The Effects of Surfactants, Nozzle Types, Spray Volumes, and Simulated Rain on 1-Methylcyclopropene Efficacy on Tomato Plants

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Abstract. A study was conducted with a wettable powder formulation of 1-methylcyclopropene (1-MCP) to determine the effects of surfactants, spray volume, nozzle type, and rain fastness on the efficacy of 1-MCP to protect tomato plants from the epinastic effects of ethephon. 1-MCP at 25 and 50 g·ha⁻¹ protected tomato plants from 250 and 500 g·ha⁻¹ of ethephon. Of the three best surfactants tested, two (Dyne-Amic and Silwet L-77) contained silicone and one (Herbimax) an emulsified petroleum oil. The efficacy of 1-MCP increased with an increase in spray volume from 150 L·ha⁻¹ to 400 L·ha⁻¹, suggesting that an increase in leaf coverage leads to greater protection and that the translocation of 1-MCP is limited within tomato plants. There was no significant effect of spray nozzle type on 1-MCP activity. 1-MCP appeared to be rainfast within 15 min after application.

Ethylene, a gaseous plant hormone, regulates many of the plant processes associated with senescence, fruit ripening, and abscission. 1-Methylcyclopropene (1-MCP) blocks ethylene from binding to receptors in plant cells, preventing ethylene-induced effects. 1-MCP is used commercially on many fruits and vegetables to maintain product quality during postharvest storage (Serek et al., 1994; Watkins, 2006). Most postharvest applications of 1-MCP involve a fumigation technique that uses a stable formulation of 1-MCP complexed in α -cyclodextrin powder. This powder dissolves in water, resulting in the release of 1-MCP to treat large storage areas at extremely low concentrations.

1-MCP can also protect against undesirable preharvest side effects of ethylene. Ethylene applications (in the form of ethephon) have been studied to aid in harvesting oranges (*Citrus sinensis* L.) by stimulating fruit drop; however, this treatment also causes unacceptable levels of defoliation (Burns, 2002). When the ethylene treatment was combined with 5 mm 1-MCP, there was a 70% reduction in leaf abscission without an

effect on fruit drop (Pozo et al., 2004). In apples (*Malus domestica*), 1-MCP alone or in combination with naphthaleneacetic acid (an auxinic plant growth regulator) provided protection against preharvest fruit drop and extended the harvest season (Elfving et al., 2007; Yuan and Carbaugh, 2007).

Another potential use of 1-MCP is to treat row crops to minimize responses to stress that are mediated by ethylene (Dahmer et al., 2007). For example, heat stress in wheat leads to higher ethylene production, which induces leaf senescence and kernel abortion (Hays et al., 2007). Spraying 1-MCP onto plants 1 d before heat stress increased wheat kernel retention as well as kernel size (Hays et al., 2007).

Direct treatment of preharvest crops with 1-MCP was first described in 2001 (Dahmer et al., 2007). 1-MCP is lipophilic, relatively labile, and has an extremely high vapor pressure; applying it to a crop by a conventional sprayer presents many challenges. The effectiveness of 1-MCP in field applications will be influenced by many factors, including spray volume, surfactants, and spray nozzle types, perhaps more so than with other non-gaseous crop protection products. To explore these factors, a model system is needed that can readily quantify responses to variations in 1-MCP treatment conditions.

Tomatoes (*Solanum lycopersicon*) are extremely sensitive to external ethylene application, showing a very strong epinastic effect within 24 h of application (Abeles et al., 1992; Blankenship and Kemble, 1996). This ethylene-induced epinasty (quantified by measuring the change in the angle of the leaves' petiole in reference to the stem) can be prevented if the plant is pretreated with 1-MCP (Kubota and Kroggel, 2006). Hence, tomato provides an excellent model system to determine the effects of different application parameters on the efficacy of 1-MCP. The objectives of this research were: 1) to determine the efficacy of different 1-MCP application rates on tomato response to ethylene; 2) to determine the impact of surfactant choice, nozzle types, and spray volumes on 1-MCP efficacy; and 3) to determine the rainfastness of 1-MCP on tomato plants in the laboratory.

Table 1. Surfactants and their characteristics.

Surfactant	% (v/v)	Description	Maker
Group 1			
Dyne-Amic	0.375	Methylated seed oil (MSO)/silicone blend	Helena Chemical Company, Helena, MT
Herbimax	0.5	Emulsified petroleum oil	Loveland Industries, Greeley, CO
LI-700	0.25	Nonionic surfactant (NIS)	Loveland Industries
Liberate	0.25	NIS	Loveland Industries
MSO	1.0	MSO	Rohm and Hass, Philadelphia, PA
Phase	0.25	Methylated seed oil (MSO)/silicone blend	Loveland Industries
Silwet L-77	0.125	NIS (organosilicone)	Loveland Industries
Group 2			
Activator 90	0.25	NIS	Loveland Industries
Agridex	1.0	Petroleum-based NIS	Bayer CropScience, Durham, NC
Destiny	1.0	MSO/NIS	AgriLiance LLC, St. Paul, MN
Dyne-Amic	0.375	Methylated seed oil (MSO)/silicone blend	Helena Chemical Company
Phase II	1.0	Methylated seed oil (MSO)/silicone blend	Loveland Industries
Preference	0.25	MSO	AgriLiance LLC

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Materials and Methods

Plant growth. Tomato (var. Beefsteak) seeds (Rocky Mountain Seed Co., Denver, CO) were planted in either 6.25-cm or 5.0-cm diameter pots (T.O. Plastics, Minneapolis, MN) in 5 cm of Fafard® Super Fine Germinating Mix (Agawam, MA) potting media. The pots were thinned to one plant (in the 5-cm pots) or two plants (in the 6.25-cm pots) per pot and fertilized with equal amounts of Osmocote® 19–5–8 pellets (Scotts-Sierra Horticultural Co., Marysville, OH). Plants were grown in a greenhouse where natural light, supplemented with sodium vapor lights, provided a 16-h photoperiod with 32:21 °C (±3 °C) day:night temperatures. Plants were randomly chosen for treatment when the third true leaf began to emerge.

General experimental design. The five experiments described subsequently were conducted in a randomized complete block design. Each block contained all treatments. A powder formulation of 1-MCP in cyclodextrin (formulation AFxRD-038, 3.8% w/w active 1-MCP; Rohm and Hass, Philadelphia, PA) was used in each experiment sprayed 24 h before the ethephon treatment in the spray chamber (described subsequently) adjacent to the greenhouse. To measure the effect of 1-MCP on the ethylene response, plants were treated with ethephon (Ethrel™, 0.023% v/v; Bayer Crop Science LP, Durham, NC) at a rate of 250 g·ha⁻¹ or 500 g·ha⁻¹ (unless otherwise noted) 24 h after 1-MCP treatment using the same spray chamber. All ethephon spray solutions contained 0.375% (v/v) Dyne-Amic® (Helena Chemical, Helena, MT). The angle of the second leaf petiole with reference to the stem was measured 24 h after the ethephon application using the method described by Bradford and Dilley (1978). All plants were placed back into the greenhouse environment described previously immediately after any treatment application.

Sprayer. Plants were sprayed with a track sprayer (Devries Manufacturing Inc., Hollandale, MN). Unless otherwise noted, a TeeJet™ 8003EVS (Spraying Systems Co., Wheaton, IL) spray nozzle and a spray rate of 200 L·ha⁻¹ at 207 kPa was used for both 1-MCP and ethephon application. All of the nozzles used in this study are commercially available and regularly used in agrochemical field applications.

Comparisons of different 1-methylcyclopropene and ethephon levels. Tomato plants (two plants per pot) were treated with five 1-MCP levels (0, 5, 10, 25, and 50 g·ha⁻¹) and four different levels of ethephon (0, 100, 250, and 500 g·ha⁻¹) in a factorial design. Each of these 20 combinations was replicated three times and the experiment was conducted twice. Dyne-Amic (Table 1) was used as the surfactant for both the 1-MCP and ethephon solutions.

Testing surfactant efficacy. Two series of surfactants were used to determine their individual effects on 1-MCP activity. A list of the surfactants, their characteristics, and rates used are shown in Table 1. Plants (two plants per

pot) were treated with three different 1-MCP levels (5, 10, and 25 g·ha⁻¹) in spray solutions containing each of the individual surfactants at the concentrations listed in Table 1. Plants were then treated with 250 g·ha⁻¹ of ethephon 24 h after the 1-MCP treatment. The treatments were replicated three times and the experiment was repeated twice.

Spray volume test. The effect of spray volume on the efficacy of 1-MCP was deter-

mined by treating plants (two plants per pot) with three 1-MCP levels (10, 25, and 50 g·ha⁻¹) in Dyne-Amic and three spray volumes (100, 200, and 400 L·ha⁻¹ at 207 kPa). All of the plants were sprayed with 250 g·ha⁻¹ of ethephon 24 h after 1-MCP treatment. The treatments were replicated three times and the experiment was repeated twice.

Comparison of different spray nozzles. Five different TeeJet™ spray nozzles

Table 2. Statistical results for each experiment, including both fixed and random effects.^a

Effect	df	F value	χ ²	χ ² df	Prob > F
<i>1-MCP/ethephon comparison</i>					
Fixed effects					
1-MCP	4, 215	25.73	—	—	<0.0001
Ethephon	3, 215	62.04	—	—	<0.0001
1-MCP * ethephon	12, 215	5.92	—	—	<0.0001
Random effects					
Block	—	—	0	5	0.5000
Experimental trial	—	—	142.6	1	<0.0001
<i>Surfactant comparison</i>					
Group 1					
Fixed effects					
1-MCP	2, 225	45.78	—	—	<0.0001
Surfactant	7, 225	2.84	—	—	0.0111
1-MCP * surfactant	12, 225	1.53	—	—	0.1261
Random effects					
Block	—	—	1.2	5	0.4724
Experimental trial	—	—	62.4	1	<0.0001
Group 2					
Fixed effects					
1-MCP	2, 193	18.80	—	—	<0.0001
Surfactant	5, 193	3.24	—	—	0.0078
1-MCP * surfactant	10, 193	0.73	—	—	0.6960
Random effects					
Block	—	—	1.8	5	0.4380
Experimental trial	—	—	140.4	1	<0.0001
<i>Dyne-Amic/water comparison</i>					
Fixed effects					
1-MCP	2, 304	3.45	—	—	0.0330
Surfactant	2, 304	14.21	—	—	<0.0001
Random effects					
Block	—	—	0	8	0.5000
Experimental trial	—	—	0	1	0.0007
<i>Nozzle test</i>					
Fixed effects					
1-MCP	3, 448	45.60	—	—	<0.0001
Nozzle	4, 448	0.74	—	—	0.5623
1-MCP * nozzle	12, 448	1.79	—	—	0.0481
Random effects					
Block	—	—	0	5	0.5000
Experimental trial	—	—	0	1	0.5000
<i>Spray rate test</i>					
Fixed effects					
1-MCP	2, 94	12.49	—	—	<0.0001
Spray rate	2, 94	13.79	—	—	<0.0001
1-MCP * spray rate	4, 94	0.59	—	—	0.6672
Random effects					
Block	—	—	0	5	0.5000
Experimental trial	—	—	139.3	1	<0.0001
<i>Rainfast test</i>					
Fixed effects					
1-MCP	2, 330	37.23	—	—	<0.0001
Rain event	6, 330	24.49	—	—	<0.0001
1-MCP * rain event	10, 330	2.38	—	—	0.0099
Random effects					
Block	—	—	0	5	0.5000
Experimental trial	—	—	10.8	1	<0.0001

^aThe significance of fixed effects is tested with F tests that account for both the variance from the random effects and the error variance. The significance of each random effect is tested using likelihood ratio tests (Littell et al., 1996).

1-MCP = 1-methylcyclopropene.

(80-03EVS, AI110-03, AITT110-03, TT110-03, XR110-03; Spraying Systems Co., Wheaton, IL) and four 1-MCP levels (0, 10, 25, and 50 g·ha⁻¹) were used in this experiment. All plants (one plant per pot) were sprayed with 250 g·ha⁻¹ of ethephon 24 h after the 1-MCP treatment. The experiment was repeated four times with four replications per experimental trial.

Rainfastness test of 1-methylcyclopropene. To test the speed of absorption of 1-MCP into tomato leaves, plants (one plant per pot) were treated with three rates of 1-MCP (10, 25, and 50 g·ha⁻¹) and then subjected to 0.65 cm of simulated rainfall applied over 17 min at four different time intervals: 15, 60, 120, and 240 min after 1-MCP treatment. Three replicates per experimental trial and three experimental trials were performed.

Statistical analysis. Response variables (second leaf angle) for each experiment were analyzed using a mixed linear model (Proc Mixed; SAS Version 8, SAS Institute Inc., Cary, NC). Experimental treatments and interactions between them were coded as fixed effects, and each block and experimental trial were treated as random effects.

Results and Discussion

Interaction of 1-methylcyclopropene and ethephon on tomato leaf epinasty. There was a significant interaction between ethephon and 1-MCP on the leaf angles of the treated tomato plants (Table 2). Within ethephon rates, those plants treated with 5 g·ha⁻¹ and 10 g·ha⁻¹ rates of 1-MCP produced results similar to those plants not treated with 1-MCP (Fig. 1). The two highest rates of 1-MCP (25 and 50 g·ha⁻¹) protected the plants from the ethephon effect. 1-MCP has been shown to be effective in protecting excised leaves from ethylene when applied as a gas (Able et al., 2003; Ella et al., 2003; Jiang et al., 2002; Kenigsbuch et al., 2007; Koukounaras et al., 2006; Porter et al., 2005; Saltveit, 2004) and when sprayed on citrus plants at the same time as exogenous ethylene (Pozo et al., 2004). However, this is the first documented case using a sprayable solution of 1-MCP to prevent an ethylene-induced stress response on a preharvest dicotyledonous row crop.

Comparison of surfactants on 1-methylcyclopropene. The effects of 12 surfactants on the efficacy of 25 g·ha⁻¹ of 1-MCP were compared in two separate groups. In Group 1, 1-MCP applied with Dyne-Amic, Herbimax, LI-700, or Silwet L-77 protected the plants from ethephon and the leaf angles were not significantly different from untreated plants (Table 3). In the second group of surfactants, only the Dyne-Amic/1-MCP spray protected the plants from ethephon (plants with similar leaf angles to controls), although 1-MCP with any of the surfactants resulted in some protection (Table 3). Based on these results, Dyne-Amic was chosen as the preferred test surfactant for determining the effects of spray volume,

Fig. 1. Effects of different 1-methylcyclopropene and ethephon rates on tomato leaf angles. Data were averaged for three replications per trial with two experimental trials run. *Means followed by the same letter are not significantly different (Saxton, 1998).

Table 3. Influence of 1-methylcyclopropene (1-MCP) rates and surfactants on postemergence tomato seedlings as measured by second true leaf angle.^z

Surfactant	MCP (g·ha ⁻¹)	Leaf angle (°)	Surfactant	MCP (g·ha ⁻¹)	Leaf angle (°)
Group 1			Group 2		
Untreated control	0	48 g ^y	Untreated control	0	51 d
Ethephon only	0	116 a	Ethephon only	0	124 a
Dyne-Amic	25	55 fg	Activator 90	25	68 bc
Herbimax	25	58 efg	Agridex	25	70 bc
LI-700	25	60 defg	Destiny	25	73 bc
Liberate	25	68 cdef	Dyne-Amic	25	60 cd
MSO	25	74 bcde	Phase II	25	70 bc
Phase	25	65 cdef	Preference	25	68 bc
Silwet L-77	25	59 defg			

^zAs a result of the significant trial effect ($P < 0.0001$) in both groups of this experiment, estimates and their SES (Group 1 SE = 6.2, Group 2 SE = 6.1) are produced by mixed linear models and account for both the variance from the random effects and the error variance, creating a common SE (Littell et al., 1996).

^yMeans followed by the same letter, within columns, are not significantly different (Saxton, 1998).

spray nozzles, and simulated rainfall on 1-MCP efficacy.

Effect of spray volume on 1-methylcyclopropene efficacy. The protection of tomato plants by 1-MCP from ethephon was sensitive to spray volume. The higher the spray volume, the more efficacious was 1-MCP (Fig. 2). At a spray volume of 400 L·ha⁻¹, even the lowest amount of 1-MCP (10 g·ha⁻¹) significantly reduced leaf epinasty compared with ethephon alone (Fig. 2). In this test, however, the only treatment that gave complete protection against ethephon was 1-MCP at 50 g·ha⁻¹ sprayed at 400 L·ha⁻¹.

These results coupled with the surfactant results suggest that foliar coverage is very important for 1-MCP efficacy and that 1-MCP may have limited translocation in tomatoes. The surfactants that provided the best efficacy with 1-MCP (Dyne-Amic, Herbimax, Silwet L-77, Li-700) have all been shown to provide better leaf deposition and leaf coverage compared with other classes of surfactants in pea (Holloway et al., 2000). Li-700 has also been shown to be the best surfactant for the uptake of glycinebetaine (an osmoprotectant) in tomato (Mäkelä

et al., 1996). The organosilicone surfactants, in particular, greatly increase the spread of spray solution over the leaf surface (Tang et al., 2008; Zhu et al., 1994) and can increase the uptake rate of many herbicides (Roggenbuck et al., 1993; Singh and Mack, 1993). In addition, the activity of many contact-type herbicides that do not readily translocate in plants is increased as the spray volume increases (Knoche, 1994). Because the maximum activity of 1-MCP appears to depend on both spray volume and on surfactants that aid in the spread of the compound over the leaf, the compound probably does not readily translocate in tomato plants. Recent studies of postharvest tomatoes, avocados, and plums support that aqueous applications of 1-MCP require adequate coverage. When tomatoes and avocados were partially immersed in an aqueous 1-MCP solution, the treated parts of these fruits had delayed ripening compared with the untreated portion of the same fruit (Choi et al., 2008). Whole plums that were dipped in an aqueous solution containing 1-MCP had delayed ripening when compared with those dipped in tap water (Manganaris et al., 2007).

Fig. 2. The effect of 1-methylcyclopropene and spray volume rates on tomato leaf angles. Data were averaged for three replications per trial with two experimental trials run. *Means followed by the same letter, within columns, are not significantly different (Saxton, 1998).

Effect of spray nozzle type. Nozzle type did not influence the activity of 1-MCP on tomato (Table 2).

Rainfastness of 1-methylcyclopropene. In the simulated rain experiment, all three variables (1-MCP, rain treatment, and the interaction 1-MCP * rain treatment) showed significant effects when all three 1-MCP rates were analyzed together (Table 2). If only the 25 and 50 g·ha⁻¹ 1-MCP rates are analyzed, the interaction of rain * 1-MCP was not significant (df = 5, 195; $P = 0.1615$). Only two treatments (ethephon only and 25 g·ha⁻¹ 1-MCP with rain at 60 min) produced leaf angle averages significantly greater than the control, suggesting that rain as early as 15 min after 1-MCP application does not affect its performance on tomato epinasty.

Conclusions

Dyne-Amic consistently outperformed other surfactants in protecting tomato plants from the effects of ethephon. Neither nozzle type nor simulated rain as early as 15 min after 1-MCP application affected its protective effects against ethephon. In each experiment, the rate of 1-MCP had a significant effect on leaf angles; greater protection against exogenous ethylene was achieved when 1-MCP was applied at rates 25 g·ha⁻¹ and higher. The results presented here and from work previously reported in wheat (Hays et al., 2007) show that 1-MCP, when sprayed as a preventive measure, can be a successful tool against ethylene-mediated stress. Inherent differences between academic greenhouse research tests and true production conditions warrant further study of the effects 1-MCP would have in a field or large production greenhouse. Future field tests should not only include Dyne-Amic, but also Silwet L-77, Herbimax, and LI-700, the three surfactants that provided similar protection to Dyne-Amic.

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