Methyl Bromide Alternatives for High Tunnel Strawberry Production in Southern Spain

José M. López-Aranda¹, Luis Miranda¹, Juan J. Medina¹, Carmen Soria¹, Berta de los Santos¹, Fernando Romero¹, Rosa M. Pérez-Jiménez¹, Miguel Talavera¹, Steve A. Fennimore², and Bielinski M. Santos^{3,4}

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SUMMARY. Field trials were conducted in two locations in Spain to determine the effect of methyl bromide (MBr) alternatives on soilborne diseases and nematodes, and strawberry (*Fragaria × ananassa*) yields under high-tunnel conditions. Fumigant treatments were applied to the same plots each year. Treatments were MBr + chloropicrin (Pic) (50:50, v/v) at a rate of 400 kg·ha⁻¹; 1,3-dichloropropene (1,3-D) + Pic (65:35, v/v) at 300 kg·ha⁻¹; Pic at 300 kg·ha⁻¹; dimethyl disulfide (DMDS) + Pic (50:50, v/v) at 500 kg·ha⁻¹; propylene oxide at 550 kg·ha⁻¹; dazomet at 400 kg·ha⁻¹; and calcium cyanamide (Ca-cyanamide) at 700 kg·ha⁻¹. A nontreated control was also included. Fumigation with MBr + Pic, 1,3-D + Pic, Pic, and DMDS + Pic consistently improved early and total marketable strawberry yields in both locations. This response was caused by successful soilborne fungus and nematode control, improving strawberry growth and development, which resulted in increased plant canopy diameters and higher strawberry early and total yield.

Strawberry production in Spain has exclusively relied upon the use of methyl bromide (MBr) alone or in combination with chloropicrin (Pic) as preplant soil fumigation treatments for control of soilborne diseases, nematodes, and weeds (Calatrava, 2002; Duniway, 2002). As a result of the Montreal Protocol on substances that deplete atmospheric ozone, MBr has been phased out for agricultural purposes in the majority of developed countries (Albritton et al., 1998; U.S. Environmental Protection Agency, 1999). Nonchemical treatments for soil disinfestation for strawberry production such as steam, soil solarization, soilless cultivation, biofumigation, and others are still considered risky and/or not economically feasible to be used alone as global alternatives to MBr (Ajwa et al., 2003). Therefore, open-field production of strawberry with standard soil fumigation will continue

being the predominant production system in the near future.

Research on MBr alternatives has been intensive throughout the world in the last 15 years (Ajwa et al., 2003; Duniway, 2002; Roskopf et al., 2005; Santos and Gilreath, 2006). Some of the proposed alternatives for mulched-vegetable crops are the combination of 1,3-dichloropropene (1,3-D) and Pic, dazomet, propylene oxide, dimethyl disulfide (DMDS) plus Pic, and calcium cyanamide (C-cyanamide). The combination of 1,3-D + Pic has been widely studied throughout the world for controlling fungal disease and nematodes. However, herbicides frequently need to be included along with this alternative to enhance activity against weeds (Noling and Gilreath, 2001).

Dazomet is a generator of the biocide methyl isothiocyanate and has shown acceptable control of soilborne diseases and nematodes in vegetable crops, but its activity can be inconsistent (Roskopf et al., 2005; Santos and Gilreath, 2006). In turf and strawberry, propylene oxide has provided broad-spectrum control against soilborne diseases, nematodes, and weeds in preliminary tests (Belcher et al., 2004; Norton, 2004). In tomato (*Solanum lycopersicum*), studies indicated that populations of sting nematode (*Belonolaimus* spp.) and nutsedge (*Cyperus* spp.) rapidly decreased with 570 kg·ha⁻¹ of shank-applied propylene oxide, and the highest fruit weights were obtained with application of 760 and 950 kg·ha⁻¹ (Santos and Gilreath, 2005). However, strawberry plots treated with this product failed to reach the same yield as in the MBr + Pic plots (Santos et al., 2006). DMDS has fungicidal and nematocidal properties and can be shank-injected and combined with other fumigants. A study demonstrated that application of DMDS reduced populations of *Pythium ultimum* and *Fusarium oxysporum* (Gerik, 2005). However, other research has shown inconsistent results in controlling soilborne diseases (De Cal et al., 2004). A strawberry study showed that application of DMDS + Pic (50:50, v/v) at a rate of 250 + 250 kg·ha⁻¹ resulted in higher early and total strawberry yields than the nontreated control, whereas there was no yield difference in comparison with MBr + Pic (Santos et al., 2006). A drawback of this fumigant is its intense odor, which persists in the soil for several weeks after application. Ca-cyanamide is mainly used a fertilizer, but it has fungicidal and nematocidal activity in soils planted with sunflower (*Helianthus annuus*) and pea (*Pisum sativum*) (Jones and Gray,

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
0.3048	ft	m	3.2808
0.0929	ft ²	m ²	10.7639
0.1242	gal/100 ft	L·m ⁻¹	8.0520
2.54	inch(es)	cm	0.3937
1.1209	lb/acre	kg·ha ⁻¹	0.8922
0.0254	mil	mm	39.3701
28.3495	oz	g	0.0353
(°F - 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

¹Instituto Andaluz de Investigación y Formación Agraria, Consejería de Innovación, Ciencia y Empresa, Junta de Andalucía, Málaga, Spain

²Department of Plant Sciences, University of California at Davis, Salinas, CA 93905

³Gulf Coast Research and Education Center, IFAS, University of Florida, Wilmauma, FL 33598

⁴Corresponding author. E-mail: bmsantos@ufl.edu.

1973; Lo and Lin, 1989; Milinko et al., 1989). Its fungicidal activity is based on the release of cyanamide, bicianamide, and guanidine (Bourdós et al., 1997).

Southern Spain is the most important strawberry-producing area of Europe (Food and Agriculture Organization of the United Nations, 2008). The most common application techniques in this area use shank-injection of $\approx 400 \text{ kg} \cdot \text{ha}^{-1}$ of MBr + Pic in preformed beds. Fungal diseases and nematodes are major causes of economic losses in strawberry throughout the world. The main soilborne diseases in southern Spain are crown rot (*Phytophthora cactorum*), verticillium wilt (*Verticillium* spp.), and black root rot (*Fusarium* spp., *Rhizoctonia* spp., *Pythium* spp., and *Cylindrocarpon* spp.) (De Los Santos et al., 2003). Root-knot nematode (*Meloidogyne* spp.) and lesion nematode (*Pratylenchus* spp.) are also serious limiting factors for strawberry production, causing severe root galling and lesions, respectively. Thus far, these pathogens have been effectively controlled with MBr. There are few research reports on the effect of MBr alternatives under high-tunnel conditions. Therefore, the objective of this study was to determine their efficacy on soilborne diseases and nematodes for high tunnel strawberry production in southern Spain.

Materials and methods

Four field trials were conducted in two grower fields located at Moguer (lat. $37^{\circ}17'N$, long. $6^{\circ}51'W$) and Palos de la Frontera (lat. $37^{\circ}14'N$, long. $6^{\circ}53'W$), Spain, during the 2003–04 and 2004–05 seasons. These experimental sites are major high tunnel strawberry production areas in Spain, and their soils are loamy sands with organic matter content between 0.4% and 0.6%, and a pH between 6.7 and 7.1. Beds were formed with a tractor-mounted bed presser, and their dimensions were 30 and 60 cm wide and high, respectively. Simultaneously with bed pressing, a single drip line with a flow rate of $1.56 \text{ L} \cdot \text{m}^{-1}$ per hour and emitters every 30 cm was placed 5 cm deep on bed centers, beds were covered with polyethylene mulch, and volatile fumigants were injected 20 cm deep with four chisels per bed. At Palos de la Frontera, fumigants were applied on 9 Sept.

2003 and 7 Sept. 2004, whereas at Moguer these operations were performed on 16 Sept. 2003 and 14 Sept. 2004. Average soil temperatures during fumigation were between 25 and 29°C at both locations.

Eight fumigant treatments with four replications were established in randomized complete blocks at each location. Experimental units were three 24-m-long beds (43.2 m^2 per plot). Fumigants used in this study were commercial-grade formulations, with the exception of DMDS + Pic and propylene oxide, which had experimental labels. Fumigant treatments were applied to the same plots each year. MBr + Pic (50:50, v/v) was applied at a rate of $400 \text{ kg} \cdot \text{ha}^{-1}$; 1,3-D + Pic (65:35, v/v) at $300 \text{ kg} \cdot \text{ha}^{-1}$; Pic at $300 \text{ kg} \cdot \text{ha}^{-1}$; DMDS + Pic (50:50, v/v) at $500 \text{ kg} \cdot \text{ha}^{-1}$; propylene oxide at $550 \text{ kg} \cdot \text{ha}^{-1}$; dazomet at $400 \text{ kg} \cdot \text{ha}^{-1}$; and Ca-cyanamide at $700 \text{ kg} \cdot \text{ha}^{-1}$. These rates were based on the total mulched area. A non-treated control was also included. Propylene oxide and Ca-cyanamide were broadcast by hand on bed tops and were incorporated 5 cm deep within 2 h after application with a conventional cultivator. The non-treated and the MBr + Pic-injected plots were mulched with black polyethylene (1 mil), which reflects the standard grower practice. All other treatments were mulched with black, virtually impermeable film (1.5 mil), which increases retention of volatile fumigants and exposure of soil pests to lethal fumes.

High tunnels were built using semicircular steel bars that reached 3.3 m high on the tunnel apex and were 8.3 m wide. These bars were mounted on 1.8 m-long side support bars. Each high-tunnel had six beds and was covered with translucent polyethylene plastic, which allowed in 60% of the photosynthetic active radiation. Tunnels were covered on 22 Nov. 2003 and 8 Nov. 2004 at Moguer, and on 14 Nov. 2003 and 11 Nov. 2004 at Palos de la Frontera. Bare-root ‘Camarosa’ strawberry plants from commercial California nurseries were transplanted on 14 Oct. 2003 and 11 Oct. 2004 at Palos de la Frontera, and on 22 Oct. 2003 and 11 Oct. 2004 at Moguer. Transplants were placed in double rows per mulched bed and were spaced $27 \times 22 \text{ cm}$, and $26 \times 25 \text{ cm}$ apart between

rows and plants at Moguer and Palos de la Frontera, respectively. Transplant establishment used intermittent application of drip and microsprinkler irrigation during the first 10 d to ensure the cooling down of strawberry crowns. Conventional crop management was followed as recommended in the region for strawberry production under plastic tunnels (López-Aranda et al., 2002).

Fumigant efficacy on soilborne fungal populations was estimated for the genera *Rhizoctonia*, *Phytophthora*, *Fusarium*, *Trichoderma*, and *Pythium* by comparison of their number of colony-forming units (cfu) per gram of soil. Five soil samples per plot were obtained before fumigant application and 30 d after fumigation during each season and location to determine number of cfu. Samples were taken 20 cm deep between two plants in the same row by using a vertical soil core sampler (2-cm diameter). Afterward, soil samples were dried and 1 g of soil per sample was suspended in 99 mL of water agar (0.3%, v/v). Aliquots of 1 mL were spread on petri dishes with P₅ARP semiselective agar medium to determine the presence of *Phytophthora* and *Pythium* (Jeffers and Martin, 1986); and KO agar medium to determine the presence of *Rhizoctonia* (Ko and Hora, 1971). *Trichoderma* isolations with 10 g of soil were suspended in 90 mL of water agar (0.3%, v/v), shaken for 15 min, and 0.1-mL aliquots were spread with a glass rod on petri dishes with *Trichoderma*-selective medium (Elad et al., 1981). Petri dishes were placed at 25°C in the dark for 3 to 7 d and the fungal colonies were counted. Nematode populations were determined at the end of each season by selecting five plants per plot (240 plants per location). Strawberry root samples from each plant were washed with distilled water and sedentary forms of root-knot nematode at the juvenile 3 and 4, and adult stages, and endoparasitic forms of lesion nematode at the juvenile 2, 3, and 4, and adult stages were extracted and quantified by the sugar centrifugation method (Nombela and Bello, 1983).

Strawberry plant diameter was recorded at 10 weeks after transplanting to assess plant growth and it was determined by averaging two horizontal measurements (north–south and east–west) of aboveground

foliage of 10 previously selected plants per plot. Marketable fruit were collected at least twice per week at each experimental site. The first strawberry harvest occurred on 30 Jan. 2004 and 21 Jan. 2005 at Moguer, and on 20 Jan. 2004 and 11 Jan. 2005 at Palos de la Frontera. At each location, a minimum of 25 harvests was conducted, which is representative of current grower practices. Early marketable yields comprised all harvests until 31 March of each season, whereas total marketable yields were the cumulative fruit weights of all harvests. Early and total weights per fruit were calculated by dividing early and total marketable yields by their respective fruit numbers. Data were analyzed with analysis of variance and treatment means were compared using Fisher's protected least significant difference test at the 5% significance level (Statistix, version 8.0; Analytical Software, Tallahassee, FL). Before analysis, nematode populations were transformed with $\log(x + 1)$ to normalize the data.

Results and discussion

There were significant season by treatment interactions at Moguer and Palos de la Frontera. Therefore, data from each season for each location were analyzed separately. At Moguer, there was significant fumigant effect on the number of recovered cfu of *Rhizoctonia*, *Phytophthora*, *Fusarium*, *Trichoderma*, and *Pythium* recovered from sampled soil during the 2003–04 and 2004–05 seasons (Table 1). There were no significant differences on the number of fungal cfu obtained from the plots before fumigation (data not shown), indicating uniform distribution of fungal populations within each experimental site and season. However, fumigant treatments affected the number of fungal cfu obtained at 30 d after application during all four trials. During the first season at Moguer, the nontreated control plots showed the largest number of fungal cfu among all treatments (47,300 cfu/g of soil), whereas all fumigated plots ranged between 0 and 22,000 cfu/g of soil. The following season at the same location, fungal cfu values ranged between 0 and 56,100 cfu/g of soil, and the lowest values occurred in plots treated with MBr + Pic, 1,3-D + Pic, Pic, DMDS + Pic, and dazomet ($\leq 9,900$ cfu/g of

soil), which were not different from each other. Soil treatment with Ca-cyanamide or propylene oxide did not reduce the number of fungal cfu in comparison with the nontreated control (56,100 cfu/g of soil). At Palos de la Frontera, the fumigants had significant effects on the number of cfu during both growing seasons. In 2003–04, plots fumigated with Ca-cyanamide had the same fungal cfu values as those obtained in the nontreated control, while during the following season, this product and propylene oxide failed to reduce the

number of cfu in relation to nontreated control plots (Table 2). At both locations, plots treated with dazomet, 1,3-D + Pic, Pic, and DMDS + Pic consistently had the same number of cfu than those treated with MBr + Pic in both seasons.

At Moguer, fumigant treatments affected the populations of juveniles of lesion nematode on strawberry roots during the 2003–04 season, but not in 2004–05 (Table 1). During the first season, control of lesion nematode was the highest in plots treated with MBr + Pic, 1,3-D + Pic,

Table 1. Effects of fumigation treatments on the number of fungal colony-forming units (cfu) and lesion nematode populations on strawberry roots during the 2003–04 and 2004–05 strawberry seasons at Moguer, Spain.

Fumigants ^z	Fungal cfu		Lesion nematode population	
	2003–04	2004–05	2003–04	2004–05
	(100/g of soil) ^y		(no./g of root)	
Control	47.3 a [*]	56.1 a	50.1 ab	181.0 a
MBr + Pic	7.7 bc	0 c	6.3 c	251.0 a
Dazomet	0 c	9.9 bc	112.0 ab	135.0 a
1,3-D + Pic	22.0 b	1.1 c	9.8 c	76.0 a
Pic	0 c	3.3 c	83.8 ab	215.0 a
DMDS + Pic	1.1 bc	3.3 c	12.7 c	18.0 a
Ca-cyanamide	4.4 bc	44.0 ab	51.5 ab	69.0 a
Propylene oxide	0 c	70.4 a	242.0 a	165.0 a
Significance ($P < 0.05$)	*	*	*	NS

^zMBr + Pic = methyl bromide + chloropicrin (50:50 v/v) at 400 kg·ha⁻¹; 1,3-D = 1,3-dichloropropene + Pic (65:35 v/v) at 300 kg·ha⁻¹; DMDS + Pic = dimethyl disulfide + Pic (65:35 v/v) at 300 kg·ha⁻¹; Ca-cyanamide = calcium cyanamide at 700 kg·ha⁻¹; Pic at 300 kg·ha⁻¹; DMDS + Pic at 500 kg·ha⁻¹; propylene oxide at 550 kg·ha⁻¹; and dazomet at 400 kg·ha⁻¹; 1 kg·ha⁻¹ = 0.8922 lb/acre.

^y1 cfu or nematode/g = 28.3495/oz.

^{*}Treatment means within each column were separated with Fisher's least significant difference test ($P < 0.05$).

NS, *Not significant and significant at $P < 0.05$, respectively.

Table 2. Effects of fumigation treatments on the number of fungal colony-forming units (cfu), and root-knot nematode populations on strawberry roots during the 2003–04 and 2004–05 strawberry seasons at Palos de la Frontera, Spain.

Fumigants ^z	Fungal cfu		Root-knot nematode population	
	2003–04	2004–05	2003–04	2004–05
	(1000/g of soil) ^y		(no./g of root)	
Control	72.6 a [*]	36.3 a	20.9 ab	22.5 a
MBr + Pic	19.8 b	1.1 c	1.8 c	2.3 a
Dazomet	3.3 b	13.2 bc	27.9 ab	10.1 a
1,3-D + Pic	14.3 b	7.7 bc	0 c	0.9 a
Pic	4.4 b	5.5 bc	0 c	3.5 a
DMDS + Pic	1.1 b	13.2 bc	0 c	0.3 a
Ca-cyanamide	36.3 ab	22.0 ab	32.4 a	20.7 a
Propylene oxide	19.8 b	34.1 a	17.0 b	16.5 a
Significance ($P < 0.05$)	*	*	*	NS

^zMBr + Pic = methyl bromide + chloropicrin (50:50 v/v) at 400 kg·ha⁻¹; 1,3-D = 1,3-dichloropropene + Pic (65:35 v/v) at 300 kg·ha⁻¹; DMDS + Pic = dimethyl disulfide + Pic (65:35 v/v) at 300 kg·ha⁻¹; Ca-cyanamide = calcium cyanamide at 700 kg·ha⁻¹; Pic at 300 kg·ha⁻¹; DMDS + Pic at 500 kg·ha⁻¹; propylene oxide at 550 kg·ha⁻¹; and dazomet at 400 kg·ha⁻¹; 1 kg·ha⁻¹ = 0.8922 lb/acre.

^y1 cfu or nematode/g = 28.3495/oz.

^{*}Treatment means within each column were separated with Fisher's least significant difference test ($P < 0.05$).

NS, *Not significant and significant at $P < 0.05$, respectively.

and DMDS + Pic (<13 juveniles per gram of root), whereas dazomet, Pic, Ca-cyanamide, and propylene oxide were equal to the nontreated control. At Palos de la Frontera, root-knot nematode juveniles on strawberry roots were influenced by fumigation in 2003–04, but not in 2004–05 (Table 2). Plots treated with MBr + Pic, 1,3-D + Pic, Pic, and DMDS + Pic showed the highest root-knot nematode control among all treatments (<2 juveniles per gram of root), whereas dazomet and Ca-cyanamide were not different from the nontreated control in the 2003–04 season.

Strawberry plant diameter, early and total marketable yield, and early and total weight per fruit were influenced by the application of the fumigants at both locations. At Moguer, there were no plant diameter differences among plots treated with MBr + Pic, 1,3-D + Pic, Pic, DMDS + Pic, and propylene oxide in the 2003–04 season, ranging between 36.3 and 38.2 cm of diameter (Table 3). The smallest plants were located in the nontreated control plots and in those fumigated with Ca-cyanamide and dazomet (≤ 34.8 cm). In 2004–05, the largest plant diameters were obtained in plots treated with 1,3-D + Pic, Pic, and DMDS + Pic (≥ 41.0 cm), whereas there were no significant canopy differences among the nontreated control, Ca-cyanamide, and propylene oxide (≤ 34.3 cm). At Palos de la Frontera, plots treated during 2003–04 with MBr + Pic,

1,3-D + Pic, Pic, DMDS + Pic, and propylene oxide had the largest strawberry plant diameters (≥ 37.0 cm). The nontreated control and Ca-cyanamide resulted in plants with the same canopy diameter (≤ 32.9 cm). In 2004–05, application of dazomet, Ca-cyanamide, and propylene oxide failed to increase plant diameter in comparison with the nontreated control (Table 3).

The highest early marketable yields at Moguer during both seasons were obtained in plots treated with MBr + Pic, dazomet, 1,3-D + Pic, Pic, DMDS + Pic, and propylene oxide, ranging between 314.1 and 374.7 g/plant (Table 3). Application of Ca-cyanamide failed to improve early marketable yields in comparison with the nontreated control during both growing seasons. At Palos de la Frontera, there were no significant early marketable yield differences in 2003–04 among all fumigated plots, with the exception of Ca-cyanamide and nontreated plots, ranging between 462.5 and 526.4 g/plant. The following season, early yields in plots treated with MBr + Pic, 1,3-D + Pic, Pic, DMDS + Pic, and propylene oxide were statistically equal. Plots fumigated with dazomet, Ca-cyanamide, and the nontreated control showed no significant early yield differences.

Across locations and seasons, the highest total marketable yields were consistently obtained with the application of MBr + Pic, 1,3-D + Pic, Pic, and DMDS + Pic, with values ranging between 1006.3 and 1268.8 g/plant

and 793.0 and 1315.0 g/plant at Moguer and Palos de la Frontera, respectively (Tables 3 and 4). During the 2003–04 season at both locations, total marketable yield in plots treated with propylene oxide did not differ from those injected with DMDS + Pic, but this effect disappeared the following season, when this fumigant performed better than the nontreated control but worse than DMDS + Pic. Application of Ca-cyanamide failed to increase total marketable yields with respect to the nontreated control. Dazomet produced comparable total yield to those in MBr + Pic plots in three of four trials.

At Moguer, values for early weight per fruit in plots fumigated with MBr + Pic, dazomet, 1,3-D + Pic, Pic, and DMDS + Pic were statistically equal within each season, with values ranging between 27.9 and 32.1 g/fruit and 30.9 and 33.2 g/fruit in the 2003–04 and 2004–05 seasons, respectively (Table 3). In 2003–04, early weight per fruit in propylene oxide-treated plots was similar to that obtained with MBr + Pic, while there were no differences between the nontreated control and Ca-cyanamide. At Palos de la Frontera, fumigation with MBr + Pic, dazomet, 1,3-D + Pic, Pic, and DMDS + Pic consistently improved early weight per fruit (≥ 30.7 g/fruit both seasons) in contrast with the nontreated control (22.5 and 23.0 g/fruit in 2003–04 and 2004–05). Total weight per fruit followed a similar trend as early weight per fruit within

Table 3. Effects of fumigation treatments on strawberry plant diameter, early and total marketable fruit, and early and total weight per fruit during the 2003–04 and 2004–05 strawberry seasons at Moguer, Spain.

Fumigants ^a	Plant diameter		Early marketable yield		Total marketable yield		Early wt		Total wt	
	2003–04	2004–05	2003–04	2004–05	2003–04	2004–05	2003–04	2004–05	2003–04	2004–05
	(cm) ^y	(cm) ^y	(g/plant) ^y	(g/plant) ^y	(g/plant)	(g/plant)	(g/fruit)	(g/fruit)	(g/fruit)	(g/fruit)
Control	32.1 d ^x	32.5 d	178.0 b	237.4 c	703.3 c	861.4 d	22.5 b	23.0 c	22.6 b	21.5 c
MBr + Pic	38.2 a	37.3 bc	349.0 a	371.0 a	1,082.0 a	1,164.0 ab	32.1 a	32.9 a	28.2 a	26.9 a
Dazomet	34.8 cd	37.7 bc	317.6 a	359.9 a	952.2 b	1,152.4 ab	27.9 a	30.9 a	26.2 a	25.8 a
1,3-D + Pic	37.8 ab	41.0 a	314.1 a	371.0 a	1,017.1 ab	1,268.8 a	29.2 a	33.2 a	26.5 a	27.2 a
Pic	36.3 abc	41.4 a	331.6 a	374.7 a	1,092.8 a	1,187.3 ab	30.8 a	32.6 a	27.6 a	26.4 a
DMDS + Pic	36.7 abc	41.0 a	314.1 a	374.7 a	1,006.3 ab	1,257.1 a	32.1 a	31.6 a	28.2 a	26.6 a
Ca-cyanamide	32.1 d	34.3 cd	205.9 b	289.4 bc	714.1 c	931.2 cd	22.1 b	27.3 b	22.8 b	23.9 b
Propylene oxide	36.7 abc	36.2 bcd	331.6 a	322.8 ab	1,049.5 ab	1,047.6 bc	30.8 a	26.0 bc	27.4 a	22.9 bc
Significance	*	*	*	*	*	*	*	*	*	*
(<i>P</i> < 0.05)										

^aMBr + Pic = methyl bromide + chloropicrin (50:50 v/v) at 400 kg·ha⁻¹; 1,3-D = 1,3-dichloropropene + Pic (65:35 v/v) at 300 kg·ha⁻¹; DMDS + Pic = dimethyl disulfide + Pic (65:35 v/v) at 300 kg·ha⁻¹; Ca-cyanamide = calcium cyanamide at 700 kg·ha⁻¹; Pic at 300 kg·ha⁻¹; DMDS + Pic at 500 kg·ha⁻¹; propylene oxide at 550 kg·ha⁻¹; and dazomet at 400 kg·ha⁻¹; 1 kg·ha⁻¹ = 0.8922 lb/acre.

^y1 cm = 0.3937 inch; 1 g = 0.0353 oz.

^xTreatment means within each column were separated with Fisher's least significant difference test (*P* < 0.05).

*Significant at *P* < 0.05.

Table 4. Effects of fumigation treatments on strawberry plant diameter, early and total marketable fruit, and early and total weight per fruit during the 2003–04 and 2004–05 strawberry seasons at Palos de la Frontera, Spain.

Fumigants ^z	Plant diameter		Early marketable yield		Total marketable yield		Early wt		Total wt	
	2003–04	2004–05	2003–04	2004–05	2003–04	2004–05	2003–04	2004–05	2003–04	2004–05
	(cm) ^y		(g/plant) ^y		(g/plant)		(g/fruit)		(g/fruit)	
Control	30.7 d ^s	28.6 c	329.6 b	237.1 c	897.2 b	547.2 e	26.3 c	27.4 c	23.3 c	23.5 c
MBr + Pic	37.4 ab	34.1 ab	492.0 a	334.0 ab	1229.0 a	793.0 ab	31.3 ab	33.0 ab	26.8 ab	27.0 a
Dazomet	35.2 bc	31.7 bc	482.2 a	283.9 bc	1179.8 a	674.1 cd	31.6 ab	30.7 b	25.7 abc	25.7 ab
1,3-D + Pic	37.4 ab	35.8 ab	487.1 a	334.0 ab	1229.0 a	824.7 ab	32.2 ab	34.7 a	27.1 ab	27.3 a
Pic	37.0 ab	35.1 ab	526.4 a	334.0 ab	1290.5 a	864.4 a	30.7 abc	32.0 b	26.0 abc	26.5 ab
DMDS + Pic	38.5 a	36.5 a	482.2 a	347.4 a	1315.0 a	872.3 a	33.5 a	33.0 ab	28.1 a	27.5 a
Ca-cyanamide	32.9 cd	29.7 c	354.2 b	290.6 bc	909.5 b	610.6 de	28.2 bc	28.4 c	24.7 bc	24.6 bc
Propylene oxide	38.9 a	33.1 abc	462.5 a	297.3 ab	1204.4 a	753.4 bc	31.0 ab	28.4 c	26.3 bc	24.6 bc
Significance (<i>P</i> < 0.05)	*	*	*	*	*	*	*	*	*	*

^zMBr + Pic = methyl bromide + chloropicrin (50:50 v/v) at 400 kg·ha⁻¹; 1,3-D = 1,3-dichloropropene + Pic (65:35 v/v) at 300 kg·ha⁻¹; DMDS + Pic = dimethyl disulfide + Pic (65:35 v/v) at 300 kg·ha⁻¹; Ca-cyanamide = calcium cyanamide at 700 kg·ha⁻¹; Pic at 300 kg·ha⁻¹; DMDS + Pic at 500 kg·ha⁻¹; propylene oxide at 550 kg·ha⁻¹; and dazomet at 400 kg·ha⁻¹; 1 kg·ha⁻¹ = 0.8922 lb/acre.

^y1 cm = 0.3937 inch; 1 g = 0.0353 oz.

^zTreatment means within each column were separated with Fisher's least significant difference test (*P* < 0.05).

*Significant at *P* < 0.05.

each location (Table 4). Considering across both planting seasons and locations, there were no significant total weight per fruit differences among MBr + Pic, dazomet, 1,3-D + Pic, Pic, and DMDS + Pic treatments (Tables 3 and 4).

In summary, fumigation with MBr + Pic, 1,3-D + Pic, Pic, and DMDS + Pic consistently improved early and total marketable strawberry yields in both locations. This response can be attributed to the successful control of soilborne fungi and nematodes species, improving strawberry growth and development, which reflected on increased plant canopy diameters and higher strawberry early and total yield. All of these fumigants could serve as part of a comprehensive soil-borne disease and nematode control program for mulched-strawberry production. Dazomet might have application as a soil-applied fumigant because of its performance during both seasons and locations. However, its nematicidal activity was weak during one of the strawberry seasons. Ca-cyanamide proved to be a weak nematicide under the conditions of these trials.

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