flour mills.

Methyl bromide consumption in Belgium decreased from 312 metric tons in 1991 to 33 metric tons in 2001, mainly due to the adoption of substrate culture techniques (Pauwels, 2002). Unfortunately, no complete information was available from Greece. In contrast, Turkey has increased the MB consumption from 643 metric tons in 1990 to 1,319 metric tons in 1998 (Yücel *et al*., 2002). However, a project has been initiated in the year 2000 to introduce chemical or non-chemical alternative methods into strawberry and vegetable crop production in Turkey (Benlioglu *et al*., 2002).

Methyl bromide alternatives in the USA

Chemical alternatives to methyl bromide in strawberry production

Strawberry plants are susceptible to nematodes such as root-knot, foliar, stem, and lesion nematodes (Bleve-Zecheo *et al*., 1980; Tacconi and Lamberti, 1987) and soilborne pathogens such as *Phytophthora cactorum*, *P. fragariae*, *Verticillium dahliae*, and *Colletotrichum acutatum*. The use of biocidal chemical compounds such as MB has long been regarded as a necessary pre-planting practice for strawberries and other small fruits, vegetables, orchards and nursery stock. Soil fumigation is a central tool in the strawberry production system because soil disinfestations maximize yield and fruit quality (Duniway, 2002a, b). Currently, only three MB alternative fumigants are registered and available for strawberry fruiting fields, and intensive research is being conducted to optimize application technologies to improve the performance and to reduce the cost. The registered chemical alternatives are chloropicrin (Pic), 1,3-dichloropropene (1,3-D), and methyl isothiocyanate generators such as metam sodium and Dazomet (Lamberti *et al*., 2003a). The chemical structures of MB and chemical alternatives are summarized in Figure 1. Although the alternative fumigants can be applied into soil by shank injection, new technologies were developed recently to apply fumigants through the drip irrigation systems (Ajwa and Trout, 2000; Ajwa *et al*., 2001; Ajwa *et al*., 2002a, b).

Despite the progress made in the search for chemicals that can replace MB, further research is required to ensure an economically and ecologically sound production of strawberries and other crops. Non-registered potential chemical MB alternatives are iodomethane (methyl iodide), propargyl bromide, sodium azide, and PlantPro (Fig. 1) that are currently being evaluated for their efficacy to control pathogenic fungi, bacteria, nematodes, and weeds.

Chloropicrin (trichloronitromethane). Chloropicrin (Pic) has been used as a pre-plant fumigant to suppress fungal pathogens in strawberry fields for many years (Wilhelm and Koch, 1956; Wilhelm and Pavlou, 1980) and as a warning agent for odorless fumigants such as MB (Awuah and Lobeer, 1991). Pic may also be used to control nematodes, bacteria, insects and weeds. Pic, although an irritant, is not an ozone depleting compound, it degrades in soil into safe byproducts, and has a very short half-life relative to MB and other alternative fumigants. Several field trials suggested that the average half-life of Pic is as little as one day (Ajwa *et al*., 2002a). Selected physical and chemical properties of Pic and other MB alternatives are summarized in Table 3.

Pic shank injected at 336 kg ha^{-1} produced strawberry yields equivalent to a MB + Pic treatment (Duniway *et al*., 2001, Duniway, 2002a). However, this rate was not effective in controlling weeds. Pic applied by drip fumigation at 336 kg ha^{-1} produced equivalent yields to the standard MB + Pic fumigation (Ajwa and Trout, 2000), and provided sufficient weed control (Fennimore *et al*., 2003a). Also, a Florida study using 336 kg ha^{-1} Pic resulted in strawberry yield levels equivalent to the standard 393 kg ha^{-1} MB + Pic (67:33) rate. These and other studies suggest that a stand-alone rate of 336 kg ha^{-1} Pic or higher might be required for effective control of pathogens and weeds. Under certain conditions, weed growth stimulation has been reported following relatively low Pic soil application rates (112–168 kg ha^{-1}) (López-Aranda *et al*., 2000; Motis and Gilreath, 2002). The drawbacks of Pic are (1) its strong odor which makes it unpleasant to handle (Anonymous, 1992), and (2) its slower dispersion into and evaporation from the soil relative to MB (Smelt and Leistra, 1974), which require longer waiting periods before planting to prevent phytotoxicity problems.

1,3-dichloropropene. The fumigant 1,3-dichloropropene is an effective nematicide with fungicidal properties, which has been used as a stand-alone fumigant (Telone II, 94% 1,3-D) (Lamberti and Noling, 1998; Lamberti, 2001; Lamberti, unpublished) or in combination with 17% (Telone C17,

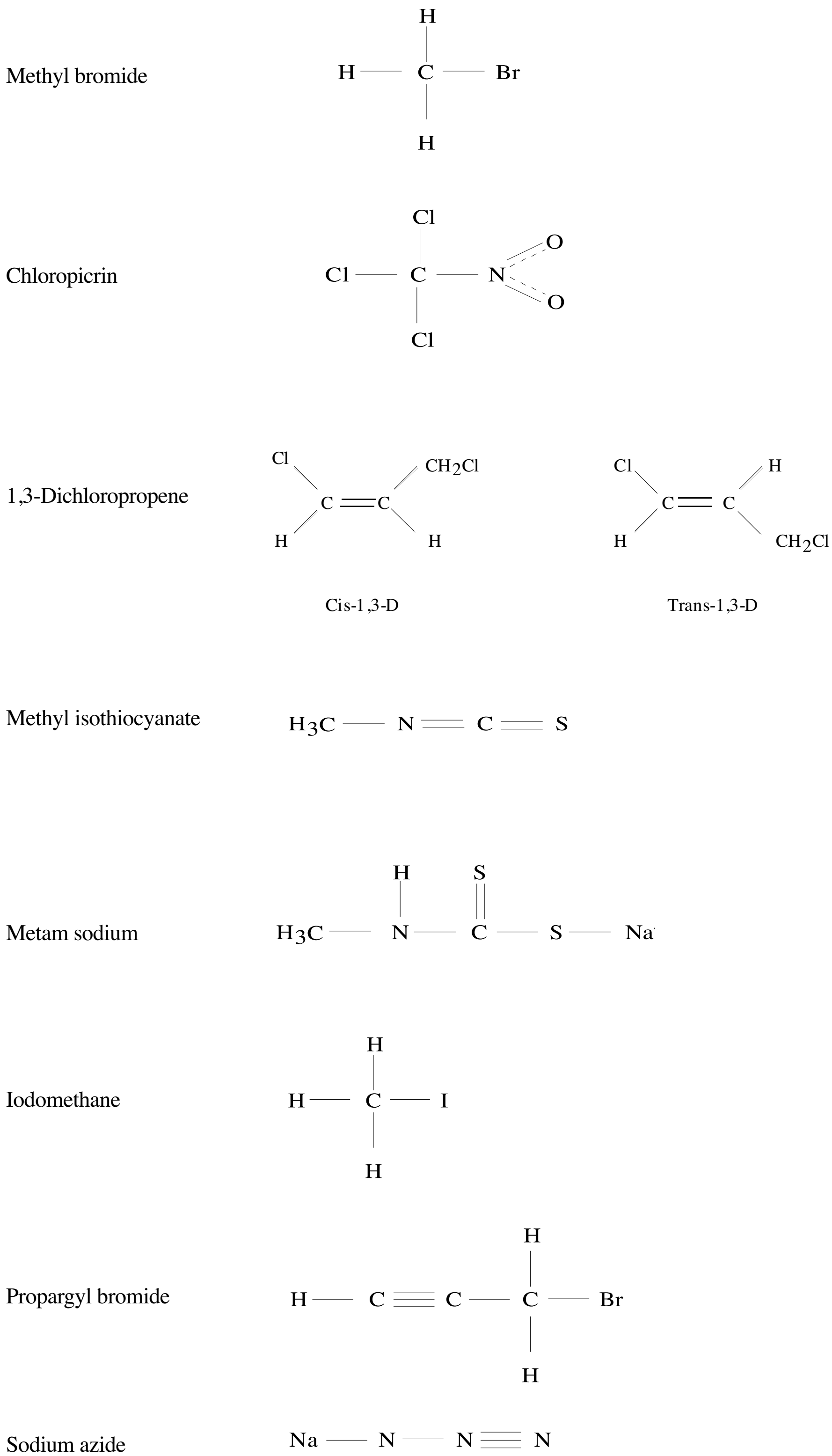

Fig. 1. Chemical structure of methyl bromide and selected alternative fumigants.

Dow AgroSciences, Redeck, North Carolina, USA) or 35% Pic (Telone C35, InLine, Dow AgroSciences). The combination with Pic improves the control of replant and soil-borne diseases such as *Verticillium* wilt and *Phytophthora* root rot. Telone is applied as a broadcast shank-injected treatment requiring subsequent surface compaction of shank traces. This treatment is followed by soil surface covering with polyethylene tarps. Bed fumigations that were covered with plastic tarp after Telone C17 treatment improved pathogen control in Florida compared to broadcast applications without tarp (Noling, 2002). Yields equivalent to standard 67:33 MB + Pic (393 kg ha^{-1}) were obtained in Florida when Telone C35 was applied to beds with the added benefit of nut sedge emergence control. However, Mirusso *et al*. (2002) reported that soils in their second and third consecutive production cycles were not experiencing reduced pathogen control efficacy in untarped broadcast applications of Telone C35 (187 kg ha^{-1}) followed by bed applications of Pic (134 kg ha^{-1}). Due to a relatively lower vapor pressure and higher boiling point of 1,3-D compared to MB (Table 3), the application of emulsified formulations of this fumigant through the drip irrigation system has been shown to be more effective and safer than traditional shank injection (Ajwa *et al*., 2002a).

InLine (an emulsifiable concentrate of Telone C35) has been used commercially for strawberry production for the last two years. InLine has shown high effectiveness in controlling soil-borne pathogens and many weeds. It is predicted that the use of this fumigant will increase in the USA in the near future (Ajwa *et al*., 2002a). Recent studies to optimize application rates of Pic and InLine found that a minimum of 336 kg ha^{-1} (based on actual treated area) is needed to maintain fruit production equivalent to MB + Pic fumigation (Ajwa *et al*., 2003). Although these studies found that the use of virtually impermeable film (VIF) did not significantly increase yields (<6%), weed control greatly benefited from VIF and was achieved at low fumigant application rates (110 to 220 kg ha^{-1}) equivalent to MB + Pic (Fennimore *et al*., 2003b). The use of VIF may reduce some of the restrictions that limit the use of 1,3-D in California. These restrictions include that the applicators are required to wear protection equipment that can be challenging during periods of high temperature and humidity (California DPR, 2002). Further, California law requires a limit on the total amount of 1,3-D applied within 93 km square townships and the use of a 33-m buffer zone (Messenger and Braun, 2000). Such restriction will reduce the strawberry land that can be fumigated with 1,3-D to 67% (Trout, 2003a).

Methyl isothiocyanate. The biocide methyl isothiocyanate (MITC) has been used as a soil fumigant for decades. Several MITC generators have been applied in aqueous solution (Lamberti *et al*., 2002) such as metam sodium (sodium N-methyl dithiocarbamate) or in granular formulations such as Dazomet or Basamid (tetrahydro-3,5-dimethyl-2H-1,3,5-thiadiazine-2-thione). Metam sodium (MS) may be used to control pathogenic fungi, nematodes, insects and weeds, although it is most efficacious in controlling weeds (Messenger and Braun, 2000). MS has been used on a limited scale for many years in California as a stand-alone strawberry fumigant even though its effectiveness is restricted to about a 10-cm sphere from the injection point (Smelt and Leistra, 1974; McGovern *et al*., 1998). Conventional application methods do not provide a uniform distribution of this fumigant in soil due to a lower vapor pressure and higher boiling point than MB (Table 3) and consequently, lower penetration capacity (Gullino, 1992). Current interest in research is focused on the improvement of the application equipment to enhance metam sodium diffusion into the soil. Metam sodium does not control root-knot nematodes, *Fusarium* and *Verticillium* spp. as well as MB (Anonymous, 1993a). Besides poor distribution of the fumigant in the soil, control failures were also caused by an increased dominance of microorganisms that are able to degrade metam sodium (Smelt *et al*., 1989). Dazomet is a cost-effective fumigant to successfully control weeds, nematodes and fungal pathogens (Anonymous, 1989; Harris, 1990). Likewise, Dazomet can have soil dissipation inconsistencies if not thoroughly mixed with the soil. However, correct Dazomet placement in soil, correct concentration, and controlled uniform sprinkler application to activate the product are crucial for successful soil fumigation and to avoid phytotoxicity. In order to improve fumigant distribution within the soil, large quantities of carrier water are needed (Lamberti *et al*., 2002), increasing the risk of

Table 3. Selected physical and chemical properties and biological activity of methyl bromide and chemical alternatives (adopted from Ajwa *et al*. 2002 and Gullino *et al*., 2003).

Soil fumigant[a]	Water solubility 20°C % (w:w)	Vapor pressure 20°C mm Hg	Boiling Point (°C)	Henry's constant (K_H) air/water	Diffusion in soil	Half-life in soil (days)	Biological activity	Performance[d]
Methyl bromide	1.34	1420	4	0.244	Very good	22	Fungicide, nematicide, herbicide	Very good
Chloropicrin	0.20	18	112	0.093	Good	1	Fungicide, nematicide	Very good
1,3-Dichloropropene	0.22	34	104	0.056	Good	11	Nemadicide	Very good[e]
Methyl isothiocyanate	0.76	13	119	0.011	Good	7	Fungicide, herbicide, (nematicide)	Fair
Iodomethane	1.40	400 (at 25°C)	42	0.21	Very good	20[b]	Fungicide, nematicide, herbicide	Very good
Propargyl bromide	1.49	72	88	0.046	Good	5	Fungicide, nematicide, herbicide	Excellent
Sodium azide	41.7	NA[c]	NA	NA	Fair	3	Fungicide, nematicide, herbicide	Fair

[a] Methyl bromide (CH_3Br); chloropicrin (CCl_3NO_2), 1,3-dichloropropene ($C_3H_4Cl_2$); methyl isothiocyanate (C_2H_3NS); iodomethane (CH_3I); propargyl bromide (C_3H_3Br); sodium azide (NaN_3).
[b] Half-life was estimated from three studies and ranged between 4 and 43 days.
[c] Not applicable, crystalline compound.
[d] For stawberry production systems.
[e] When combined with chloropicrin (60% 1,3-D + 35% Pic) as Telone C35, InLine, or Telopic.

groundwater contamination (Kim, 1988; Anonymous, 1992). Limitations in the use of this fumigant are also related to the fact that Dazomet requires a 60-day re-entry period in cool climates to prevent phytotoxicity symptoms (Anonymous, 1993b).

Iodomethane. Iodomethane (IM) (methyl iodide) has the potential of serving as a viable replacement for MB. Although, it has a vapor pressure of 400 mm Hg which is less than that of MB (Table 3), it still expresses a good soil diffusion activity (Ohr *et al*., 1996; Eayre *et al*., 2000). Iodomethane can be applied with popular soil fumigation equipments, providing a broad-spectrum pathogen control, and having the advantage of being a non-ozone depleting compound. Presently, it has been tested as a replacement for MB in strawberry (Ajwa *et al*., 2002a), carrot (Hutchinson *et al*., 1999) and peach production systems (Eayre *et al*., 2000). When applied at an equivalent weight, IM + Pic were found to be more effective than MB + Pic in strawberry production in California (Ajwa *et al*., 2001). Product registration by the USEPA is expected by 2004, and the California registration by 2005.

Propargyl bromide. An increase in the stability of propargyl bromide (PB) in soil stimulated further research of its potential to serve as an alternative soil fumigant. PB expressed fungicidal, nematicidal and herbicidal activities and excellent distribution characteristics in soil (Table 3). Ajwa *et al*. (2001) applied 67 kg PB ha^{-1} by shank or drip injection into strawberry production fields in California and reported yields equivalent to the common broadcast MB + Pic (67:33, 308 kg ha^{-1}) treatment applied by local growers. Increasing the application rate of PB from 134 to 179 kg ha^{-1} improved yields by 20% above the standard MB + Pic treatment. Further increases in drip application rates to 202 kg PB ha^{-1} in strawberry production resulted in improved weed control relative to the MB + Pic treated plots. A minimum of 134 kg ha^{-1} for adequate pathogen control was suggested for PB (Ajwa *et al*., 2001). The half-life of PB in different soils ranged between 1 and 7 days (Yates and Gan, 1998; Ma *et al*., 2001) and was averaged at 5 days (Table 3). Presently registrations for this product are not available and it is likely that much more information will have to be gathered about this potentially effective fumigant before it can become available as a registered soil fumigant.

Sodium azide. Sodium azide (NaN_3) mixed with a carrier/stabilizer can be injected into irrigation lines prior to water distribution into drip tapes. At pH 9 or higher, NaN_3 is stable. A major drawback of NaN_3 is the poor diffusion properties of this chemical when applied as a fumigant in soil (Table 3). Below pH 8, NaN_3 is converted to hydrazoic acid (HN_3), an effective biocide. Formulations being tested keep the material stable at high pH until it enters the root zone. Some studies suggested that NaN_3 can be used for control of soilborne pathogens, nematodes, and weeds in vegetable crops and cotton production (Rodriguez-Kabana 2001a, b; Rodriguez-Kabana and Abdelhaq, 2001; Rodriguez-Kabana and Robertson, 2001; Rodriguez-Kabana *et al*., 2003). However, recent field evaluations of NaN_3 applied through the irrigation systems in combination with other alternative fumigants for strawberry production in California reported that a minimum of 200 kg NaN_3 ha^{-1} is required for an adequate pathogen control in the root zone (Ajwa, work in progress).

PlantPro. PlantPro is an iodine-based product that has been tested in field trials for strawberry and tomato production in California and Florida. Due to its experimental character, no detailed information on physical and chemical properties of this fumigant is currently available. Although this compound provided an adequate control of fungal pathogens and parasitic nematodes in tomato production, it was unable to effectively control *Verticillium* wilt in strawberry production at rates of 655 l ha^{-1} (168 kg active ingredient, a.i.) (Ajwa, work in progress). In some soils, phytotoxicity caused by residual iodide may limit the use of this product for strawberry systems (Norton, 2003). Currently, research is being conducted to evaluate different application methods that will support a faster dissipation of iodide from the soil.

Recent studies in several regions in California, USA, showed that drip application of Pic (336 kg ha^{-1}), InLine (448 kg ha^{-1}), PB (202 kg ha^{-1}), and a mixture of IM + Pic (224 + 224 kg ha^{-1}) produced strawberry yields equivalent or higher than MB + Pic (390 kg ha^{-1}) shank fumigation. The performance of sodium azide (224 kg ha^{-1} a.i.) or PlantPro (168 kg ha^{-1} a.i.), however, resulted in inconsistent and lower yields than the MB + Pic treatment (Fig. 2). Higher application rates of these two chemicals might be needed to control the high disease pressure, especially by *V. dahliae* in these soils.

Browne *et al*. (2003) evaluated the efficacy of fumigants to control *P. cactorum* in these soils and found that PB (200 kg ha^{-1}) was the most effective in eradicating the pathogen and exceeding the performance of MB + Pic. IM + Pic was similar in effectiveness to MB + Pic. Inline and Pic approached or matched the performance of MB + Pic when conditions were optimal, but were less effective under suboptimal conditions. However, Na-Azide and PlantPro were not effective in either of two trials for control of the pathogen.

Other chemical alternatives are being evaluated for crop production. Fosthiazate, Multiguard (active ingredient, furfural) (Agriguard Company LLC, Cranford, New Jersey, USA), and Propozone (propylene oxide, C_3H_6O, Aberco Inc., Seabrook, Maryland, USA) were included in the USDA-IR-4 programs as potential alternatives (Norton, 2003). Ethanedinitrile (C_2N_2) (Mattner *et al*., 2003; Ren *et al*., 2003), dimethyl disulfide (CH_3SSCH_3) (Charles, 2003; Gillis, 2003; Rodrigues-Kabana,

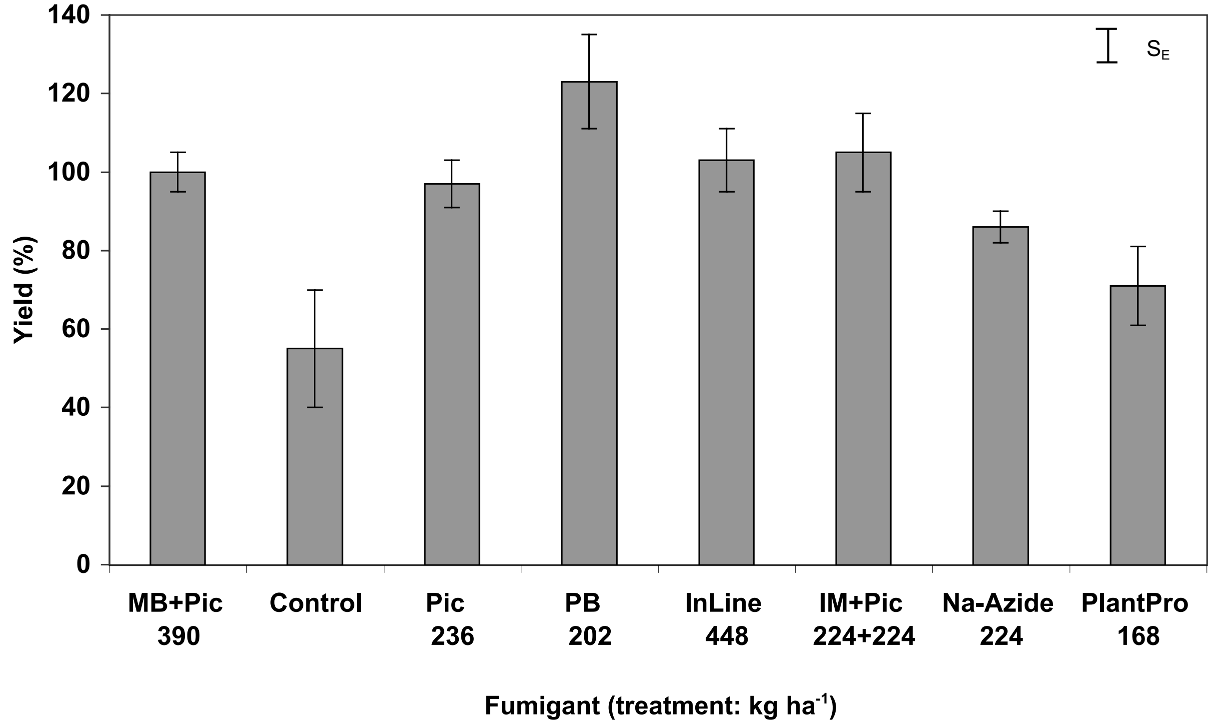

Fig. 2. Total strawberry yields from drip fumigation with alternative fumigants relative to standard MB + Pic (390 kg ha^{-1}) (87.9 t ha^{-1}) fumigation. Values are averages of data collected from two regions in California, USA, over a 2-year study period with the exception of sodium azide and PlantPro which are averages of data collected over a 1-year. Abbreviations: MB, methyl bromide; Pic, chloropicrin; PB, propargyl bromide; IM, iodomethane; Na-Azide, sodium azide; S_E, standard error.

2003) are also being tested. Recent studies suggested that that acrolein [2-propenal (CH2=CH-CHO, acrylaldehyde)] is a potential alternative to methyl bromide for soil fumigation (Rodriguez-Kabana *et al*. 2003). These studies found that acrolein applied at 50 mg kg^{-1} effectively controlled the reniform nematode (*Rotylenchulus reniformis*) in greenhouse experiments. When applied as post-emergence at >200 mg kg^{-1}, acrolein eliminated yellow nutsedge (*Cyperus esculentus*). However, little is known about the efficacy of these fumigants against the various soilborne pathogens and weeds. Even though there is potential for optimism regarding MB replacement, only Pic, 1,3-D, and metam sodium are currently registered alternative fumigants in the USA, Italy and Spain that hold potential as efficacious replacements for MB in strawberry production. In order to improve the activity of fumigants towards pathogenic fungi, nematodes and weeds, they will likely be used in a combination.

Economic feasibility of registered methyl bromide alternative

Due to the high value of strawberries, growers found it more profitable to continue to use methyl bromide than to move to an alternative, even though the price of methyl bromide has increased. Recently, the California Strawberry Commission published an economic feasibility studies of currently registered alternatives to methyl bromide for California strawberry producers (Goodhue *et al*., 2003). These study restricted the attention to the costs for weed control, tarp, and chemical material for the registered MB alternatives (Pic and 1,3-D) applied by shank or the drip irrigation system, and metam sodium applied by the drip irrigation system. Fumigant, tarp, and weeding costs were compared for Pic applied by shank or drip, Pic applied with or without metam sodium, 1,3-D applied by shank or drip, and 1,3-D applied with or without metam sodium.

With the exception of shank-applied Pic, alternative fumigants resulted in higher costs of fumigation materials plus weeding labor than methyl bromide at costs prior to 1998. Total costs (weeding, plastic mulch, and fumigant costs) for the alternative fumigants relative to methyl bromide cost of 1998 were 130% for Pic drip-applied, 144% for InLine drip-applied under black VIF, 99% for Pic shank-applied, and 133% for Telone shank-applied. Metam sodium reduced the weeding cost and did not increase the total costs relative to MB + Pic. However, about 10% of the California strawberryland was drip fumigated with InLine (alone or with metam sodium), and 15% is expected in 2003 (Trout, 2003b). Drip applied Pic (alone or with metam sodium) is expected to be about 10% of strawberry land in 2003.

Methyl bromide alternatives in the Mediterranean region

Chemical alternatives to methyl bromide for strawberry production

Worldwide, Spain is the second largest strawberry producer after the USA. Huelva is the most important agricultural region in Spain with about 8,000 ha cultivated (250,000 metric tons annually of fresh fruit production). Strawberry production consumes the largest amounts of MB in Spain and other European countries. The Spanish national project to find chemical, non-chemical, and mixed MB alternatives was initiated in 1997 (Medina *et al*., 2003). The treatments tested in a 4-year field trial in Huelva were (i) nonfumigated controls, (ii) MB + Pic (50:50) (current standard practice), (iii) annual shank-application of Telopic (Telone C35: 1,3-D/35% Pic mixture) or Pic under pre-formed raised beds (40 ml m^{-2} of treated area) and shank-application with half-dosage (20 ml m^{-2}) under VIF (Bromostop®, Industrial Plastica Monregalese, Mondovì, Italy) (Telopic + VIF), (iv) annual incorporation of Dazomet under pre-formed raised beds (50 g m^{-2}), and (v) soil solarization (Sol, 4 weeks, August) with simultaneous shank application of metam sodium (MS, 75 ml m^{-2}, broadcast area) (Sol + MS), and soil solarization (4 weeks, August) with simultaneous biofumigation (incorporated 4–5 kg m^{-2} fresh chicken manure, Biof) (Sol + Biof) (López-Aranda *et al*., 2002a, b). Telopic, Telopic + VIF and Dazomet showed very similar yields to MB, but lower yields were obtained in the Sol + MS plots. Potential productivity in the Sol + Biof treatment was similar to MB, except of the abnormal abiotic plant mortality observed on some farms (López-Aranda *et al*., 2002a). Phytotoxicity problems after manure application to control strawberry diseases in Spain were also reported by Cebolla *et al*. (1999).

The most promising and cost-effective short-term MB alternatives in the strawberry production systems in Spain were shank application of 1,3-D + Pic (Telopic) under polyethylene (PE) or VIF, Pic alone, Dazomet, solarization plus MB, solarization plus MS under shank application, and solarization plus biofumigation with chicken manure (Anonymous, 2002; López-Aranda *et al*., 2002b). However, the efficacy of these treatments varies with the quality of the soil preparation and chemical application technique.

Spain is the leading country in Europe in strawberry runner plant production (De Cal *et al*., 2002). Soil sterilization is essential for the production of disease-free runner plants in nurseries. Melgarejo *et al*. (2001) and De Cal *et al*. (2002) tested different MB + Pic combinations, Telone C-17, Telopic, Pic alone, Dazomet, metam sodium and metam potassium in high-elevation strawberry nurseries in central-northern Spain. Melgarejo *et al*. (2001) suggested that none of the tested treatments could efficiently replace MB in high-elevation strawberry nurseries in Spain. Difficulties arise from the geographic mobility of strawberry nurseries due to farm-leasing that could result in the establishment of nurseries on non-sterile soils, and from the winter period of fumigant treatments.

Melgarejo *et al*. (2001) argued that MB + Pic applications in strawberry nurseries in high elevations should be considered as a "critical use" case within the EU, especially since the evaluation of the efficacy of MB alternatives under these specific geographical and climatic conditions requires more time. De Cal *et al*. (2002), however, found that all treatments reduced the total number of fungal pathogenic colonies such as *Fusarium*, *Verticillium*, *Pythium* and partially *Rhizoctonia* and *Phytophthora*. These results demonstrated that Dazomet and 1,3-D + Pic (61:35) hold potential to efficiently replace MB at high-elevation nurseries in Spain. Furthermore, this study indicated the necessity to disinfest soil for runner-plant cultivation. Similar findings by Melgarejo *et al*. (2001) were suggested for this location as a "critical use" case of a MB + Pic (50 + 50) combination after 2005.

Cebolla (2002) evaluated two 1,3-D-Pic combinations (32.7 and 52.8%), double treatment with 1,3-D followed by metam sodium, Basamid (Dazomet, an MITC generator), manure, solarization plus manure, metam sodium or ammonium fertilizer at strawberry production locations in the Valencian province, Spain. The 1,3-D + Pic mixtures performed well if application technique and soil preparation was done cautiously, except on heavy soils that tend to have compaction difficulties. Basamid and metam sodium application resulted in less efficient pathogen control than MB, probably due to a poor distribution of the fumigant in the soil.

Metam sodium is another alternative fumigant in strawberry production systems in Spain and for strawberry plant nurseries in France (Rabasse, 2002). Metam sodium applied at a rate of 1200 l ha^{-1} by drip irrigation sealed with PE film mulch or water resulted in a yield similar the MB treatment. The findings from this field trial are supported by results from commercial strawberry fields (Cebolla, 2002). A drawback of metam sodium is its limited diffusion in the soil, as previously discussed. Therefore, proper application techniques are crucial for a high-level efficacy of this alternative fumigant (Rabasse, 2002).

Recent studies by López-Aranda *et al.* (2003) evaluated several fumigant treatments (MB + Pic, dimethyldisulfide, propylene oxide, Dazomet, Telopic, and Pic alone) for fruit production and found that average yield and fruit weight obtained with Telopic and Pic alone were satisfactory and similar to those obtained with the standard MB treatment. Results with the other fumigants were unsatisfactory and inconsistent. However, Melgarejo *et al*. (2003) found poor efficacy with Telopic and inconsistent results with the alternative fumigants in nursery production. Lack of viable alternatives required Spain to submit applications for critical use exemption for the Spanish strawberry nurseries. In Spain, the registered fumigant alternatives to MB for strawberry and nursery are Dazomet, metam sodium, and 1,3-D + Pic (Telopic). Currently, the registration of Pic alone as MB alternative for the strawberry industry is being pursued in Spain.

In Italy, the registered fumigant alternatives to MB are Dazomet, metam sodium, 1,3-D and Pic (Lamberti *et al*., 2003a). Dazomet and metam sodium are registered for soil disinfestations purpose and have been used for many years in open fields and under greenhouse conditions (Lamberti *et al*., 2000b; 2003c). They are commonly applied by growers, unlike MB that requires authorized and skilled fumigators. Dazomet is generally applied as a granular formulation to the soil surface followed by mechanical soil incorporation. The liquid formulation of metam sodium is commonly applied by sprinkler irrigation systems without soil mulching. However, both Dazomet and metam sodium do not always provide complete disease control (Minuto *et al*., 1995, 2000). A higher efficacy of these fumigants is achieved by applying them under plastic films to minimize fumigant loss (Gullino and Clini, 1997, Gullino *et al*., 2002).

The compound 1,3-D has been registered for soil fumigation under greenhouse conditions in Italy since November 2001. A recent registration introduced to the Italian market of an 1,3-D emulsified formulation is suitable for application through drip irrigation systems. In July 2002, an emulsified formulation of Pic was registered for soil disinfestations. Contrary to the other alternative fumigants, Pic can only be used to fumigate soil subsequently cultivated with strawberry, tomato, eggplant, melon, watermelon and zucchini crops (Minuto *et al*., 2003). Currently, experiments are in progress to include the use of Pic on lettuce and ornamental crops.

The application of alternative fumigants through subsurface drip irrigation systems is the most practical and safest strategy for greenhouse conditions. Pesticide application by shank injection is limited due to the narrow working spaces in Italian greenhouses. However, the drip irrigation technology is becoming popular for greenhouse crops because it can easily be adapted to any greenhouse size. Moreover, drip fumigation has been demonstrated to reduce emissions when compared to shank injection (Gan *et al*., 2000). Furthermore, this technique does not require the presence of workers in the greenhouse, and thus reduces worker exposure.

Since 1995, MB application rate has been reduced in Italy due to the availability of VIF, which significantly reduces emissions and increases the efficacy of fumigants (Tacconi *et al*., 1998). After more than 8 years of experimental and commercial application, it has been shown that the commercial VIF has similar physical properties (i.e., thickness, resistance to high temperatures and mechanical stretching) as low-density polyethylene (LDPE) films (Gamliel *et al*., 1998). These improvements in film physical properties enable VIF to be used under harsh field conditions. Among the European countries, Italy probably has the highest percentage of MB use under VIF. In 2001, more than 2,500 ha have been fumigated adopting VIFs in strawberry, tomato, pepper, eggplant, basil, zucchini, melon, gerbera, rose and bulb crop production, thus resulting in a 50% reduction of MB use by decreasing the application rate. The use of VIF has been supported by several countries such as France, Spain, Belgium, and Israel (Cebolla *et al*., 1996; Gamliel *et al*., 1997, 1998).

Volatile nematicides, such as Fenemiphos or Oxamyl can be profitably used in Italy to control *D. dipsaci* (Vovlas *et al*., 1978). Both compounds prevented massive root invasion by root-knot nematode juveniles in tomato seedlings for 30 to 60 days (Lamberti *et al*., 2000c, 2003b).

In Israel, MS and Dazomet are intensively used as pre-plant fumigants to control various soil-borne pests and weeds in potatoes, peanuts and other crops (Di Primo *et al*., 2003). Common application rates range from 300 to 1000 l ha^{-1} (Ben-Yephet *et al*., 1983; Frank *et al*., 1986). The efficacy of Basamid (i.e., Dazomet, an MITC generator) was tested in arid and semiarid regions in Israel in fields with a history of infestation with soilborne pathogens (Gamliel *et al*., 2001). Basamid applied at 45 g m^{-2} was successful to control fungi and weeds under the tested climatic conditions when incorporated to a depth of 20 cm and covered by LDPE tarp. Fungi control by Basamid was insufficient when applied into deeper soil layers. However, improved pathogen control was achieved when Basamid was combined with soil solarization. Di Primo *et al*. (2003) reported that repeated applications of metam sodium resulted in decreased efficacy to control *Pythium myriothylum* and *V. dahliae*. These results are believed to be related to a rapid microbial degradation of the fumigant in soils with a history of metam sodium and Dazomet fumigation, leading to an enrichment of microbial populations in soils able to degrade pesticides. Similar results were reported previously from the Netherlands (Verhagen *et al*., 1996) and Australia (Warton and Matthiessen, 2000). In the latter study, the concentration of the active degradation products of metam sodium (i.e., MITC) decreased to undetectable levels after 7 h instead of 17 d in a non-history soil. The accelerated MITC degradation capacity of soils with a pre-exposure fumigant history was still evident for 18 to 30 months after soil fumigation (Di Primo *et al*., 2003). Among the several alternative fumigants tested in Israel, formaldehyde (liquid formulations), alone or in combination with MB, was evaluated to control bacterial diseases (Grinstein *et al*., 1996). However, formaldehyde use for soil fumigation may be restricted or banned because it is a potential carcinogenic compound (Jensen and Andersen, 1982).

In Turkey, the first MB alternatives trials for strawberry production were initiated in the year 2000 to meet Turkey's aims to phase out MB by 2008 (7 years earlier than required by the Montreal Protocol) (Yücel *et al*., 2001, 2002; Benlioglu *et al*., 2002). The MB alternatives that were studied were Dazomet (50 g m^{-2}) and metam sodium (100 ml m^{-2}) as well as combinations of solarization (3–7 weeks) with Dazomet (i.e., Basamid) at doses of 300, 400 or 500 kg ha^{-1}, chicken manure (1 ton ha^{-1}), cow manure (30–40 ton ha^{-1}) or *Trichoderma* spp. covered by plastic tarp. Soil solarization plus Basamid application at 400–500 kg ha^{-1} were able to suppress soilborne pathogens such as *Fusarium*, *Sclerotinia*, *Rhizoctonia* and *Macrophomina* spp., nematodes, and weeds over a 2-year experimental period (Yücel *et al*., 2002). Solarization alone or with *Trichoderma* spp. appeared to be an inexpensive method to control pathogens in strawberry production systems. Yields of strawberry and vegetables (peppers and eggplants) achieved with these treatments were equal to those achieved with MB (Yücel *et al*., 2002). However, all results are considered preliminary data due to the short-term character of the experiments.

Benlioglu *et al*. (2002) investigated the efficacy of (i) soil solarization (over 6 weeks), (ii) Dazomet mulched with PE film (50 g m^{-2} granular formulation applied with a granular sprayer, incorporated by a rototiller), (iii) metam sodium under PE (100 ml m^{-2} applied by drip irrigation), and (iv) untreated control at four commercial strawberry fields in the Mediterranean. The following two treatments were tested at one field (v) raised bed solarization (over 6 weeks) under PE film, and (vi) soil solarization (2 weeks) plus metam sodium under PE (50 ml m^{-2}) applied by drip irrigation. Preliminary results showed that raised bed solarization under black plastic mulch was the most effective alternative to MB for fruit production, soil sanitation, and costs. However, some weed species such as purple nut sedge (*Cyperus rotundus*) and horseweed (*Conyza canadensis*) and soilborne diseases of strawberry remained problematic in the Aydin province of Turkey (Benlioglu *et al*., 2002).

In Lebanon, Jordan, and Morocco, the most likely chemical alternatives to MB are 1,3-D, Pic, and MITC generators such as Basamid (i.e., Dazomet) applied through the irrigation systems (Besri, 2002). Basamid was evaluated for strawberries production in Lebanon. Much lower yields, however, were obtained with Basamid than with MB due to various biotic (e.g. edaphon) and abiotic factors such as soil type, soil temperature, soil moisture, organic matter content, soil pH, and concentrations of certain cations. The latter can affect the transformation rate of the fumigant into the active compound MITC, and its distribution characteristics in soil (Hafez *et al*., 2000). Metam sodium and 1,3-D were tested in combination with soil solarization for their impact on root-not nematodes, weeds and yield performance in strawberry production systems in Morocco. These combined treatments suppressed nematodes, and weed densities and resulted in fruit yield similar to MB (Ammati *et*

Table 4. Microorganisms linked to the degradation of methyl bromide and selected alternative fumigants in soil (Dungan and Yates, 2003).

Soil fumigant[a]	Organism	Description
Methyl bromide (MB)	*Nitrosomonas europaea*	Consumes MB in the presence of aluminum chloride
	Nitrosolobus multiformis	
	Methylloccus capsulatus	Oxidizes MB in the presence of methane
	Gram-negative aerobe	Utilizes MB as a sole carbon and energy source
Chloropicrin	*Pseudomonas* spp.	Successive reductive dehalogenations to produce nitromethane
	Pseudomonas putida PpG-786	
1,3-Dichloropropene (1,3-D)	*Pseudomonas* sp.	Capable of completely metabolizing *cis*- and *trans*-3-CAA[a]
	Rhodococcus rhodochrous NCIMB13064	Can utilize 1,3-D as a sole carbon source, and can also grow on 3-CAA and 3-CAAC[b]
	Pseudomonas sp.	Preferentially degrades *trans*-1,3-D
	Burkolderia cepacia CAA1	Grows on *cis*-3-CAAC
	Burkolderia cepacia CAA2	Grows on both *cis*- and *trans*-3-CAAC
	Pseudomonas cichorii	
	Alcaligenes paradoxus	Contain a *dhl*A-like gene, which is suspected of being involved in 1,3-D degradation
	Pseudomonas corrugata	
	Pseudomonas putida	
	Pseudomonas sp.	
	Pseudomonas pavonaceae 170	Can utilize low concentrations of 1,3-D as a sole carbon source, and can also grow on 3-CAA and 3-CAAC. Produces at least three different dehalogenases
	Rhodococcus sp. AS2C	Cometabolically degrades *cis*- and *trans*-1,3-D to *cis*-3-CAA and *cis*-3-CAAC, and *trans*-CAA and *trans*-CAAC, respectively
Methyl isothiocyanate (MITC)	*Bacillus* spp.	*Rhodococcus* spp. consortium enhanced the degradatation of MITC when spiked into sterile soil
	Unidentified spp.	

[a] CAA, chloroallyl alcohol.
[b] CAAC, chloroacrylic acid.

al., 2002). A drawback of these fumigants was that they undergo accelerated biodegradation after only one application. Soil solarization was proposed to support the pesticidal effects of these fumigants in the long-term by eliminating the specific soil microflora generated by repeated application of these pesticides.

In the USA and the Mediterranean countries strawberry production will heavily depend on chemical alternatives in the future. Further research is needed to determine not only atmospheric volatilization losses and degradation in soil, but also the effect of the chemicals on structural and functional diversity of soil microbial communities.

Repeated soil fumigation with MB, Pic, InLine, IM, and PB significantly reduced microbial respiration, denitrification potential and biochemical key reactions involved in cellulose degradation, phosphorus and sulfur mineralization in soil (as revealed by soil enzyme activities), while total amounts of microbial biomass showed no response (Klose and Ajwa, 2002, 2004). Repeated applications of a fumigant may selectively enrich for a microbial community able to utilize the chemical as a source of carbon and energy, and thereby resulting in an enhanced biodegradation. A biological degradation of fumigants has been reported for MB, Pic, 1,3-D and MITC, and pesticide metabolizing microorganisms have been isolated from soil (Dungan and Yates, 2003) (Table 4).

Non-chemical alternatives to methyl bromide in the USA and the Mediterranean Region

In continuous strawberry production systems, the soil may host many deleterious pathogens that can be lethal to mature plants or responsible for root rot infections that reduce plant growth and berry yields. Potentially lethal pathogens, such as *V. dahliae*, are employed as bioindicators for deciding pesticide control strategies. In strawberry production systems where transplants are used, biological control agents may be applied to plugs prior to transplant or via the drip irrigation systems (Ajwa *et al*., 2001). Seasonal changes in microorganisms ecology that affect plant growth in either a negative or positive manner could better be addressed with precision subsurface drip systems that provide the opportunity for prescription application of biological control agents and precision water management strategies.

Non-chemical methods proposed as alternatives to MB fumigation are increasingly being considered to meet the demand for organic or low-chemical input into foods and to satisfy public demand for more sustainable methods of food production. Several non-chemical alternatives to MB are evaluated worldwide for their efficacy towards major soil pathogens in the strawberry industry. These are soil solarization, steaming, biofumigation, organic amendments, integrated pest management (IPM), and biological control agents (BCAs) (Katan, 2000; Porter and Mattner, 2002). Based on a review of relevant scientific publications, proceedings of conferences and several recent reviews (McGovern *et al*., 1998; Katan, 2000; Chellemi, 2002; Martin and Bull, 2002), significant non-chemical MB alternatives are evaluated.

Soil solarization

Soil solarization is a disinfection technique that employs solar radiation during summer months to increase the soil temperature under a polyethylene-tarped field in which the soil-water content is brought to field capacity (Medina-Mínguez, 2002). This methodology has been used as a pathogen control strategy at least since 1976 (Katan *et al*., 1976) and has worldwide applications (Chellemi, 2002). Successful solarization requires 30–45 days and soil temperatures exceeding 50°C. Soil heating was reported to be lethal or sub-lethal for many pathogenic fungi, bacteria, and weeds (Katan, 1981; Katan, 2000), and very effective against the stem nematode (Greco *et al*., 1985), but was less effective on nematodes that are able to move in the soil over longer distances.

Species of *Phytophthora*, *Pythium*, *Pyrenochaeta*, *Fusarium*, *Verticillium*, *Sclerotinia*, *Sclerotium* and other pathogenic fungi were successfully controlled by soil solarization (Ghini, 1993). In some field, the effect of soil solarization lasted for 1 or 2 additional years, and re-infestation of solarized soil by *Verticillium* was delayed relative to MB treated soils (Katan and DeVay, 1991; Katan, 2000). Soil solarization has shown to be effective in controlling and reducing weeds such as Bermuda grass (*Cynodon dactylon*) and Johnson grass (*Sorghum halepense*) in some parts of California (Elmore *et al*., 1993). Soil solarization effectively controlled winter annual weeds (*Avena fatua*, *Capsella bursa-pastoris*, *Lamium amplexicaule*, *Poa annua*, *Raphanus raphanistrum*, *Senecio vulgaris*, and *Montia perfoliata*) (Katan and DeVay, 1991; Katan, 2000) and summer annual weeds (*Echinochloa crus-galli*, *Malva parviflora* and *Solanum nigrum*) (Bill, 1993).

Enhanced pathogen control has been observed where soil solarization has been used in conjunction with soil fumigants (i.e., MS or MB) or nonvolatile nematicides (Lamberti *et al*., 2000a), crop rotation, biocontrol agents, and soil amendments to improve its efficacy and reduce the use of soil fumigants (Kokalis-Burelle, 1999; Eshel *et al*., 2000; Gamliel *et al*., 2000; López-Aranda *et al*., 2000; Pinkerton, 2000). Soil solarization plus manure application at moderate rates, to avoid ground water contamination, performed well at strawberry production locations in Spain (Cebolla, 2002). This result may partially be attributed to an increase in organic matter content in the tested soils.

In strawberry and raspberry production in Oregon, USA, soil solarization was economically effective in the reduction of root rot diseases (Pinkerton and Bristow, 2002; Pinkerton *et al*., 2002). Limitations to the effectiveness of soil solarization are found in areas where high temperatures, significant cloud cover and precipitation are coincidental, thereby making the beneficial effects of solar radiation under plastic tarps unpredictable. Soil solarization is considered labor-intensive and tarping of the soil requires an unproductive period of 6-8 weeks. Soil solarization is not effective towards deeply located fungal pathogens (e.g. *Armillaria* spp.) and certain weeds (e.g. nut sedge, *Cyperus* spp.) (Anonymous, 1993b). However, soil solarization has surely the potential of pathogen control in combination with other fumigation methods. Jordan, for example, is intensively employing this technique for soil sterilization.

Soil steaming

Soil disinfestations by steaming (at 80–100°C) is an agricultural technique that has been acknowledged recently for its low ecological impact. This technique is considered as a viable alternative to MB, particularly because there is no chemical residue soil contamination and a relatively short waiting period prior to planting. Air steaming effectively controls most soilborne pathogens such as *Fusarium* spp. (at 50–60°C for 30 min) and weeds (King and Greene, 2000). However, high fuel costs (70–80% of the total treatment costs) make steaming economically feasible only for high-revenue cultures. In addition, due to the high energy consumption of treatments (1.5–2.5 l gasoline m^{-2}), steaming may actually contribute to the global warming process. New developments, including negative pressure steaming (Runia, 1983, 2000), and the Fink method (Ellis, 1991), were developed for greenhouses that are more energy efficient, economical, and reliable than conventional steaming methods.

The most common steaming technique is sheet steaming, which involves covering the soil with a thermo-resistant sheet that is sealed at the edges. The steam is slowly applied underneath the sheet allowing it to penetrate the soil. The efficacy of this technique relies on both soil-dependent (e.g. soil type, mineral composition, texture, porosity, moisture content and tillage system) and host-dependent (e.g., microbial and weed seed resistance to pasteurization) factors. Currently, all phases of this technique are controlled manually and the decision on exposure times is left to the expertise of operators.

Due to the lack of knowledge on the behavior of soil temperature with increasing depth, steam has been applied for fixed and for arbitrary periods, but frequently longer than required. Moreover, there are cases in which the exposure time has not been sufficient to reach the pasteurization of soil. The adoption of a decision support system which is based on modeling the development of the soil temperature is proposed as a control algorithm. In a study, such a control system reduced the necessary treatment time by 23% and, subsequently, fuel consumption under experimental conditions relative to a traditional steaming practice (Dabbene *et al*., 2003).

Recently, an increase in the efficacy of steaming practice has been reported by optimizing the soil humidity content (Minuto *et al*., 2003). Results highlighted that the heat propagate in the soil with isothermal fronts parallel to the soil surface, and thus, spreading mainly through conduction. The efficiency of heat diffusion in soil depends on its physical properties, in particular on the soil humidity content. The latter is controlling the time necessary for efficient disinfestations. Shorter steaming length corresponds with humidity values between 8.5 and 12% in a sandy loam soil, and between 6 and 7% in a sandy soil. Under these conditions, there was an effective control of two major soil pathogens, *Fusarium oxysporum* f. sp. *basilici* and *Rhizoctonia solani* in different soil types as long as a temperature of 80˚C was maintained in the treated soil layers for a minimum of 20 min. Nevertheless, the total costs of soil disinfestations by traditional steaming techniques and boilers are higher than other soil disinfestations approaches (Minuto *et al*., 2003).

Steaming is currently used for small surfaces (benches, seedbeds, soilless cultivation), mainly because of the discontinuous character of the steam application that requires waiting periods between subsequent treatments. In addition, high biocidal efficacy of steaming causes a "biological vacuum" and the consequent risk of pathogen re-colonization, resulting in a so called "boomerang effect". Moreover, an increased release of heavy metals, decomposition of organic matter and consequently accumulation of ammonia, mineralization of inorganic compounds, and modifications in the solubility and availability of nutrient elements and the suppression of beneficial mycorrhizal fungi have been observed and could cause unpredictable phytotoxicity problems (Runia, 1983; 2000; Mus and Huygen, 1992).

Biofumigation of soils

Biofumigation is based on the release of volatile compounds that suppress pathogens during biodegradation of organic amendments or crop residue (Bello *et al*., 1999). Materials that hold potential as biofumigants are livestock manure, refuse from waste paper bins, fishing factory waste, agricultural and food industrial waste and plant residuals with allelopathic compounds (Hoitink, 1988). The biocidal effect of these materials is caused by the release of nitrogen compounds like ammonium and nitrate, organic acids, and various volatile substances (Mian *et al*., 1982). However, high rates of organic matter amendments may produce phytotoxicity or increase the risk for ground water contamination (Cebolla, 2002).

Potential biofumigants that reduced densities of nematodes and suppressed weeds in Lebanon cropping systems were green manure crops such as barley, buckwheat, castor bean, horse bean, mustard, oil radish, Sudan grass, rape seed and velvet bean (Hafez *et al*., 2000). A combination of biofumigation and solarization between July and October was shown to be effective against soilborne pathogens even when soil temperature was as low as 40°C (Lacasa *et al*., 1999). However, losses in soil biodiversity have been observed after such a treatment. Cebolla (2002) reported that solarization in combination with manure was a good alternative to MB if the manure was applied at moderate rates to reduce risk of ground water contamination. The higher crop yield obtained from field plots in Spain after this treatment was attributed to both soil disinfestations and increased soil organic matter contents. Incorporation of olive mill wastes into the soil suppressed populations of plant parasitic nematodes in Italy (Sasanelli *et al*., 2002; 2003).

Controlling soilborne pathogens with antagonistic microorganisms has been suggested by various studies in Europe (Whipps and Lumsden, 1991; Clarkson *et al*., 2002; Georgakopoulos *et al*., 2002). Several species including bacteria (*Pseudomonas* spp. and *Bacillus* spp.) and fungi (*Trichoderma* spp., *Gliocladium* spp., *P. oligandrum*) have been tested as potential biological control agents (Whipps and Lumsden, 1991). Currently most commercial products are based on fungal antagonists. Despite the numerous reports of successful control of *P. ultimum* with several bacterial species (Whipps and Lumsden, 1991), only two bacteria, *Pseudomonas* (*Burkolderia*) *cepacia* and *Streptomyces griseoviridis*, are registered for biological control of *Pythium* spp. (Georgakopoulos *et al*., 2002).

The nematicide BioNem, currently registered in Israel, was shown to be an effective biological tool to control root knot nematodes in tomatoes, cucumbers, pepper and basil (Keren-Zur *et al*., 2002). BioNem is based on a natural isolate of the bacterium *Bacillus firmus* and includes some nontoxic additives. BioNem applied to soil prior to planting significantly increased crop yield relative to the untreated control (Keren-Zur *et al*., 2002). Current efforts are focusing on the development of a BioNem-formulation that can be applied through the drip irrigation system.

Combinations of selected *Trichoderma* strains are being evaluated as soil additives to increase the efficacy and range of pathogen control (Llobell *et al*., 2000). Furthermore, such strains are tested in combination with soil disinfection methods, such as solarization and ozone application, allowing for the establishment of long-term pathogen-antagonistic soil systems. Traditional *Trichoderma* strains were combined with novel antifungal agents derived from *Trichoderma* enzymes that appear to have potential as foliar sprays or post-harvest treatments. Synergistic effects of biocontrol organisms and products with minimal doses of chemical agents, as well as optimal control systems, are currently being identified by a research team from the UK, Spain, Italy, and Israel (Llobell *et al*., 2000). Further research on the mode of action of non-chemical methods for pest and weed control in strawberry production systems are needed to improve their efficacy under a broader spectrum of soil types and climatic conditions.

Plug planting, breeding for disease resistance, and grafting

The strawberry plug planting technology has been developed in California as a non-chemical alternative to commercial strawberry culture for conventional and organic producers (Sances, 2002). Plug planting is currently exclusively used in the southern regions of California with the Camarosa and Ventana cultivars, since previous efforts to use plugs in the northern regions of California have been unsuccessful. The application of this technology in non-fumigated soil resulted in yield equal or greater than in bare root plants in fumigated soil through March (Sances, 2002). However, weeding requirements are significantly higher without soil fumigation and thus, questioning the economical feasibility of plugs and clear plastic mulch. With plug plant technology with opaque plastic mulch for weed suppression, yields are reduced and initiate later in the season than with clear plastic mulch. This technology was shown to be successful in organic plantings, where good yields were obtained from strawberry plugs planted with selective wavelength green plastic mulch and wheat straw mulch in furrows (Sances, 2002). The plug plant system out yielded bare root plants seasonally by 14 to 41%, although differences were greatest early in the season (Sances, 2001).

A limitation of plug planting is the increased incidence of fruit deformation that occurs sporadically in early in the season in March from 12 to over 50% of the total fruits. Consequently, fruits need to be sold for processing instead of fresh, which lowers the return to the grower. Recently, tip material used for plantings were contaminated with antracnose disease (*Colletotrichum acutatum*) that resulted in a complete loss of the plantings. Numerous commercial strawberry plug growers have lost their crops and further expansion of this alternative technology has been stopped (Sances, 2003).

Developing plant cultivars that adapted to specific environmental conditions could be the most effective strategy to reduce or eliminate the use of pesticides. In general, new varieties are still being developed by traditional plant breeding techniques. The possibility of using resistant varieties together with other approaches to control pests may encourage plant pathologists, geneticists and biotechnologists to develop resistant crop varieties. Although resistant or tolerant varieties to one or few specific pathogens are already available for several crop species, breeding strawberry varieties that are resistant to *V. dahliae* have not been successful (Browne *et al*., 1999).

Although grafting is a technique that is not relevant to strawberry production, it plays an important role for many other crops that relied on soil fumigation with MB in the past. Grafting susceptible crops onto resistant rootstocks has been documented for several crops including tomato hybrids resistant to *Verticillium* and *Fusarium* wilts and to *Pyrenochaeta lycopersici*, cucumber (*Cucurbita vicifolia*) and melon (*Benincasa cerifera*) resistant to *Fusarium* wilt (Lee, 1994). Grafting on resistant rootstocks is extremely popular in Asia and may also find application in Italy. Currently, the use of grafting as a non-chemical technique against soilborne pest and diseases is increasing in Italy. In 1997, four million grafted plants were produced mainly for tomato, melon, watermelon, eggplant and cucumber production, while in 2002 this number increased to eighteen million. Nevertheless, high production costs and incompatibility to certain environmental conditions may limit the use of this practice in large-scale agricultural production systems (Cuartero *et al*., 1999). The use of horticultural robotics is being developed in Japan which has the potential of revolutionizing the presently meticulous practice of plant grafting and could have attractive economic possibilities.

Soilless cropping systems

In Italy, soilless cultivation has been used as an alternative to MB fumigation for high value crops (i.e., rose, carnation, gerbera) as well as for vegetable crops (tomato and lettuce) and some minor crops such as basil. In 2001, when a 60% reduction of MB production and consumption was scheduled within the EU, only 400 ha were managed by open soilless systems for vegetables (200 ha) and cut flowers (200 ha) in Italy. Although soilless systems could represent a suitable alternative to control soilborne pathogens and weeds, it appears unlikely that the importance of such systems will increase in Italy (Garibaldi and Gullino, 1995) or in the northern European countries such as The Netherlands, Denmark, Sweden, Norway, Belgium and Germany (Van Os and Postma, 2000).

The introduction of a closed soilless system could be an effective tool to reduce the negative environmental effects caused by nutrient leaching. However, such a production system would require preventive strategies to avoid the risk of dispersing root-infecting pathogens (Jarvis, 1992; Stanghellini and Rasmussen, 1994). The future development of soilless cultivation could be limited by effective technologies to permit the recycling of drainage water and to reduce the risk of root rot pathogen infestation in such production systems.

Cultural practices

In the USA and the EU, the practice of rotating crops as a pathogen control strategy has received less emphasis than it has historically. Successful management of many, but not all, soilborne pathogens has a direct relationship with the time in which host plants are found in the soil. McSorley (1996) and Shetty *et al*. (1999) found that broccoli residues have inhibitory effects on soil pathogens. Some recalcitrant pathogens such as *V. dahliae* were significantly reduced in strawberry production fields rotated with broccoli or Brussels sprouts and thus, plant disease incidences. The effect of these crop rotations was comparable to the efficacy of MB and Pic (McSorley, 1996; Shetty *et al*., 1999). Currently, several *Brassica* spp. that possess high levels of glucosinilates during residue degradation in soil are being evaluated by growers and researchers. However, adoption of crop rotation is limited by environmental or economic factors. Worldwide, several government policies and programs encouraged farmers to specialize. Land and water costs may be too high in some areas such as in California, USA, to adopt diversified farming practices. Nevertheless, regulatory schemes can be very effective and convenient in the production of nematode-free nursery stocks (Tacconi and Lamberti, 1994).

Conclusions

Strawberry production after 2005 is likely to be controlled by even more stringent regulations regarding the use of chemical fumigants. The present state of knowledge about registered chemicals does not provide much optimism for a simple drop-in replacement for MB or MB + Pic mixtures for soil fumigation. Of all the alternatives to MB fumigation, chemical fumigants with a broad-spectrum pesticide currently provide the most reliable disease and pest control and economical yield. In the short-term, growers will need to use combinations of registered fumigants such as Pic, 1,3-D and MITC generators to improve the efficacy of these compounds towards a broad spectrum of pathogens, pests and weeds, similar to the effect of MB. Emulsified formulations of alternative fumigants, singly or in combination, can be applied at pre-plant with irrigation water through the irrigation systems which is applied to strawberries during the growing season. An advantage of drip fumigation is that a more uniform distribution of chemicals can be achieved by spreading them in the liquid phase. Application of soluble formulations through drip irrigation systems would be economical and environmentally-friendly, reduce worker exposure, and would reduce the amount of chemicals applied. However, researchers and growers will have to evaluate new protocols for application techniques and integrated pest management systems to develop economically-viable cropping systems. Although research is promising for some chemical alternatives (e.g., IM and PB) to conventional MB fumigation, many of these compounds are currently not registered and depend on their approval in the near future. In addition, their use will doubtless require modifications of current cropping systems and rigorous testing for economic viability.

Sustainable and economical long-term alternatives are currently emerging. Non-chemical options, such as soil solarization, crop rotation, biological control, soil amendments, steam, and others, are considered too risky and/or uneconomical when used alone. In the future, combinations of chemical and non-chemical MB alternatives, as well as integrated pest management approaches using old and new technologies to control soilborne pathogens and weeds, are vital for the long-term economic success of strawberry production in the USA and the Mediterranean Region.

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Accepted for publication: November 21, 2003