Progress Toward Liquid Formulations of Particle Films for Insect and Disease Control in Pear

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ABSTRACT Particle film technology is aimed at controlling both arthropod pests and diseases of plants with a hydrophobic particle barrier primarily composed of kaolin. Field studies were conducted from 1996 to 1998 to compare the efficacy of dust and liquid applications, and hydrophobic and hydrophilic particle films, against key pests of pear. In addition, the effects of particle film applications on pear yield and quality were investigated in 1998. Dust and liquid applications of hydrophobic and hydrophilic particle films obtained high levels of early-season pear psylla control and prevented pear rust mite damage. We also found that prior seasonal applications of particle films in 1997 can carry over into the 1998 season to suppress early season pear psylla oviposition. A major concern in the shift from hydrophobic to hydrophilic particle films was the loss of disease control. We found that a water-repellant particle film was not required to control the fungal disease fabraea leaf spot. Pear yields were nearly doubled by liquid formulations of hydrophobic and hydrophilic particle films. Particle film deposits were measured using a spectrophotometer method we developed. Particle deposition differed among formulations for both leaf age and leaf surface (top or bottom). Yet, the particle formulations performed about the same against insects and fungal diseases, and in how they influenced the horticultural traits. None of the particle film formulations were found to be phytotoxic to pear foliage or fruit during the study period. A shift from hydrophobic to hydrophilic particles makes it possible to more easily formulate and disperse the particles in water so that conventional spray equipment can be used. The multifunctionality and low toxicity of particle films could make them an attractive alternative to conventional pesticides.

KEY WORDS particle films, insect repellent, kaolin, insect barrier

PARTICLE FILM TECHNOLOGY has emerged as a new method for controlling arthropod pests and diseases of agricultural crops (Glenn et al. 1999). The particle film is based on kaolin, a white nonabrasive fine-grained aluminosilicate mineral ($Al_4\ Si_4O_{10}[OH]_8$) that has been purified and sized so that it easily disperses in water. Kaolin particles can be coated with chrome complexes, stearic acid, organic zirconate, or other materials to make them hydrophobic (Harben 1995). The hydrophobic kaolin particle, M-96-018 (M96, Engelhard, Iselin, NJ) was the first prototype of particle film technology applied to trees as dust to make the plant surfaces water repellent (Glenn et al. 1999). This material suppressed arthropod pests and diseases by a number of different mechanisms. Fungal and bacterial diseases that require moisture to become infective were suppressed by coating the plant with a hydrophobic particle film barrier that prevented disease inoculum or water from directly contacting the leaf surface.

Arthropod infestations were suppressed by particle films for several reasons. Plants coated with a hydrophobic particle film barrier become visually or tactilely unrecognizable as a host. In addition, insect movement, feeding, oviposition, and other activities can also be severely impaired by the attachment of particles to the bodies of the arthropods as they crawled upon the film (Glenn et al. 1999).

Dust applications of particle films are not considered practical because of drift and lack of particle adhesion to the plant surfaces. For this reason, our research on particle film formulations was directed toward the development of kaolin particles suspended in water so these formulations could be applied with conventional spray equipment. We developed a method in which M96 hydrophobic particles are premixed with methanol (MeOH) so the particles can be disperse in water (Sekutowski et al. 1999). Once the spray solution dries, an even hydrophobic particle film resulted on plants that was capable of preventing arthropod infestations or disease infection (Puterka et al. 2000, Sekutowski et al. 2000). We conducted further laboratory research on particle films and found that hydrophobic and hydrophilic kaolin particles applied as liquid suspensions or dust essentially had the same activity in suppressing pear psylla oviposition

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(Puterka et al. 2000). Liquid formulations have now been developed that are based on M-97-009 kaolin (M97, Engelhard), which is the hydrophilic parent material of M96. With the aid of proprietary nonionic spreader stickers (Engelhard), M97 can be applied by conventional sprayers to coat the plant with a hydrophilic particle barrier.

A shift from the M96 plus MeOH formulation (M96/MeOH) to a nonmethanol formulation, such as M97 plus a spreader-sticker, would greatly improve the practical field use of particle films. To this end, a number of spreader-sticker agents were developed for liquid formulations of M97. This article reports our research on the effects of dust and liquid foliar applications of hydrophobic and hydrophilic particle films on two key pests of pear, the pear psylla *Cacopsylla pyricola* Foerster and fabraea leaf spot caused by the fungal organism *Fabraea maculata* Atkinson. In addition, we evaluated the influence of particle film formulations on other arthropod pests, along with the yield and quality components of harvested fruit.

Materials and Methods

Treatments and Experimental Design—1996. Experiments were conducted from 1996 to 1998 at the USDA-ARS Appalachian Fruit Research Station, Kearneysville, WV. In 1996, a 4-yr-old 'Seckel' pear orchard was used. Six treatments were evaluated: (1) hydrophobic M96 applied as dust, (2) hydrophilic M97 kaolin particles applied as dust, (3) M96 plus (S01) spreader-sticker (M96/S01) suspended in water, (4) S01 spreader-sticker control, (5) a conventional fungicide program, and (6) an untreated control. M96 solutions of 20% solids were made by adding 37.0 kg M96 to 189.0 liter of water that already contained 1.89 liter of S01 spreader-sticker. Vigorous agitation by an electric powered paint mixer was needed to mix the hydrophobic particles into water. Once M96/S01 was applied to foliage, an even film was produced, but M96 lost its hydrophobic properties and produced a hydrophilic particle film. This system was chosen because attempts to use the hydrophilic particle M97 with S01 did not produce a satisfactory film because the material spotted and ran off the leaves after application. The S01 spreader-sticker is a proprietary formulation (Engelhard) composed of plant and mineral-based materials.

Both dust and liquid applications were applied with a Solo backpack sprayer model 423 with a duster kit and mister kit (Solo, Newport News, VA) calibrated to deliver 100 g of dust or 2.0 liter of liquid suspension per tree. This spray rate was enough to coat the entire foliage of the tree with a white uniform particle film. Sixteen particle applications were made from 30 April to 10 August. The conventional fungicide program (Anonymous 1995) consisted of rotating Benlate 50 W ([wettable], 4.38 ml [AI]/ha), Ferbam 76 WDG (wettable dispersable granules], 3.36 kg [AI]/ha), and Ziram 76 WP ([wettable powder], 3.36 kg [AI]/ha) on a 14- to 20-d spray schedule for a total of five applications from 30 April to 10 August. No insecticides were used. Treatments consisted of single trees arranged in a randomized complete block with four replications. Untreated rows were left between treatment rows and untreated trees were left at both ends of each treatment within rows to serve as spray buffers.

Treatments and Experimental Design—1997. The study was conducted in a 6-yr-old Seckel pear orchard. Five treatments were evaluated: (1) M96 suspension of 3% solids with 4% MeOH in water (5.6 kg M96 premixed with 7.5 MeOH then added into 189.0 liter of water) to produce a hydrophobic particle film; (2) M97 suspension of 3% solids with 0.8% spreader-sticker (5.6 kg M97 added to 189.0 liter of water that contained +0.8 liter M03 and 0.9 liter T01 = M97/M03 + T01) to produce a hydrophilic particle film; (3) conventional fungicide and insecticide spray programs; (4) 0.8 liter M03 and 0.9 liter T01 spreader sticker control; and (5) an untreated control. A MeOH and M03 + T01 control was not included because previous studies found that water solutions containing as high as 10% MeOH, and M03 + T01 at 3 times the 0.8% use rate in water (vol.:vol.) did not affect psylla nymphal survival or adult ovipositional activity (G.J.P., unpublished data). Both the M03 and T01 are proprietary formulations (Engelhard) composed of a mixture of plant oils and nonionic surfactants. Treatments were applied by a tractor mounted PTO-driven sprayer (AirKadet II, Friend Manufacturing, Gasport, NY) configured with a handgun that was adjusted to apply 1,893.0 ml per tree in 40 s at 3.45 kg/cm^2. Spray applications completely wetted the pear leaves to drip and are what would be considered a dilute application (3740 liter/ha). Spray times were reduced to 20 s to reduce spray volumes to those required for the conventional pesticidal materials. Spray applications were made 24 March to the 1 August. Particle film and spreader-sticker control treatments were applied on a 7- to 14-d schedule for a total of 16 applications during the study period. Applications were made after rains whenever possible in the spring season and short application intervals (7–10 d) were used to cover new plant growth. Application intervals were extended for up to 14 d when new tree growth and rains subsided during late June and July. The conventional fungicide and insecticide programs used materials and spray schedules recommended in spray guide recommendations for our region (Anonymous 1995). The conventional pesticide program included the same fungicides and spray schedule used in 1996. The insecticides included 2% Superior Oil 435 (37.4 liter [AI]/ha) applied at delayed-dormant and Agri-Mek 0.15 EC (20.86 g [AI]/ha) applied on the 20 June when pear psylla nymphal densities peaked. The treatments consisted of four-tree blocks that were arranged in a randomized block design with three replications Untreated rows and buffers were included as in the 1996 study.

Treatments and Experimental Design—1998. This study was conducted in an 8-yr-old Seckel pear orchard. Seven treatments were examined: (1) M96 suspension of 3% solids with 4% MeOH in water, (2) M97

suspension of 3% solids with 0.8% spreader-sticker, (3) M97 suspension of 3% solids with 0.12% L01 spreader sticker (Engelhard) (5.6 kg M97 added to 189.0 liter of water that contained +0.23 liter L01), (4) a conventional pesticide program (Anonymous 1995), (5) M03 (0.8 liter/189.0 liter water) + T01 control (0.9 liter/189.0 liter water), (6) L01 control (0.23 liter/189.0 liter water), and (7) untreated control. A MeOH control was not included for the same reasons given in the 1997 study. However, M03 + T01 control was included in this study to examine long-term use effects. The L01 spreader-sticker is similar to M03 and T01 in that it is a proprietary product (Engelhard) composed of a mixture of plant oils and nonionic surfactants. The conventional insecticide program was directed toward control of pear psylla and included Asana XL (3.65 ml [AI]/ha) and 2% Superior oil 435 (37.4 liter [AI]/ha), Mitac (0.13 g [AI]/ha) or Mitac (0.08 g [AI]/ha) plus Imidan 70 WP (3.48 kg [AI]/ha), and Agri-Mek 0.15 EC, 20.86 g [AI]/ha). The fungicides used were the same as those in the 1996 study except that seven applications were made because of the severity of fabraea leaf spot infections. Treatments were applied by a tractor mounted PTO-driven sprayer at the same rates used in the 1997 study. Spray applications of conventional pesticides, particle films and spreader-sticker controls began 1 April and ended 1 August. Particle film and spreader-sticker control treatments were reapplied on a 7- to 14-d schedule as in 1997 for a total of 15 applications. Treatments consisted of single trees arranged in a randomized complete block with four replications. Buffer rows and untreated trees were included in the design.

Arthropod and Disease Sampling and Data Analyzes. Season-long effects of the treatments on arthropod pests and disease were determined by sampling the trees every 12-16 d. Sampling began 22 May 1996, 17 March 1997, and 10 April 1999 and continued up to, or several weeks after, pear harvest.

Egg, nymph, and adult psylla numbers were counted on 25.4-cm twig terminals. In 1996 and 1998, psylla numbers were obtained from 20 terminals per single tree treatment. In 1997, psylla numbers were recorded from 10 terminals per tree from the center two trees of a four-tree treatment block. In 1996, we measured the numbers of leaves per 25.4 cm of terminal. Pear rust mite [*Epitrimerus pyri* (Nalepa)] and fabraea leaf spot damage was also evaluated on four 25.4-cm long terminals, using a 1–4 scale (1 = none, 2 = 1–25%, 3 = 50–75%, 4 = 75–100%). In 1997 and 1998, total numbers of leaves, infected leaves, and number of fabraea leaf spot lesions per leaf were recorded on four 25.4 cm long twig terminals. Numbers of fallen leaves within a 1-m^2 wire hoop were recorded by tossing the hoop under the tree canopy in three random locations.

Because of early-season frosts in 1996 and 1997, no fruit was available for damage and yield assessment. Arthropod and disease damage from 50 fruits per tree was assessed in 1998, as was fruit yield per tree and number of fruit per tree. The uniformity of tree size did not require fruit yield to be converted to yield per unit of trunk cross-sectional area. Fruit weight, diameter, firmness, and percentage of red area was determined from 10 randomly selected fruit per tree.

Arthropod, disease, and harvested fruit data were analyzed by analysis of variance and those data sets with significant treatment effects ($P < 0.05$) were compared using the least significant differences method least significant difference (LSD) at $\alpha = 0.05$ (SAS Institute 1998).

Quantification of Particle Film Deposits. The amount of particles deposited on leaves by the various particle film treatments were measured to determine deposition and weathering characteristics. Leaves were collected 24 h before and 4 h after the 5 May 1998 application. At this date, a total of five particle applications had been made. Leaves were collected from the inner (mature leaves) and outer (fresh growth) canopy, and data on particle weights were taken from the top and bottom leaf surfaces. Leaves ($n = 10$ per branch position per tree) were collected from the fourth fully expanded leaf position (new growth treated only once) and from leaves 0.5 m down the tree branch (mature and treated five times).

The upper and lower leaf surfaces of the leaves ($n = 10$ per position per tree) were imaged using a Canon RE 350 Video Visualizer (Lake Success, NY) and Snappy video analyst package (version 3.0) (Rancho Cordova, CA) using 1,280 × 1,024 dpi resolution and black and white imaging to determine leaf area. Once the photos of the upper and lower surfaces were taken, five leaves were used to quantify the particle film on the top surface and the remaining five leaves were used for the bottom surface analysis. When quantifying particles on the top surface, the particle film on the lower surface was carefully wiped away with an alcohol-dipped cotton ball. The top surface of the leaf was cleaned in the same manner for analysis of particles on the lower leaf surface.

After the leaves were imaged for leaf area, the particles were removed from a leaf surface by placing a 5-leaf sample into a 50-ml centrifuge tube, adding 25 ml MeOH, and shaking the tube for 15 s to dislodge the particles before the leaves were removed. Each sample was sonicated for 10 s to disperse the particles before 0.5 ml of sample was placed in a microcubette so that an absorbency value could be determined by a spectrophotometer (Pharmacia Biotech Ultrospec 3000, (Piscataway, NJ)) at 400 nm. The weight of the particles in solution (μg particles per milliliter of MeOH) was calculated by entering the absorbency value of a sample into a regression equation (x-axis = absorbency value, y-axis = μg particles per milliliter of MeOH) for that particular particle formulation. Regression equations were generated by obtaining absorbency values from a series dilution of that particle formulation (10 increments of 100 μg of particles from 1.6 to 1,600.0 μg) that was regressed against known particle weights for each sample. Three replicates per dilution rate were done for each particle formulation so that the spectrophotometer could generate a standard curve, coefficient of determination (r^2) and standard errors, before leaf samples were evaluated. Par-

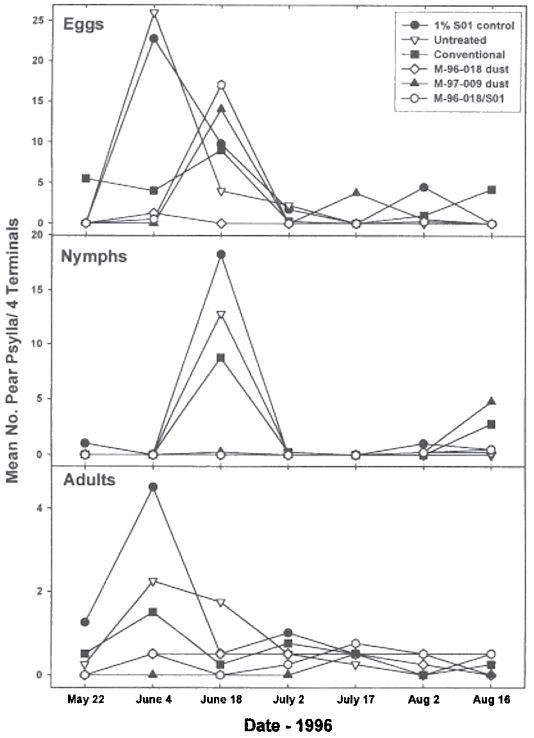

Fig. 1. Seasonal dynamics of pear psylla egg, nymph, and adult levels on Seckel pear in the particle film study, 1996, Kearneysville, WV.

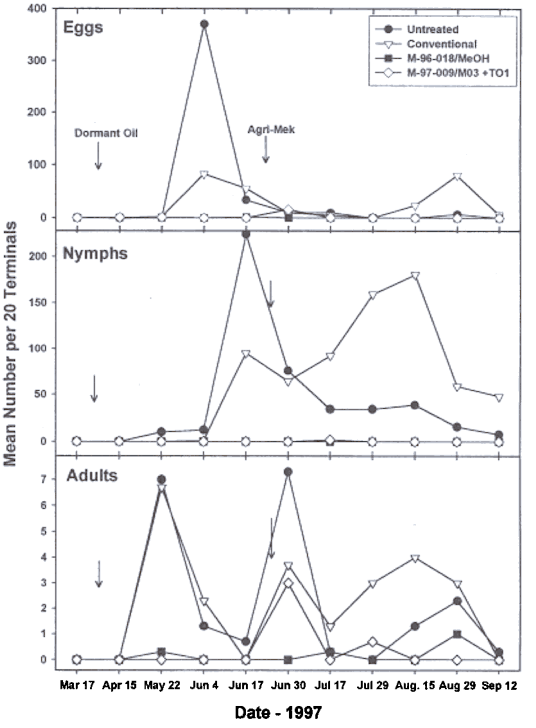

Fig. 2. Seasonal dynamics of pear psylla egg, nymph, and adult levels on Seckel pear, in the particle film study, 1997, Kearneysville, WV.

ticle densities for each sample (micrograms of particles per milliliter of MeOH) could then be automatically estimated by the spectrophotometer. With the total leaf area known, we could calculate μg particles per square centimeter of leaf surface. Data were analyzed as a 3(treatment) × 2(leaf age) × 2(leaf surface) factorial experiment and treatment means were compared using the LSD method at $\alpha = 0.05$ (SAS Institute 1998).

Results

Pear Psylla and Rust Mite, 1996 Season. Pear psylla egg and nymph numbers were significantly reduced by the particle film treatments, regardless of whether applications were as liquid or dust (Fig. 1). Low adult psylla numbers and variability among treatments resulted in no significant differences among treatments.

Egg numbers peaked 4–18 June, and declined after (Fig. 1). During peak ovipositional activity, 4 June, there were no significant differences between the particle film treatments and conventional spray program ($P = 0.007$). Particle film and the conventional treatments had significantly reduced egg numbers compared with the untreated and S01 controls on 4 June, but not on 18 June. Suppression of oviposition resulted in significantly fewer nymphs on 18 June ($P = 0.01$) in the particle film treatments compared with the

Table 1. Mite and disease damage levels for dust and liquid applications of kaolin particles versus other treatments in a 'Seckel' pear orchard, 15 August 1996, Kearneysville, WV

Treatment	Type of application	Mite damage[a]	Fabraea damage[a]	No. leaves/terminal
M-96-018 Kaolin				
M-97-009 Kaolin				
20% M-96-018/1% SO1				
1% S01 control				
Untreated control				
Conventional fungicides				

Means within columns followed by the same letter are not significantly different, Kruskal–Wallis k sample test ($P > \chi^2 = 0.01$). Means for four 25.4-cm terminals per replicate; 4 replicates. M-96-018 and M-97-009 treatments had 16 applications 7-10 d apart starting 30 April 1996.

[a] Mite damage and fabrea leaf spot damage scale: (1) none, (2) light (1–25% leaf area), (3) moderate (50–75% leaf area) (4) Heavy (75–100% leaf area). Leaf damage on 10 6-inch terminals per tree.

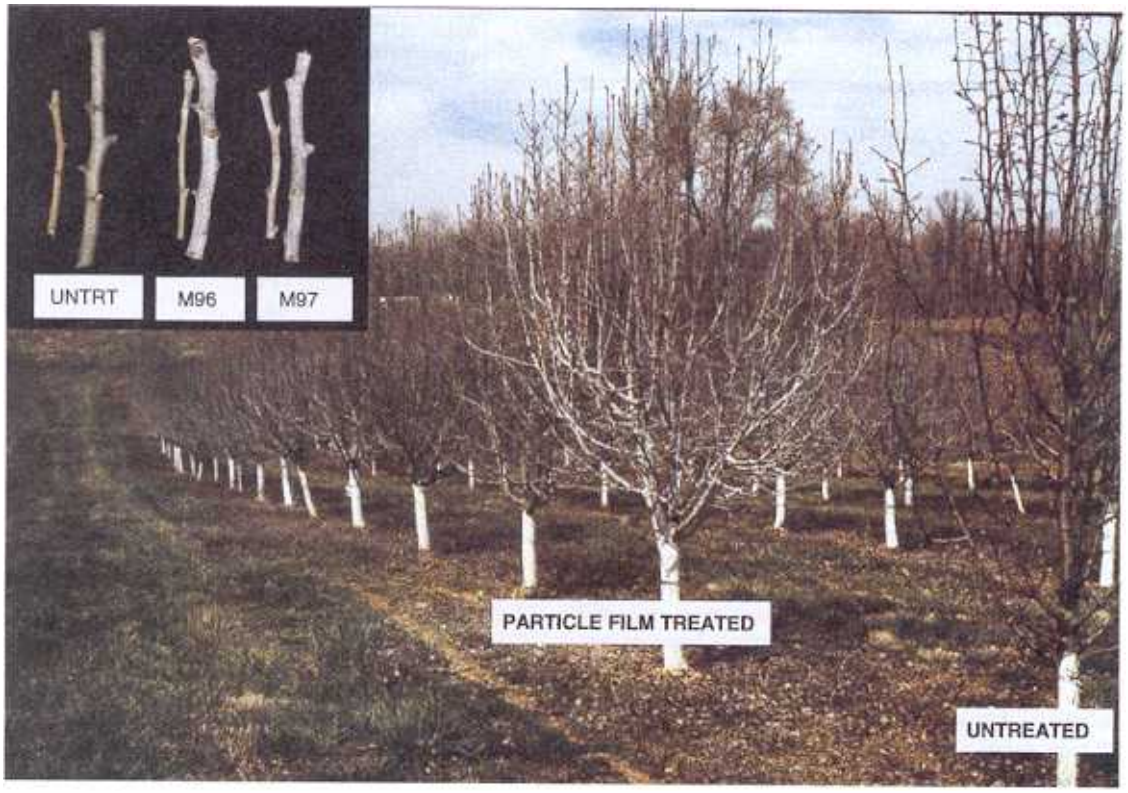

Fig. 3. White particle film residues present on dormant pear trees, March 1998, after particle film treatments in 1997. White residues had significant carry-over effects by suppressing pear psylla oviposition. Inset: Twigs showing the differences in white color between the untreated control (UNTRT) and the particle film formulations, M-96-018 + MEOH (M96) and M-97-009 + M03 and T01 spreader-stickers (M97).

conventional treatment, and the S01 and untreated controls.

Pear leaf russet that resulted from pear rust mite infestations were significantly reduced by the particle film treatments (χ^2 = 20.49, df = 5, $P > \chi^2$ = 0.001) compared with the S01 spreader sticker control, conventional fungicide, and untreated control (Table 1).

Pear Psylla—1997 Season. Both the M96/MeOH hydrophobic and M97/M03+T01 hydrophilic particle films greatly suppressed pear psylla egg, nymph and adult numbers (Fig. 2). During peak ovipositional periods on 4 June, egg numbers in the particle and conventional insecticide treatments were significantly lower than the untreated control (P = 0.01). On 17 June, particle film treatments did not differ significantly from each other or from the untreated control. However, these treatments had significantly lower egg numbers than the conventional insecticide treatment (P = 0.05).

Both particle film formulations significantly reduced nymphal densities compared with the conventional and untreated control treatments beginning 17 June, and continued to do so until 29 August (P = 0.001–0.05). Adult numbers were similarly reduced by both particle films treatments during the season. All growth stages of pear psylla began to increase a few weeks after the 20 June Agri-Mek treatment. Yet, psylla numbers generally declined over the season in particle film treated and untreated control plots.

Carry-Over Effect of the 1997 Treatments on Pear Psylla Oviposition in 1998. All of the particle film treatments had turned the bark of the pear trees noticeably white at the end of the 1997 season (Fig. 3). The twigs and limbs remained white through the winter into the spring, 1998. The white residues from all of the particle film treatments, excluding M97/M03 + T01, significantly reduced pear psylla oviposition in comparison to the conventional treatment and untreated control (P = 0.02) during the delayed-dormant period of bud development, 27 March (Table 3). Suppression of oviposition continued through green-tip bud stage, 2 April, as all particle film treatments significantly reduced oviposition compared with the untreated control and conventional treatment (F = 7.85; df = 3, 6; P = 0.01). There were no significant differences among treatments after 2 April when leaves and flower buds began to appear (data not shown).

Pear Psylla—1998 Season. Particle film formulations significantly suppressed early season pear psylla ovipositional activity during the delayed-dormant (F = 3.51; df = 6, 18; P = 0.01) to green-tip stages (F = 10.54; df = 6, 18; P = 0.0001) of pear tree development

Table 2. Carry-over effects of 1997 particle film applications on early season psylla oviposition the following year, 1998, Kearneysville, WV

Date	Mean no. of eggs/terminal		
	19 Mar.	26 Mar.	2 April
Untreated			
Conventional			
M-96-018/MEOH			
M-97-009/M03 + T01			

Means within columns followed by the same letter are not significantly different, LSD, $P = 0.05$. Mean eggs per terminal found on ten 6-inch terminals on 2 trees per treatment ($n = 20$); 3 replications.

(Table 3). The most pronounced effect of particle films on oviposition was during the green-tip stage, as all particle film formulations significantly reduced egg numbers in comparison to the untreated control, spreader-sticker and conventional Asana plus Superior oil treatments. Particle films continued to significantly suppress oviposition ($P = 0.05$) in comparison to the untreated control and spreader-sticker controls up to 18 May (Fig. 4). After this time, no meaningful differences occurred among treatments because egg counts became quite variable and continued to do so up to the 30 June. Oviposition declined sharply after 30 June and remained low for the rest of the season in all treatments.

From 10 April to 5 May, all particle film treatments yielded significantly lower nymphal densities ($P = 0.003$) than those in the untreated control, sticker controls, and conventional treatments (Fig. 4). A difference in particle film performance was noted on 5 June where M96 and M97/M03+T01 treatments had lower nymphal densities than M97/L01 and the untreated control, spreader-sticker controls, and conventional treatments ($F = 2.65$; df = 6, 18; $P = 0.05$). No significant differences among treatments occurred after 5 June.

Adult numbers peaked only once during the season on 18 May (Fig. 4) and this was the only time a difference among treatments was noted. During this peak ovipositional period, egg numbers were significantly lower for M96 and M97/T01+M03 than in the rest of the treatments and controls ($F = 3.35$; df = 6, 18; $P = 0.03$).

Table 3. Mean pear psylla egg densities in the particle film study following delayed-dormant applications, of particle films in 'Seckel' pear beginning 23 March 1998, and 7- to 10-d intervals thereafter

Treatment	Eggs/terminal	
	3/27	4/2
M-96-018/MEOH	5.0 ± 4.3bc	0.3 ± 0.2b
M-97-009/L01	2.0 ± 0.9c	0.3 ± 0.1b
M-97-009/M03 + T01	8.9 ± 3.9abc	0.9 ± 0.2b
L01 control	19.2 ± 2.7a	4.4 ± 0.3a
M03 + T01 control	16.1 ± 2.5a	3.2 ± 0.3a
Conventional	13.8 ± 4.9ab	3.9 ± 1.4a
Untreated	20.2 ± 4.0a	6.2 ± 1.2a

Means within columns followed by the same letter are not significantly different, LSD, $P = 0.05$. Mean eggs per terminal found on 20 6-inch terminals per tree; 4 replications.

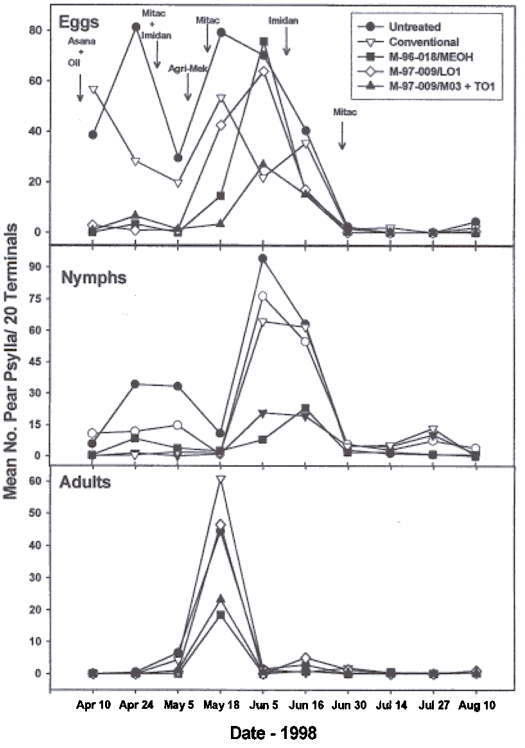

Fig. 4. Seasonal dynamics of pear psylla egg, nymph, and adult levels on Seckel pear in the particle film study, 1998, Kearneysville, WV.

Particle Film Treatment Effects on Fabraea Leaf Spot—1996 to 1998. In 1996, both the kaolin dust treatments and the kaolin liquid treatment significantly reduced fabraea leaf spot damage ($\chi^2 = 19.62$, df = 5, $P > \chi^2 = 0.002$) compared with the untreated control (Table 1). Furthermore, both hydrophilic kaolin dust (M97) and liquid (M96/S01) applications significantly reduced fabraea leaf spot damage to lower levels than the hydrophobic M96 dust application. Reduced leaf damage by mites and disease was evident by the greater numbers of leaves per terminal that resulted from much less leaf drop in the particle film treatments than in the conventional fungicide or control treatments ($F = 38.1$; df = 5, 15; $P = 0.0001$).

In 1997, the hydrophobic and hydrophilic particle films had similarly reduced fabraea leaf spot late in the season (Table 4). These two particle formulations had significantly lower percent infected leaves ($F = 8.17$; df = 3, 11; $P = 0.01$), fewer lesions per leaf ($F = 4.56$; df = 3, 11; $P = 0.05$), more leaves per terminal ($F = 10.5$; df = 3, 11; $P = 0.008$), and had fewer leaves drop ($F = 6.13$; df = 3, 11; $P = 0.02$) from disease in comparison to the conventional fungicide program and untreated control. By the end of the season, the untreated control trees had become almost completely defoliated from disease, while the particle film treated trees still had full healthy canopies (Fig. 5).

Table 4. Mean ± SE fabraea leaf spot infection comparison among liquid particle film applications, conventional fungicide program, and untreated control in 'Seckel' pear, 5 September 1997, Kearneysville, WV

Treatment[a]	% infected leaves	No. of lesions per infected leaf	No. of leaves per 10″ terminal	No. of fallen leaves
Untreated	98.6 ± 1.3a	45.1 ± 7.7a	5.7 ± 2.5c	47.2 ± 15.2ab
Conventional	86.0 ± 14.0a	41.3 ± 14.4a	16.5 ± 4.9b	62.3 ± 35.8a
3% M-96-018/4% MEOH	26.6 ± 17.6b	6.1 ± 4.0b	28.9 ± 1.2a	9.5 ± 6.0b
3% M-97-009/M03 + T01	20.6 ± 8.5b	6.0 ± 3.5b	25.3 ± 1.2a	8.8 ± 1.7b

Means within columns followed by the same letter are not significantly different, LSD, $P = 0.05$. Mean for 4, 10-inch terminals per replicate; 3 replicates.

[a] M-96 and M-97 treatments had 16 applications since 11 March 1997. Conventional program had three monthly fungicide applications of Rubigan + Ferbam or Benelate + Ziram.

The monthly conventional spray program apparently was not sufficient to control leaf spot, yet, it did not become defoliated like the untreated control.

In 1998, the progression of fabraea leaf spot damage was significantly affected by all particle film treatments through midseason (Fig. 6). Particle film treatments significantly reduced percent infected twig terminals and leaves over the other treatments from 5 May to the 5 June. No treatments, including conventional fungicides, were able to significantly reduce late season leaf spot infection. There were no significant differences in total numbers of leaves, infected leaves, and number of leaf spot lesions per leaf among treatments.

None of the particle film treatments used in the 1996–1998 studies caused any characteristic signs of phytotoxicity (e.g., leaf yellowing, leaf burn), not even toward at the end of the season when particle residues had accumulated.

Postharvest Evaluations of Insect and Disease Damage to Fruit—1998. Insect damaged fruit was generally low, which resulted in few significant differences among treatments (Table 5). Particle film formulations significantly reduced plum curculio [*Conotrachelus nenuphar* (Herbst)] ovipositional scarring of the fruit ($F = 6.54$; df = 6, 18; $P = 0.0009$), compared with the untreated control. However, ovipositional scarring did not significantly differ between the M97/M03 +

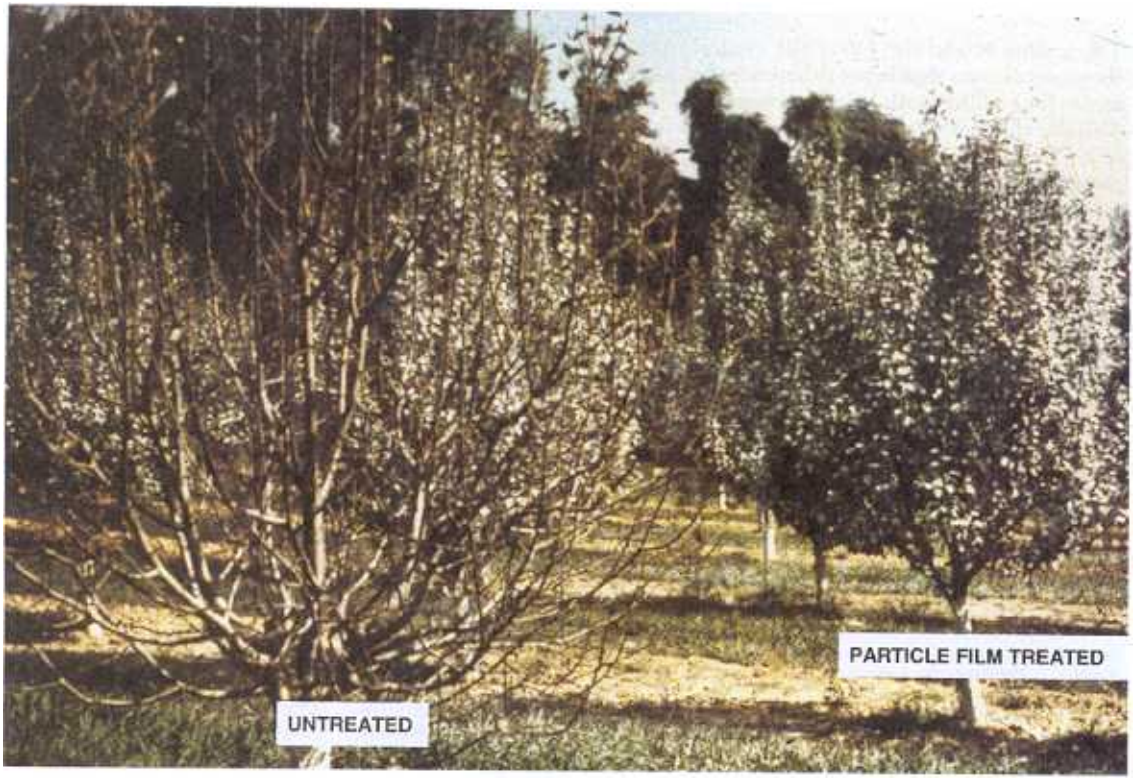

Fig. 5. Severe fabraea leaf spot infections in Seckel pear trees caused nearly total defoliation in untreated control trees, whereas particle film treated trees had healthy full canopies, 1997, Kearneysville, WV.

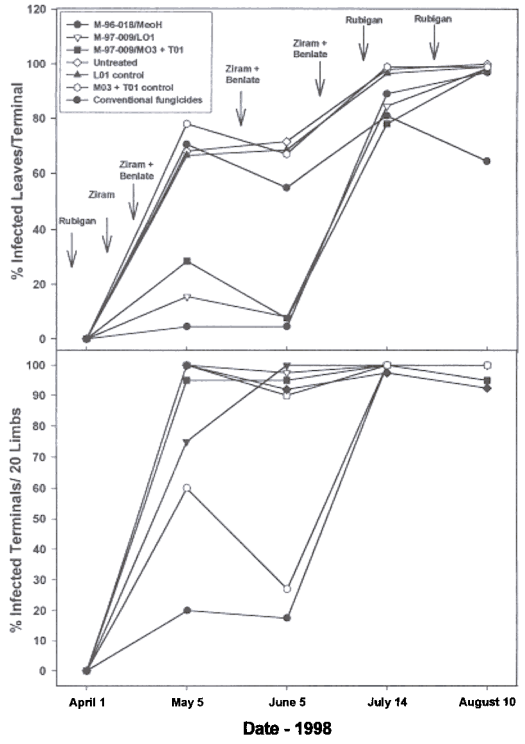

Fig. 6. Progression of fabraea leaf spot damage in the particle film study on Seckel pear, 1998, Kearneysville, WV.

T01 treatment and the M03+T01 control. Although there were some significant differences among treatments for codling moth [*Cydia pomonella* (L.)] (F = 4.87; df = 6, 18; P = 0.004) and stinkbug [*Acrosternum hilare* (Say)] (F = 3.18; df = 6, 18; P = 0.02) damage, particle film treatments did not differ significantly from the untreated controls or the spreader-sticker controls.

Fruit damaged by fabraea leaf spot was significantly reduced by the M97/M03 + T01 treatment (F = 5.22; df = 6, 18; P = 0.002) (Table 5), compared with the M03 + T01 and untreated controls. However, the other particle film formulations had no effect on leaf spot damaged fruit.

The hydrophobic film, M96/MeOH, had a neutral effect on pear scab [*Venturia pirina* Aderhouse], whereas the hydrophilic films, M97/L01 and M97/M03 + T01, significantly increased scab damage in comparison to the untreated control (F = 3.18; df = 6, 18; P = 0.02). The M03 + T01 spreader-sticker system did not contribute to scab infection. However, the high infection levels for the L01 spreader-sticker control indicated that this formulation additive alone may have contributed to increased scab infection.

Yield and Quality Assessments on Pear Fruit Harvested in 1998. Particle film treatments significantly enhanced yield in Seckel pear that had not been chemically or hand thinned (Table 6). All three particle film treatments had nearly doubled pear yield (F = 10.1; df = 6, 18; P = 0.0001) in comparison with their respective spreader-sticker controls, conventional program, and untreated control. This increase was reflected by higher numbers of fruit per tree in the M96/MeOH and M97/L01 treatments. Fruit weight and diameter were not significantly different among the treatments despite higher fruit loads in the particle film treatments. Fruit firmness was affected only by M-96-018 (F = 9.10; df = 6, 18; P = 0.002). Seckel pear color is normally bicolored green and red. Increases in red fruit color were most pronounced in the M96/MeOH treatment, followed by M97 formulated with either spreader-sticker (F = 13.9; df = 6, 18; P = 0.0001). Pear color had a uniform red blush and no spotting from particle film deposits was evident (Fig. 7). Furthermore, none of the particle film treatments showed any signs of phytotoxic effects to pear fruit (e.g., necrotic lesions, discoloration) during the course of the study. All particle film residues could be easily wiped from the fruit.

Particle Film Deposition. Absorbency values obtained for the serial dilutions of each particle formulation (data not shown) were highly correlated with light absorbance at 400 nm (r^2 ranged from 99.9 to 100, df = 6, P = 0.01). Weathered particle film residues evaluated 24 h before re-treatment (Table 7) showed significant main effects for particle treatment (F = 22.68; df = 2, 36; $P < 0.0001$), leaf age (F = 16.4; df = 1, 36; P = 0.0003), and leaf surface (F = 8.64; df = 1, 36; $P < 0.006$). First-order interactions for treatment × leaf age (F = 8.57; df = 2, 36; P = 0.0009) and leaf age × leaf surface (F = 8.00; df = 1, 36; P = 0.008) were significant, whereas the treatment × leaf surface interaction was not (F = 0.92; df = 2, 36; P = 0.40).

Particle residues measured 4 h after the particle treatments were applied had significant main effects

Table 5. Mean ± SE insect and disease damage on 'Seckel' pear harvested 19 August 1998

Pest type	Organism	Treatments						
		Untreated	Conventional	M-96-018/ MEOH		L01 control	M-97-009/ M03 + T01	M03 + T01 control
Insect	Plum curculio feeding	0.0 ± 0.0b	0.7 ± 0.5a	0.0 ± 0.0b	0.0 ± 0.0b	0.0 ± 0.0b	0.2 ± 0.2ab	0.3 ± 0.3ab
	Plum curculio oviposition	3.3 ± 1.1ab	1.7 ± 1.0bc	0.0 ± 0.0c	0.0 ± 0.0c	3.7 ± 0.8a	0.0 ± 0.0c	1.0 ± 0.4c
	Coding moth	5.3 ± 0.8bc	11.5 ± 3.9ab	1.5 ± 0.0c	6.8 ± 1.9bc	14.7 ± 2.4a	2.7 ± 0.2c	5.7 ± 1.7bc
	Green stinkbug	1.3 ± 0.5b	3.2 ± 1.2a	0.2 ± 0.2b	0.75 ± 0.2b	1.8 ± 0.6ab	0.2 ± 0.2b	2.0 ± 0.4ab
	Fabraea leaf spot	34.3 ± 8.1a	6.7 ± 2.9c	29.0 ± 4.0ab	35.7 ± 3.8a	35.0 ± 6.7a	17.2 ± 2.9b	34.8 ± 5.4a
	Pear scab	4.0 ± 1.7c	7.7 ± 2.1bc	6.5 ± 0.5bc	14.7 ± 2.7a	10.7 ± 2ab	11.7 ± 1.2ab	3.0 ± 2.3c

Means within rows followed by the same letter are not significantly different, LSD, P = 0.05. Means for 50 fruit per tree; 4 replicates.

Table 6. Particle treatment effects on pear yield components following harvest on 16 August 1998, Kearneysville, WV

Treatment	Yield and quality components					
	Yield, kg	No. fruit/Tree	Fruit wt, g	Fruit diam, mm	Fruit firmness	% red area
Untreated	28.3 ± 4.5b	793.0 ± 145cd	36.5 ± 2.0c	38.5 ± 0.8b	16.9 ± 0.5a	27.5 ± 4.4c
Conventional	27.0 ± 4.1b	590.3 ± 120.8d	47.4 ± 3.0a	42.7 ± 0.9a	17.6 ± 0.5a	32.3 ± 4.3c
M-96-018/MEOH	54.0 ± 4.8a	1237.0 ± 130.8ab	44.2 ± 2.8ab	40.9 ± 1.2ab	14.6 ± 0.3b	56.5 ± 0.6a
M-97-009/L01	54.8 ± 5.0a	1392.3 ± 225.2a	41.2 ± 4.6abc	41.7 ± 1.9a	16.6 ± 0.3a	45.5 ± 1.5b
L01 control	28.2 ± 4.8b	782.0 ± 160.4dc	37.1 ± 1.9bc	38.5 ± 0.8b	16.9 ± 0.8a	31.6 ± 2.0c
M-97-009/M03 + T01	45.4 ± 0.8a	1129.3 ± 41.9abc	40.4 ± 1.5abc	41.5 ± 1.0ab	16.4 ± 0.3ab	40.5 ± 3.3b
M03 + T01 control	30.6 ± 1.3b	860.5 ± 41.9bcd	35.8 ± 1.6c	38.8 ± 0.4b	17.8 ± 0.4a	31.8 ± 2.2c

Means within columns that are followed by the same letter are not significantly different (LSD, $P = 0.05$). Mean yield and fruit/four replicates. Mean fruit weight, diameter, firmness and percent red area for 10 fruit/tree; four replicates for 100 fruit/treatment/replicate.

for particle treatment ($F = 3.24$; df = 2, 36; $P = 0.05$), leaf age ($F = 18.0$; df = 1, 36; $P = 0.0001$), and leaf surface ($F = 199.3$; df = 1, 36; $P = 0.0001$). All first-order interactions for treatment × leaf age ($F = 4.45$; df = 2, 36; $P = 0.02$), leaf age × leaf surface ($F = 8.71$; df = 1, 36; $P = 0.005$), and treatment × leaf surface interactions ($F = 3.26$; df = 2, 36; $P = 0.05$) were significant. The second-order interactions were not significant before ($F = 0.35$; df = 2, 36; $P = 0.37$) or after ($F = 0.43$; df = 2, 36; $P = 0.65$) treatment.

Comparisons among treatments revealed that those weathered particle residues present 24 h before treatment (Table 7) did not differ on the top ($F = 2.38$; df = 2, 6; $P = 0.17$) or bottom ($F = 0.67$; df = 2, 6; $P = 0.50$) surfaces of young leaves. However, both the hydrophobic M96/MeOH and hydrophilic M97/L01 formulations had significantly lower particle residues than the M97/M03+T01 formulation on the top ($F = 11.34$; df = 2, 6; $P = 0.009$) and bottom ($F = 36.67$; df = 2, 6; $P = 0.0004$) surfaces of mature leaves.

Measurements of fresh particle deposits taken 4 h after treatment (Table 7) revealed that M96/MeOH and M97/M03 + T01 had significantly greater residue than M97/L01 on the tops of young leaves ($F = 10.95$;

Fig. 7. Seckel pear with typical particle film residues just before harvest, 16 August 1998. Note uniform red color and healthy appearance of leaves and fruit after a season-long particle film program.

Table 7. Quantification of particle film residues on young and mature pear leaves at pre- and postapplication periods, 5 May 1998

Sample period	Treatment	Particles ($\mu g/cm^2$)[a] on young leaves		Particles ($\mu g/cm^2$)[a] on mature leaves	
		Top	Bottom	Top	Bottom
24 h before treatment	M-96-018	11.9 ± 2.7a		24.6 ± 4.9b	
	M-97-009/L01	23.0 ± 5.4a		33.6 ± 3.5b	
	M-97-009/M03 + T01	25.7 ± 7.9a		56.0 ± 5.8a	
4 h after treatment	M-96-018	103.7 ± 13.3a		124.0 ± 13.4a	
	M-97-009/L01	74.8 ± 8.8b		109.9 ± 8.9a	
	M-97-009/M03 + T01	90.4 ± 6.0a		151.6 ± 14.2a	

For each sample period, means within columns followed by the same letter are not significantly different, LSD, $P = 0.05$. Mean for five leaves/surface; four replications.

[a] Mean values ($\mu g/cm^2$) for the particle treatments were adjusted by subtracting background particle values obtained from corresponding spreader/sticker controls.

df = 2, 6; $P = 0.01$). This relationship was reverse on the bottom sides of young leaves ($F = 9.59$; df = 2, 6; $P = 0.01$). Particle residues did not differ significantly on the top or bottom surfaces of mature leaves ($P > 0.05$).

Discussion

Particles applied as liquids or dust in 1996 provided strong early season suppression of psylla oviposition and nymphal infestations, as well as late season suppression of rust mites. We established that hydrophobicity of a particle film is not a key factor in arthropod pest suppression and that hydrophilic films gave satisfactory suppression in 1997 and 1998. Our field results are consistent with those obtained by Puterka et al. (2000) who found that hydrophobic or hydrophilic kaolins gave similar control of pear psylla.

We discovered that prior seasonal applications of particle films in 1997 can carry-over into the 1998 season to suppress early season pear psylla oviposition. Pear psylla adults are known to visually respond to color and their preference for yellow changes over the season (Krysan and Horton 1991). Overwintering adults also use tactile cues to determine suitable oviposition sites on pear budwood and leaves (Horton 1990). Particle residues that carried over into the next season on dormant budwood no longer had a loosely bound particle film and the white particles appeared to be incorporated into the waxy cuticle of the bark. This finding suggests that alterations in the color or cuticle structure of tree bark could be responsible for reduced oviposition. We have also found that psylla adults will visit particle treated plants in confined laboratory arenas, but are quickly repelled (G.J.P. and D.M.G, unpublished data). Therefore, alterations in the color or surface texture of bark by a white particle film are plausible mechanisms that warrant further investigation, along with other factors such as particle attachment to the insect's body. These mechanisms may also change over the season, based on studies of other researchers (Horton 1990, Krysan and Horton 1991).

Pear psylla management is mainly directed toward reducing oviposition of overwintering adults by the use of dormant oils, and control of first generation nymphs with conventional insecticides. Particle films may offer a suitable alternative to these materials for control of early season pear psylla infestations. Pear russet caused by the pear rust mite is a significant problem that particle films could potentially solve. Insect damage on harvested fruit was largely inconclusive because of the low levels of insect damage and only one season's data. Particle film treatments did show promise in reducing plum curculio ovipositional damage.

Glenn et al. (1999) suggest that the waterproof barrier produced by a hydrophobic particle film is required for disease control. We obtained high levels of fabraea leaf spot suppression by particle films applied as liquid or dust, regardless of whether the films were hydrophobic or hydrophilic. How particle films influence infection by disease organisms is not well understood. Hydrophilic particle films do control this particular disease, but it is probable that the influence of particle films on infections by other diseases will be as variable as their etiology. Our results indicate that high levels of leaf spot suppression can be obtained up to midseason. However, fungicide treatments will likely be needed after this time to protect the leaves and fruit. This would also be about the time fungicide applications for pear scab would be required because neither hydrophobic nor hydrophilic particle films controlled scab. Limiting fungicide treatments to the later half of the season could still greatly reduce fungicide input in pear orchards.

We documented that pear yield and quality were enhanced by hydrophobic and hydrophilic particle films. Increased fruit yields from particle film treatments resulted from higher fruit numbers, possibly a result of better fruit set and less fruit drop. Although fruit set was higher in the particle film treatments, the fruit size was higher or equal to conventional and untreated controls. Our results support those obtained by Glenn et al. (1999, 2000) on apple in other fruit growing regions. Yet, more years of data are needed to determine if these horticultural benefits are consistent phenomenons for pear. The formulations we tested lacked phytotoxicity (e.g., leaf burn, leaf yellowing, leaf drop), which is a critical issue when particulate materials are applied numerous times to plant foliage over the season.

The spectrophotometer method we developed is as accurate and faster than direct measurements in which residues were washed from leaves, dried in aluminum pans overnight, and weighed (Glenn et al. 1999). We obtained initial particle deposition rates near the lower range (85 μg particles per square centimeter of leaf surface) reported by Glenn et al. (1999) for M96/MeOH. Differences in how the residues were measured and the type of sprayer that was used could account for lower deposition rates. Particle deposition differed among formulations for both leaf age and leaf surface (top or bottom). Yet, when leaf age and surface (top or bottom) are considered, no specific pattern emerged from the deposition data that suggests one formulation had superior deposition characteristics over another. Furthermore, differences among formulations were not great enough to show substantial differences in control of pear psylla, fabraea leaf spot, or horticultural benefits. These formulations were designed to have similar mixing, spreading and deposition characteristics, therefore, the lack of differences between these formulations was not entirely unexpected. However, the lack of differences among formulations could have resulted from the short 7- to 10-d spray intervals we used. Broadening spray intervals may show greater particle formulation effects for both particle deposition and efficacy.

Finally, we demonstrated that particle films can be successfully applied as liquids and that films produced by hydrophilic particles can provide control of key arthropod pests and disease of pears, as well as enhance pear yield and color. The shift from hydrophobic to hydrophilic particle films is a significant improvement in the utility of this technology. Use of the M96/MeOH particle film version by collaborators in 1996 and 1997 revealed that this formulation was difficult to mix, and there were safety concerns over the use of MeOH. Both the spreader-sticker versions used with M97 can be tank mixed like conventional pesticides. The M97/M03 + T01 formulation used in this study is the progenitor of the M97/M03 formulation, Surround® (Engelhard), that was commercially available to fruit growers in the states of Washington and Oregon in 1998. This particle film material was very successful in suppressing early-season pear psylla infestations and in rescuing psylla infested orchards later in the season when insecticides failed because of resistance. Other researchers have found that codling moth can be controlled in apple and pear (Unruh et al. 2000) and that obliquebanded leafroller [*Choristoneura rosaceana* (Harris)] can be controlled in apple (Knight et al. 2000) with particle films. In addition, other pests of apple and pear that have been controlled by particle films include apple maggot, leafhoppers, plum curculio and thrips (Puterka et al. 2000, G.J.P., unpublished data). The multi-functionality of particle films could make them a desirable component for crop pest management. The particle film is based on a nontoxic kaolin particle and a spreader-sticker made of natural materials. Both Surround® and its spreader-sticker, M03, were approved for organic use in the state of Washington in 1998. Adoption of particle film technology as an alternative to conventional pesticides will lead to reductions of insecticide use in pear. Undoubtedly, further research on this technology will find it has utility against other arthropod pests and diseases in many other crops.

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