DELIVERY OF CHEMICAL AND MICROBIAL PESTICIDES THROUGH DRIP IRRIGATION SYSTEMS

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ABSTRACT. *Applying pesticides uniformly to the target area with drip irrigation systems is essential for achieving effectiveness of efficient insect or disease control and for the sustainability of a safe environment. The uniformity and recovery rate of water-soluble and insoluble materials of chemical and microbial pesticides with different physical properties discharged from emitters throughout driplines was evaluated. The materials were a water-soluble fluorescent tracer (BSF), a flowable water-dispersible insecticide (Imidacloprid), a suspendible microbial entomopathogenic fungus (EPF), a suspendible microbial soil fungicide (SF), and microbial entomopathogenic nematodes. Treatments also included three different flow capacities of emitters with nominally rated flow capacities of 1.9, 3.8, and 7.6 L h^{-1}, respectively. Although all materials were readily deliverable through the drip irrigation system, the uniformity of the materials discharged varied with the material formulations and emitter flow capacity. For all emitter flow capacities, BSF had the lowest coefficient of variation, followed by nematodes, Imidacloprid, SF, and EPF. Conversely, the recovery rate of the five materials was in the reverse order. Emitter flow capacity affected the recovery rates of Imidacloprid and SF discharged from the emitters, but not of BSF, EPF and nematodes. Drip irrigation was demonstrated as a viable alternative for application of water-soluble and insoluble materials; however, the discharge rates of EPF and SF must first be determined to compensate for their non-uniformity of delivery and low recovery rates from emitters.*

Keywords. *Chemigation, Distribution uniformity, Entomopathogenic fungus, Entomopathogenic nematodes, Microbial fungicide, Micro irrigation, Pest control agent.*

The floral and ornamental nursery industry is one of the fastest growing agricultural enterprises in the United States and China (Jerardo, 2007). Uses of pesticides have ensured adequate and high quality floral and nursery crops for a large number of varieties, complex canopy structure characteristics, various growing circumstances, and broad marketing requirements. In nurseries, pesticides are primarily applied by sprayers, but there are several impediments with spraying pesticides. For example, pesticides may not be efficiently applied to intended targets because of large gaps between trees where pesticides are not needed; spray drift may affect residential areas nearby nurseries; plants physically disturbed or damaged by spraying may have lower market values; and extensive skills are required for applicators to properly operate sprayers.

Chemigation includes applications of insecticides, fungicides, herbicides, fertilizers, microbial biopesticides and nematicides by means of irrigation systems. In production nurseries with drip irrigation systems in place, injection of pesticides into irrigation lines (or chemigation) offers an alternative strategy for efficient and economical application of pesticides to targeted zones in soil or container substrates The drift problem caused by spraying pesticides and costs associated with sprayers can be eliminated by using chemigation. This method has been shown to increase crop yields and reduce chemical leaching (Leib et al., 2000).

Injection of pesticides into drip irrigation lines takes advantage of the fact that active ingredients can be carried by water into root zones (Lamm et al., 2007). The ingredient distribution pattern in the soil plays an important role in pest control efficacy. Drip irrigation was demonstrated as an effective technique to apply water-soluble fumigants to the target soil (Ajwa et al., 2002). Leib and Jarrett (2003) reported limited leaching of Imidacloprid with 70% of the pesticide still located in the root zone at the end of the 40-day evaluation period when efficacy ended.

Because of these efficient delivery characteristics, drip irrigation has become a convenient method to deliver bio-chemicals in the root zone (Reed et al., 1986; Ellsbury et al., 1996). Wennemann et al. (2003) applied entomopathogenic nematodes through drip irrigation with

Submitted for review in May 2009 as manuscript number SW 8012; approved for publication by the Soil & Water Division of ASABE in September 2009.

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2.0 L h^{-1}emitters in a vineyard and found the recovery rate of nematodes from drip emitters in 51 m long driplines ranged from 42% to 92%. Lumsden and Locke (1989) reported a very promising control of diseases caused by fungal root rot organisms in the greenhouse production of bedding plants by adding a microbial pesticide *Gliocladium virens* into the soilless substrate before planting seeds.

Improving water distribution uniformity of drip irrigation systems has been studied extensively (Wu et al., 1979; Lamm et al., 1997; Camp et al., 2003; Clark et al., 2005; Grabow et al., 2006). However, the specific evaluation of a designated pest control agent's uniformity throughout driplines is lacking, especially for the microbial bio-pesticides before they are used for field trials. Uniform distribution of the pest control agents throughout driplines and in targeted areas is essential to assure drip chemigation can achieve both efficient pest/disease control and environmental safety. Physical properties of pest control agents, especially bio-pesticides, are quite variable. There are questions whether drip chemigation can uniformly distribute them throughout driplines and within targeted areas. Deliverability and uniformity of many of these materials have not been evaluated comprehensively under controlled conditions before they are released for field use. Little information is available on distribution patterns of different water-soluble or insoluble materials discharged from different flow-capacity (or flow-rate) emitters throughout driplines. A quantitative relationship among emitter size, flow rate and chemical type may be helpful to develop strategies to apply suspendible granular biopesticides through drip irrigation systems. The objective of this research was to investigate the capability of drip irrigation systems for delivering water-soluble chemicals, suspendible microbial bio-insecticides and bio-fungicides, and entomopathogenic nematodes. To achieve the objective, the distribution uniformity and recovery rate of these materials throughout driplines were evaluated under controlled conditions as they were discharged from emitters of three flow capacities.

Materials and Methods

Drip Irrigation System Design

A drip irrigation system was developed to test the application uniformity of agrochemicals and microbial bio-pesticides throughout driplines. Variables including emitter flow, amount of injected materials and injection time could be individually controlled with the system. The system included three 79-m long driplines, a portable chemical injection unit, a shutoff valve for pressure control, a pressure sensor (Model 242PC60G, Micro Switch, Freeport, Ill.), a flow meter (Model DFS-2, DGH Corporation, Manchester, N.H.), and a backflow prevention check valve (Model T-413, Nibco Inc., Elkhart, Ind.). The portable chemical injection unit was installed at the beginning (upstream end) of each dripline. The injection unit (fig. 1) included an injection valve assembled with a 1.27-cm (nominal - in.) thread PVC tee, a nominal 1.27-cm (nominal - in.) NPT electric wire connector (Kleinhuis North America, Inc., Worthington, Ohio), a bladder valve removed from a 40-cm diameter plastic toy ball (Item# 3314903313, Ball, Bounce, and Sport Inc., Ashland, Ohio), and a modified 50-mL Pro-Pistol™ pistol grip syringe (Model 1005, Neogen Corporation, Lexington, Ky.). The bladder valve performed as a one-way check valve for chemicals injected into the dripline with the syringe. After the syringe was removed, the valve prevented leakage of the pressurized liquid at the injection point. The backflow prevention valve was installed in the dripline upstream of the injection valve to prevent chemicals from flowing upstream to the main water line. The pressure and flow rate near the injection point were measured with the pressure sensor and flow meter, which were connected to a micro data logger (Model CR23X, Campbell Scientific, Logan, Utah). The data logger was programmed to acquire these data at 1-s intervals during the experiment.

The driplines were three polyethylene tubes with external pressure-compensating emitters (Model WPC, Netafim USA, Fresno, Calif.) of three different flow capacities. The nominal flow capacity of emitters on the three driplines was 1.9 L h^{-1} (line 1), 3.8 L h^{-1} (line 2), and 7.6 L h^{-1} (line 3), which covers the flow capacity ranges normally used for drip irrigation systems in ornamental nursery applications. The flow path of pressurized liquids within each emitter was controlled with a flexible diaphragm in the center donut-shaped chamber that reduces the flow path dimension with increasing pressure and with a series of baffles projecting from inside and outside the walls of the chamber. The diaphragm functioned as a variable-flow storage compartment and for pressure compensation. The inside and outside baffles alternating within the emitter formed a resistive flow path to discharge the pressurized liquid. The length, depth and width of the flow path in the chamber of the emitters for line 1 were 61, 1.07 and 1.17 mm; for line 2 they were 60, 1.30 and 1.40 mm; and for line 3 they were 17, 1.60 and 1.60 mm, respectively.

Each dripline contained a polyethylene tubing with 13.2-mm nominal inside diameter and 1.27-mm nominal wall thickness. The total number of emitters on each 79-m dripline was 87 spaced at 0.9-m intervals. In nurseries, it is common to grow crops in a row with less than 79-m length. The barb of emitters was inserted 4.2 mm inside the dripline tubing. Distance from the injection point to the first emitter was 0.45 m. For each replication of the treatment, only one line was used while the other two lines were disconnected.

To determine the flow rate and pressure to be used, water flow rate uniformity from emitters throughout each dripline

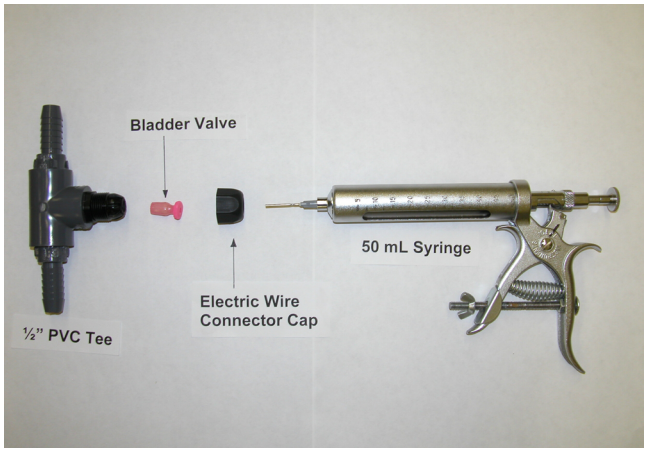

Figure 1. Chemical injection unit assembly used to inject pesticide into driplines.

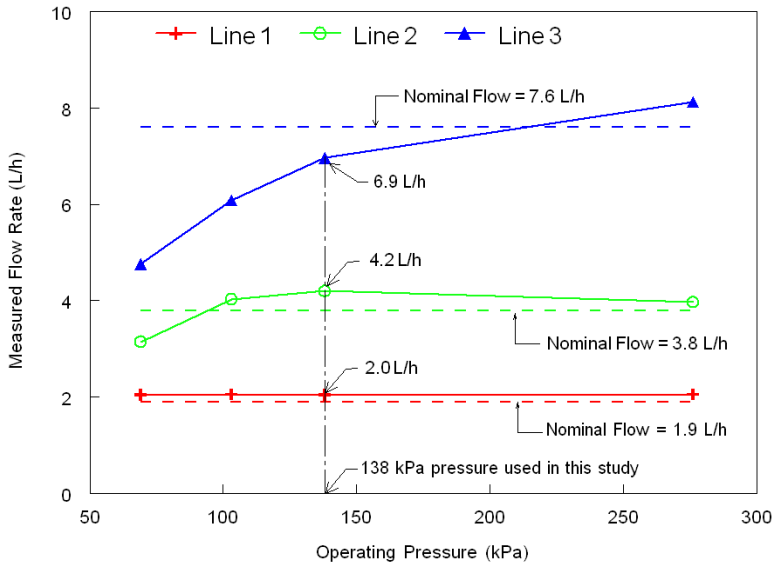

Figure 2. Measured flow rate vs. pressure of the three different emitter capacities used in this study.

was examined at four pressures of 69, 103, 138, and 276 kPa, respectively. The amount of water from 7 emitters at 4.1, 17.6, 31.1, 44.6, 58.1, 71.6, and 77.9 m (or 13.5 m apart) from the injection point was measured for 10 min and repeated three times. Figure 2 shows the relationship between the average water flow rate of the 7 emitters and the operating pressure for the three lines of different nominal flow capacities tested. The emitter flow rates on line 1 (nominal flow capacity of 1.9 L h^{-1}) and line 2 (nominal flow capacity of 3.8 L h^{-1}) were almost constant over pressure ranging from 69 to 276 kPa, but on line 3 (nominal flow capacity of 7.6 L h^{-1}) the emitter flow rate increased as the pressure increased from 69 to 276 kPa. The measured flow rate at 138 kPa on line 1 and line 2 was 2.0 and 4.2 L h^{-1}, respectively, which were very close to the nominal values, but on line 3 it was 6.9 L h^{-1} which was 15% (or 1.14 L h^{-1}) lower than the nominal value. Because of these preliminary test results, the operating pressure of 138 kPa was chosen for all treatments in this research. Also, the pressure 138 kPa was within the pressure range between 50 and 310 kPa recommended by the dripline manufacturer.

Materials Tested

Tests were conducted with five different materials with different types and formulations (table 1): Brilliant Sulfaflavine (BSF, MP Biomedicals, Inc., Aurora, Ohio), Imidacloprid (Marathon II, OHP, Inc., Mainland, Pa.), an entomopathogenic fungus (EPF) (Novozymes Biologicals, Inc., Salem, Va.), a microbial soil fungicide (SF) (SoilGuard 12G, Certis USA, LLC., Columbia, Md.), and entomopathogenic nematodes (EPN, cultured by The Ohio State University, Entomology Department, Wooster, Ohio).

BSF is a water-soluble, non sunlight degradable fluorescent tracer normally used to track pesticide deposition (Zhu et al., 2005). Also, the BSF solution has a nearly constant intensity over the pH range of 6.9 to 10.4. It was selected for this test because results of BSF could provide a reference to compare performances of other materials discharged through drip emitters.

Imidacloprid is the active ingredient of Marathon II which is a flowable formulation (suspension concentrate dispersible in water) with a viscosity of 84 mPa·s. It is a systemic chloronicotinyl insecticide normally applied to the soil for control of root feeding beetles such as scarab larvae (white grubs) or foliar feeding insects such as scale and leafhoppers in ornamental trees. The concentration of Imidacloprid in Marathon II is 0.24 kg L^{-1}.

EPF is a suspendible conidial powder microbial insecticide. Its active ingredient is Met52G and Tick EX EC with 2.0% by weight *Metarhizium anisopliae* Sorokin strain F52. The conidial powder contains approximately 5×10^{10} conidia per gram. The product has very uniform size. The sizes of conidia are typically 3-4 um wide and 7-9 um long while the average length of the powder granule is about 0.039 mm. The material is insoluble in water and remains on the top of water after standing for 10 min. Therefore, for this study, a suspension of conidia was made in 0.05% non-ionic surfactant Tween 80 (Sigma-Aldrich, St Louis, Mo.) to improve dispersion. The EPF was a fungus normally used to control insects, primarily beetle larvae and ticks on non-food use greenhouse and nursery crops.

Table 1. Materials used in the test.

Material	Type	Formulation	Amount Applied[a]
Brilliant Sulfaflavine (BSF)	Fluorescence tracer	Water soluble	150 mg
Imidacloprid	Insecticide	Flowable suspension	2.8 mL
Entomopathogenic fungus (EPF)	Microbial insecticide	Suspendible granule	5.5 g
Soil fungus (SF)	Microbial fungicide	Suspendible granule	10 g
Entomopathogenic nematode (EPN)	Microbial insecticide	Living organism suspension	2,000,000 unit

[a] Amount of the material applied per test.

SF is a suspendible, granular formulation of a naturally occurring soil fungus (*Gliocladium virens* strain GL-21), containing 12% by weight fungal fermentor biomass with 2×10^7 viable propagules per gram. The compound was formulated to be applied through irrigation lines or drenched into growing media to control diseases caused by fungal root rot pathogens such as *Pythium* and *Rhizoctonia*. The suspendible granules had irregular shapes with a considerably wide range of equivalent diameter: 10% volume less than 0.136 mm, 50% volume less than 0.32 mm, and 90% volume less than 1.06 mm. The maximum granule equivalent diameter was 1.47 mm, and the average diameter was about 0.345 mm. The granules suspend in the water when injected into the dripline.

Lastly, nematodes used in this study were *Heterorhabditis bacteriophora* Poinar strain GPS11 with a concentration of 2.0×10^6 nematodes per 100 mL of solution, estimated by counting with a microscope (Woodring and Kaya, 1988). They are typically 500 to 1000 μm long and 18 to 50 μm wide, and are normally used to carry and introduce symbiotic bacteria (*Xenorhabdus* spp.) into the body cavities of insects that eventually kills them within 48 h. The species and strain of nematodes has shown efficacy for controlling scarab larvae in ornamental nurseries (Reding et al., 2008). The nematodes can be suspended in water, but normally settle out within a few minutes if not agitated.

Experiments

Driplines were attached horizontally to three 2.5-mm diameter high-tensile electric fence wires suspended over 30 cm above the ground (fig. 3). Only one dripline was connected to the water source for each application. In each replication, the tested line was filled with water at a stabilized pressure (138 kPa) before injection and water sample collection.

The 50-mL syringe with a 0.9-mm inside diameter needle was modified to inject a fixed amount of materials into the dripline through the chemical injection unit (fig. 1). Each of the five materials was injected over a 1-min period for each replication. All materials were mixed with water before they were injected into the dripline. Water samples mixed with each injected material were collected with 3.8-L plastic bottles from seven emitters at 4.1, 17.6, 31.1, 44.6, 58.1, 71.6, and 77.9 m along the 79-m dripline, respectively. The seven emitters were the same ones at the same locations used for the water uniformity distribution test as mentioned above. The water flow test verified that the driplines were able to uniformly distribute water flow through the driplines as discussed in Results and Discussion section. The sampling began 1 min before the start of injections. The collection time for samples from line 1 was 30 min, and 15 min from line 2 and 3. An estimated time for materials to flow from the injection point to the last emitter was 16.3 min in line 1, 7.8 min in line 2, and 4.7 min in line 3, respectively. These estimated times were calculated with a plug-flow equation similar to the flow equation used for boom sprayers (Zhu et al., 1998). The volume of collected sample from each emitter in line 1 was 1.0 L, 1.05 L in line 2, and 1.72 L in line 3. Each sample was shaken and sub-samples were decanted into glass bottles, and then taken to the laboratory for analysis. After samples were collected, the dripline was flushed by opening the end of the line for 10 min and a sample of the flush water was collected from the end of the dripline at the beginning of the flushing cycle. These flushing water samples were analyzed for observation only but not for quantitative comparison because it was very hard to control the amount of water collected at the end of lines during the flushing process. The above process that included the injection of a material into the dripline, the collection of samples and the flushing of dripline was repeated for three times representing three replications for each material and each dripline.

The starting concentration of the BSF solution was 3 g BSF per liter of water which was selected based on pre-trial tests for fluorescent intensity, and fell within the detection range of the spectrometer (Perkin-Elmer Limited, Beaconsfield, Buckinghamshire, England) used in this research. The viscosity of the solution was 0.887 mPa·s, and

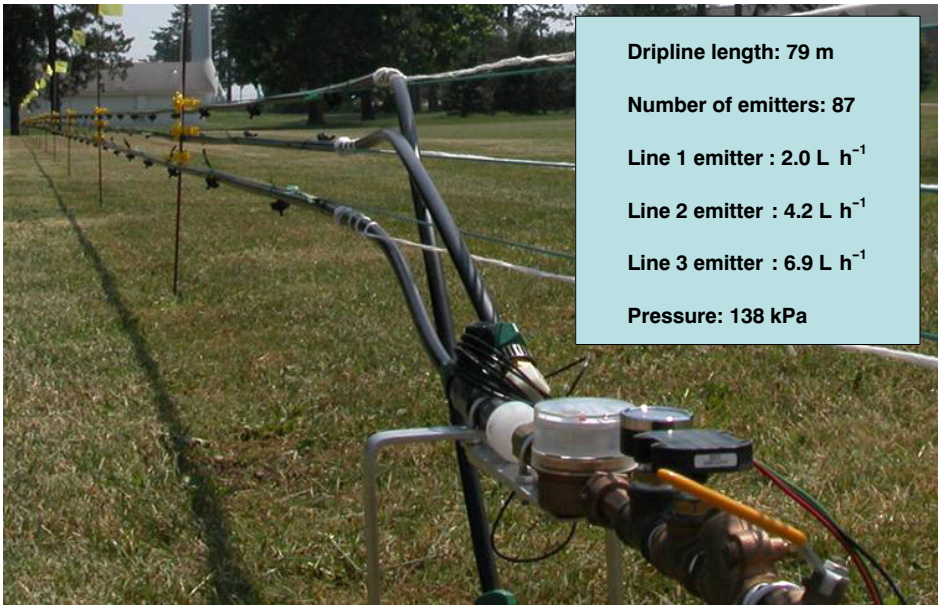

Figure 3. Three driplines with three different capacity emitters suspended above the ground used in this study.

the amount of BSF solution injected into the dripline for each replication was 50 mL, equaling 0.06 g of BSF. Water samples collected from the emitters were taken to the laboratory where the BSF concentration was measured with the spectrometer calibrated to detect an emission wavelength of 500 nm (Zhu et al., 2005).

The Imidacloprid mixture for each replication was 13 mL of Marathon II and 25 mL of water. This rate was calculated based on the label rate of 50-mL Marathon II per 305 m row. After sample collection, the concentration of Imidacloprid was measured by filtering samples and adjusting the pH to 2. Aliquots of 2 mL were subsequently analyzed using liquid chromatography tandem mass spectrometry (LC-MS/MS). The LC-MS/MS system consisted of a ProStar® 210 solvent delivery module with a ProStar 430 autosampler and a 1200-L triple-stage quadrupole mass spectrometer with a dual off-axis ESI interface (Varian Inc., Walnut Creek, Calif.). A standard concentration of 5 mg L^{-1} prepared in methanol and water was used to optimize the instrument and attain precursor and transition ions using argon as the collision gas. A molecular mass to charge ratio of 256 in positive ion mode was used with transition ions (collision energy voltages in parenthesis) 208.8 (12.5), 175.1 (12.0), and 212.0 (8.5). Optimized parameters were 350°C for the drying gas; ion transfer capillary, nebulizer needle, and shield voltages were 40, 4500 and 200, respectively. Injection volume was 20 uL and scan time was 0.1 s. A Nova-Pak® C18 column (4 μm, 150 mm × 3.9 mm) and packing-matched guard were used for retention of the analyte (Waters Corporation, Milford, Mass.). A gradient elution using 0.1% formic acid (A) and 0.1% formic acid in acetonitrile (B) was used at a flow rate of 0.4 mL min^{-1}. Solvent B was held for 1 min at 5%, and ramped to 95% over 4 min, held for 3 min, then gradually returned to initial conditions over 1 min and held for three additional minutes for equilibration. A standard calibration curve, using matrix-matched standards, used the most abundant transition ion for quantitative analysis. The remaining ions, along with retention time as compared to the spiked matrix samples, were used for further confirmation in the sample matrix. The system was calibrated with Imidacloprid at known concentrations ranging from 0.036 to 3600 mg L^{-1}.

In the EPF trials, 5.5 g of the EPF formulation was mixed with 50 mL of water and 25 uL of Tween 80 for each replication. The mixture was stored at 5°C for 24 h and then shaken well before the injection. After water samples were collected at seven locations, they were shaken and sub-samples were poured into 15-mL plastic vials, then sent overnight with an ice pack to a laboratory for analysis. In the laboratory, the water samples were placed in a sonicator for 20 min, and 1 mL of each sample was added to 99 mL of phosphate buffer, then 100 uL of this solution was spread on selective (Veen's) media for CFU's incubation (Veen and Ferron, 1966). The media plates were incubated for 4 to 5 days at 27°C and then fungal colonies were counted.

The SF mixture injected into the dripline for each replication was 10-g SF mixed with 100-mL water and was shaken well before injecting into the pressurized dripline system. After samples were collected from emitters for each replication, they were transferred to the laboratory. Each collected sample was diluted two or three times and then 1-mL aliquoits from the diluted sample were deposited onto the surface of a semi-selective medium containing antibiotics to suppress bacterial growth (three plates/dilution/sample). Following a period of incubation, colonies were counted and calculations made to determine the number of units (CFU) of active ingredient that were dispensed through each emitter.

The nematode mixture for each replication was 100-mL water and 2.0×10^6 nematodes. It was stored at 5°C for 24 h before the application. After nematode samples were collected, each plastic bottle was held at room temperature 20°C for 24 h to allow the nematodes to settle at the bottom of the bottles, and then most of the water was poured off. The solution remaining in the bottle was then poured into a glass bottle and allowed to set for another 24 h until the nematodes again settled at the bottom. A pipette was then used to remove most of the water until 15 mL of nematode suspension remained. Three 10-μL drops containing nematodes were taken from this suspension and spread on glass microscope slides, then all the nematodes on a slide were counted under a stereoscopic microscope (Model SZX12, Olympus, Japan) at 50× magnification. The mean number of nematodes in three drops was reported.

After all samples were analyzed, the amount of materials discharged from emitters for each test was normalized for the specific emitter flow rate tested. To determine the effect of emitter flow capacity on the amount of materials discharged throughout the dripline, each group of data for the specific material treatments was first analyzed by one-way ANOVA to test the null hypothesis that all treatments had equal means of the material quantity with Duncan's methods using ProStat version 3.8 (Poly Software International, Inc., Pearl River, N.Y.). If the null hypothesis was rejected, the multiple comparison procedure was used to determine differences among means of the material distributed throughout the dripline. Multiple comparisons for recovery rates across the dripline were also conducted among the five materials and three flow capacities. All differences were determined at the 0.05 level of significance.

Coefficient of variation (CV) and distribution uniformity (DU) were used to quantify the uniformity of distribution of each of the five materials throughout the dripline. CV and DU were calculated by replacing the flow rate with the amount of materials discharged from each emitter defined by *ASABE Standards* (2008), Kruse (1978), and Keller and Bliesner (2000):

$$CV = \frac{s}{q_{ave}} \cdot 100 \tag{1}$$

$$DU = \frac{q}{q_{ave}} \tag{2}$$

where s is the standard deviation of the amount of materials discharged from emitters, q_{ave} is the mean amount of materials discharged from emitters, and q is the mean of the lowest one-fourth of the amount of materials discharged from each emitter sampled. These equations have also been used for evaluation of fertigation and chemigation performances such as the effect of injection methods and injection rates on fertigation uniformity (Bracy et al., 2003; Li et al., 2007). Since there were seven samples of each material collected for each replication, the value of q was calculated by the following equation with expansion of the 7 data to 28 data:

$$q = \frac{4q_{L1} + 3q_{L2}}{7} \quad (3)$$

where q_{L1} and q_{L2} are the lowest and second lowest amounts of the material among the seven samples, respectively.

Results and Discussion

Figure 4 shows the amounts of water collected from emitters at seven different distances from the injection point on line 1 for 30 min and lines 2 and 3 for 15 min, respectively. Data in the figure illustrates that there was little variation in the amount of water discharged from emitters along the driplines 1 and 2 while there was 6% variation in line 3. That is, water distribution throughout the 79-m dripline varied very little with the 2.0- and 4.2-L h^{-1} flow rate emitters and varied considerably with the 6.9-L h^{-1} flow rate emitters. It is understandable that the 6.9-L h^{-1} emitters could not maintain a constant flow rate at various pressures because their short flow path and limitation of the flexible diaphragm limited the pressure compensation capability. Based on Bernoulli's equation in hydraulics, the flow rates from any hydraulic components are proportional to the multiplication of a flow constant, the cross-section area of the flow path, and the square root of pressure. For the pressure-compensated emitters with low flow capacity, the flexible diaphragm could automatically maintain the flow constant and cross-section area very well, and pressure changes within a small range will not produce noticeable changes in the flow rate.

Amounts of measured BSF, Imidacloprid, EPF bio-compound insecticide, SF bio-compound fungicide, and nematodes throughout the three driplines are shown in figures 5 through 9. Table 2 shows the predicted and measured amounts of the five materials discharged from three different capacity emitters. The predicted amount was calculated by the amount of material injected into the dripline divided by 87 (the number of emitters in the dripline). The recovery rate shown in table 2 is the percentage of the average measured amount of materials divided by the predicted amount of materials. Table 3 reports the mean CV and DU of the five materials throughout the entire driplines with three different capacity emitters, respectively.

There was no significant difference in the amount of BSF discharged from different flow capacity emitters on three driplines (fig. 5). The recovery rate of BSF was from 86% to 93% for the three driplines (table 2). The average CV and DU of BSF throughout the 79-m dripline for all three driplines was 1.9% and 0.96, respectively (table 3). The flow velocity near the injection point was 0.38 m s^{-1} in Line 1, 0.80 m s^{-1} in Line 2, and 1.32 m s^{-1} in Line 3. The Reynolds' number was 4807, 10120, and 16697 for the three lines, respectively. The flow near the injection point in all three lines was a turbulent flow. The flow rate in driplines had little influence on the amount of BSF discharged from emitters. Therefore, the water-soluble material could be well delivered throughout driplines regardless of the emitter capacity.

The amount of Imidacloprid discharged from individual emitters varied with the emitter flow capacity (fig. 6). Emitter capacity also significantly influenced the distribution uniformity of Imidacloprid discharged throughout the dripline. The amount of Imidacloprid discharged from all emitters throughout dripline 3 (6.9 L h^{-1} emitters) was significantly lower than the other two driplines. High concentrations of Imidacloprid were found in the flushing water samples collected from dripline 3. A large portion of the chemical injected into line 3 might have been carried by the high-speed water to the end of the line and then trapped. Dripline 2 (4.2 L h^{-1} emitters) had the highest amount of Imidacloprid discharged from emitters and highest recovery rate among the three lines (table 2). The average CV

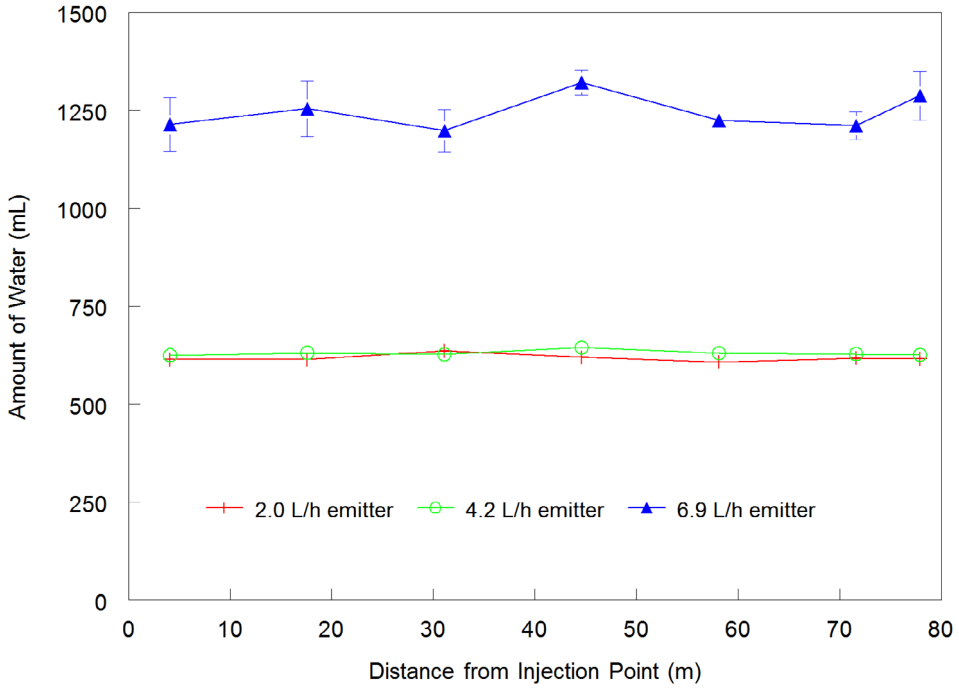

Figure 4. Actual amounts of water samples collected from seven locations throughout the 79-m long driplines for each replication of the tests for the 2.0-L/h (line 1), 4.2-L/h (line 2), and 6.9-L/h (line 3) emitters. Error bars represent standard deviations around means.

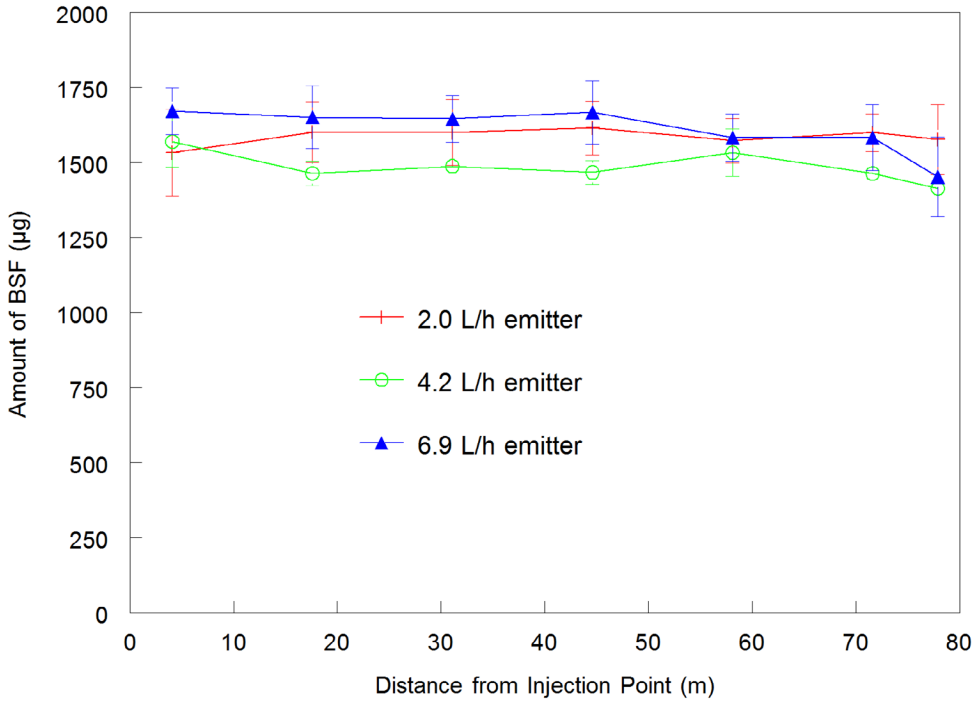

Figure 5. Amounts of BSF discharged from individual 2.0-, 4.2-, and 6.9-L/h emitters throughout three different driplines. Error bars represent standard deviations around means.

and DU of Imidacloprid throughout the 79-m dripline for all three driplines was 44% and 0.78, respectively (table 3). Compared to BSF, Imidacloprid had greater variation with the emitter flow capacity and the emitter location throughout the dripline.

The emitter flow capacity did not significantly affect the amount of EPF discharged from individual emitters throughout the driplines (fig. 7), which might be because the recovery rate of EPF was very low. Less than 10% EPF was recovered from all three driplines (table 2). The low recovery rate might be caused by the adherence of EPF to the wall of driplines. During preparation of the mixture of EPF and water, some suspensions were observed to adhere to the wall of plastic cups after standing for several minutes. The

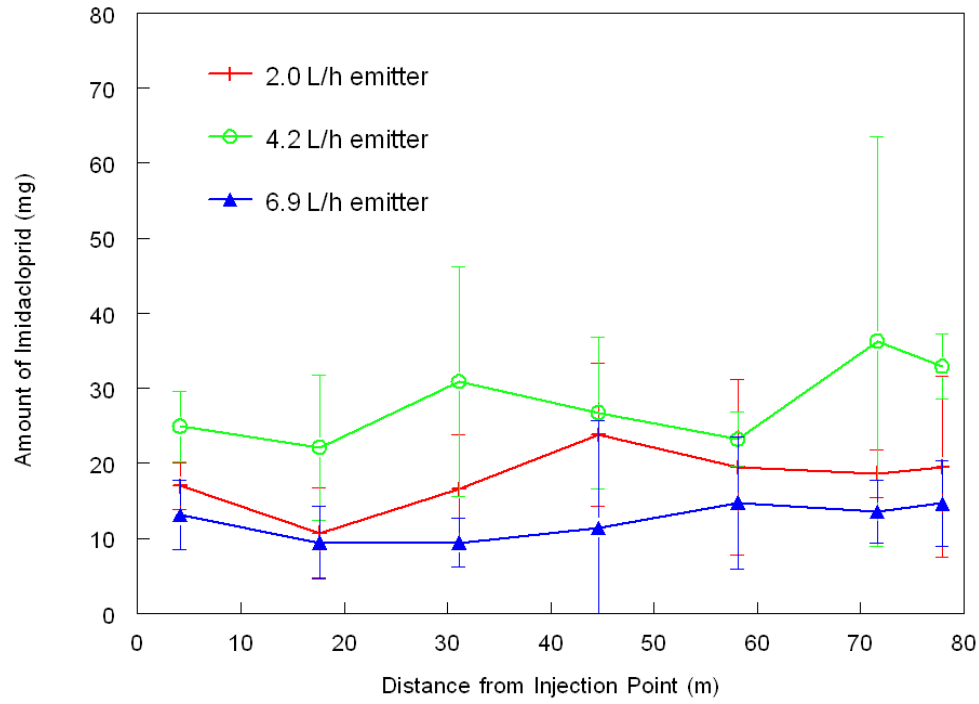

Figure 6. Amounts of Imidacloprid discharged from individual 2.0-, 4.2-, and 6.9-L/h emitters throughout three different driplines. Error bars represent standard deviations around means.

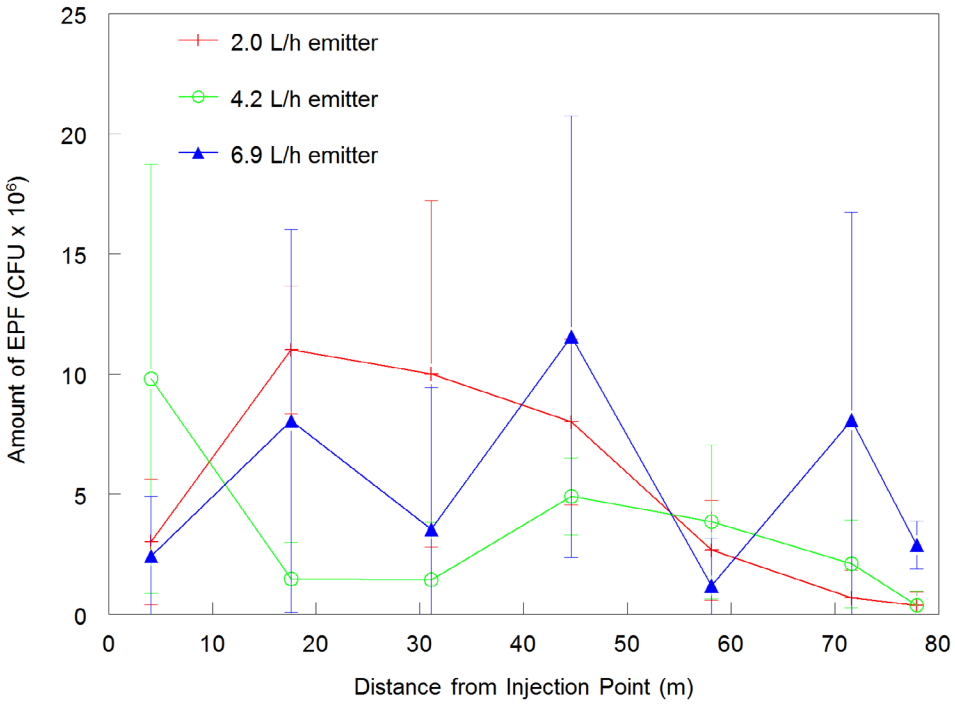

Figure 7. Amounts of EPF discharged from individual 2.0-, 4.2-, and 6.9-L/h emitters throughout three different driplines. Error bars represent standard deviations around means.

hydrophobic nature of *M. anisopliae* conidia combined with an emulsifiable concentrate formulation might require greater agitation to maintain suspension in water than that could be provided by a drip irrigation system. The CV for the amount of EPF throughout the entire dripline increased as the capacity of emitters increased, while the DU tended to decrease as the emitter capacity increased (table 3). The average CV and DU of EPF throughout the 79 m dripline for all three driplines was 104% and 0.39, respectively (table 3).

Similar to the Imidacloprid, the amount of SF discharged from emitters was also affected by the emitter flow capacity (fig. 8). The amount of SF discharged from all emitters throughout dripline 3 was significantly lower than the other

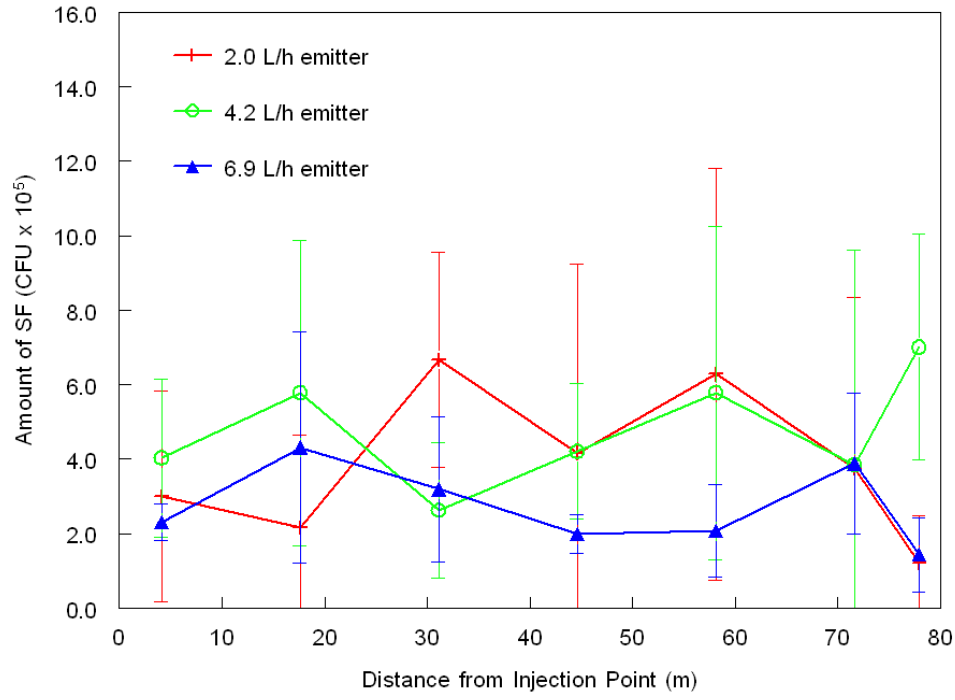

Figure 8. Amounts of SF discharged from individual 2.0-, 4.2-, and 6.9-L/h emitters throughout three different driplines. Error bars represent standard deviations around means.

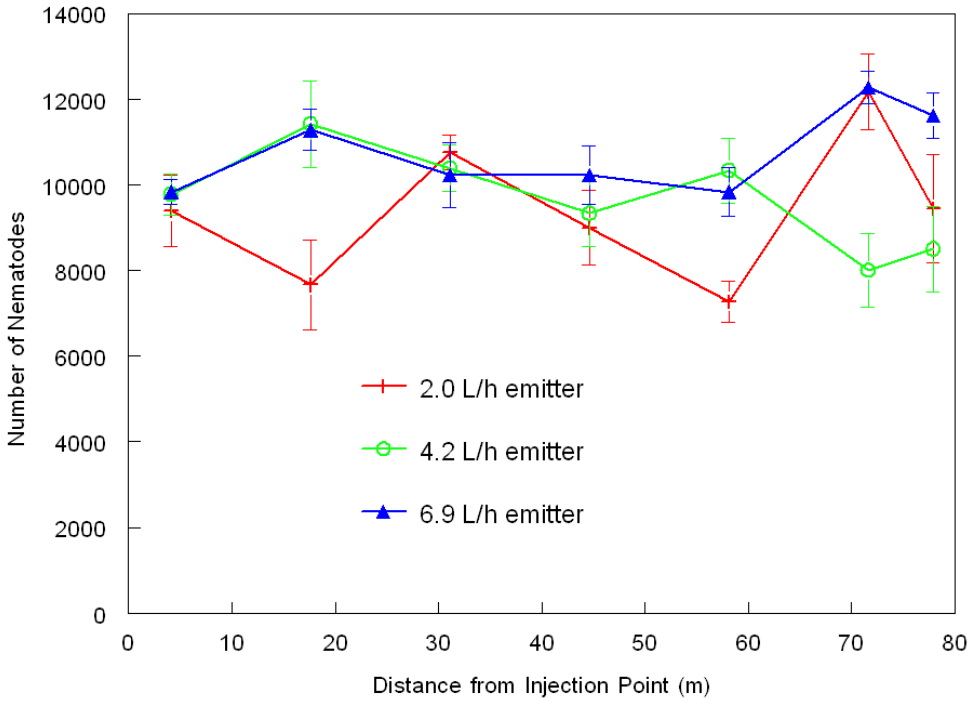

Figure 9. Number of nematodes discharged from individual 2.0-, 4.2-, and 6.9-L/h emitters throughout three different driplines. Error bars represent standard deviations around means.

two driplines while line 2 with 4.2-L h^{-1} emitter flow capacity had the highest amount of SF discharged (table 2). The recovery rate of SF ranged from 12% to 21% for all three emitter capacities. During three replications, there were three emitters clogged by materials in line 1, and 3 emitters clogged in line 2, but no emitters were clogged in line 3. The clogging problem was caused by particles with sizes larger than the depth of emitter flow path. Very high concentrations of SF remained in flushed water samples, which indicated that most SF remained in the dripline. Unlike EPF, the CV for

Table 2. Comparison of predicted and measured amounts of five materials discharged from individual emitters throughout driplines with three different size emitters.

Material	Emitter Flow (L/h)	Mean Quantity of Material per Emitter			Recovery Rate (%)[c]
		Predicted	Measured[a][b]	Unit	
BSF	2.0	1724	1586 (99)A	µg	92a
BSF	4.2	1724	1486 (47)A	µg	86a
BSF	6.9	1724	1608 (98)A	µg	93a
Imidacloprid	2.0	35.9	18.0 (7.5)B	mg	50b
Imidacloprid	4.2	35.9	28.1 (10.7)A	mg	78a
Imidacloprid	6.9	35.9	12.3 (6.6)B	mg	34bcd
EPF	2.0	5.69×10^7	5.1×10^6 (2.8×10^6) A	CFU	9.0de
EPF	4.2	5.69×10^7	3.4×10^6 (2.9×10^6) A	CFU	6.0e
EPF	6.9	5.69×10^7	5.4×10^6 (6.6×10^6) A	CFU	9.5de
SF	2.0	2.3×10^6	3.89×10^5 (3.52×10^5)A	CFU	17cde
SF	4.2	2.3×10^6	4.75×10^5 (3.31×10^5)A	CFU	21cde
SF	6.9	2.3×10^6	2.74×10^5 (1.45×10^5)A	CFU	12de
Nematode	2.0	2.3×10^4	9387 (826)A	Number	41bc
Nematode	4.2	2.3×10^4	9679 (774)A	Number	42bc
Nematode	6.9	2.3×10^4	10754 (528)A	Number	47b

[a] Means for the measured quantity of the same material in a column followed by a different uppercase letter are significantly different ($p < 0.05$), but not for the comparison between materials.
[b] Standard deviation is presented in parenthesis.
[c] Recovery rate (%) = Measured quantity × 100 / Predicted quantity. Means for the recovery rate in a column followed by a different lowercase letter are significantly different among all the materials ($p < 0.05$).

Table 3. Mean coefficient of variation (CV) and distribution uniformity (DU) of BSF, Imidacloprid, EPF, SF, and nematodes discharged from emitters with three different flow capacities (2.0, 4.2, and 6.9 L/h) at 138-kPa pressure.

Treatment	CV (%)[a]			DU[a]		
	2.0 L/h emitter	4.2 L/h emitter	6.9 L/h emitter	2.0 L/h emitter	4.2 L/h emitter	6.9 L/h emitter
BSF	2.3	1.7	1.8	0.95	0.97	0.96
Imidacloprid	43	36	54	0.76	0.80	0.76
EPF	90	104	119	0.56	0.26	0.33
SF	98	72	51	0.44	0.62	0.68
Nematodes	8.8	8.0	4.9	0.80	0.83	0.91

[a] Each value of CV or DU is the mean from seven emitters in each dripline with three replications. CV and DU were calculated with equations 1 and 2, respectively.

the amount of SF throughout the entire dripline decreased and DU increased as the emitter capacity increased (table 3). The average CV and DU of SF throughout the 79-m dripline for all three driplines was 74% and 0.58, respectively. The lowest and highest amounts of SF among all the emitters investigated in this study were 1.22×10^6 CFU and 6.67×10^6 CFU, respectively, both of which occurred on line 1, but the difference was not significant at the 0.05 probability level.

The average number of nematodes discharged from individual emitters slightly increased as the emitter capacity increased, but the differences were not significant (table 2). The recovery rate of nematodes discharged from the 6.9-L h^{-1} emitters on line 3 was higher than that from the 2.0- and 4.2-L h^{-1} emitters. The emitter flow capacity influenced the distribution uniformity of nematodes throughout the driplines (fig. 9). The value of CV decreased from 9.1% to 5.0% and DU increased from 0.80 to 0.91 when the emitter flow rate changed from 2.0 to 6.9 L h^{-1} (table 3).

Among the five materials tested, BSF had the highest recovery rate, the lowest CV and the highest DU across the three 79-m driplines, followed by nematodes, Imidacloprid, and SF, while EPF had the highest CV and lowest DU and recovery rate for all three lines (tables 2 and 3). The amount of BSF and number of nematodes discharged throughout all three driplines had excellent distribution patterns (DU>0.80). The Imidacloprid DU was greater than 0.76 for all three driplines. For the suspendible SF and EPF, their DU was less than 0.70, which was possibly caused by their particles not easily mixing with water. To compensate for the non-uniform delivery and low recovery rate of EPF and SF throughout the driplines, the rate of EPF and SF required for effective insect/disease control must be determined before they are used in the field.

Both BSF and Imidacloprid solutions were soluble in water, but the viscosity of the Imidacloprid solution was much higher than the BSF solution. The Imidacloprid did not mix as well with the water in the dripline as the BSF after it was injected, which might be the reason that the Imidacloprid had higher CV and lower DU throughout all driplines than the BSF. For nematodes and the bio-compound suspensions, the former were tiny worms suspended in water, while the latter were suspended organic particles with foam presumably from the wetting agent. Although the nematodes behaved as suspendible particles in solution, due to their small size and easy flow with water, their recovery rate and distribution uniformity throughout the entire driplines performed much better than the two bio-compound suspensions EPF and SF.

The movement of chemical and microbial pesticides throughout the dripline is a complicated two-phase flow. Many factors influence the recovery rate and distribution uniformity of those materials throughout driplines. The findings in this article demonstrate the importance of evaluating these materials under controlled conditions before they are applied in the field. Future studies should further discover the influence of specific physical properties of these materials on the chemigation performances, and develop methods to improve the recovery rate and distribution uniformity of the suspended powder formulation of the microbial insecticide EPF and the suspended granular formulation of the microbial fungicide SF.

Summary and Conclusions

Drip irrigation uniformly dispensed the water-soluble BSF, water-dispersible insecticide Imidacloprid and suspended nematodes, but not the suspended powder formulation of the microbial insecticide EPF or the suspended granular formulation of the microbial fungicide SF. The uniformity of distribution of the various test agents throughout the dripline varied with their physical properties of the individual product formulation. The distribution uniformity of EPF discharged from emitters throughout the dripline was the lowest among the five materials tested, followed by SF, Imidacloprid, nematodes, and BSF.

Except for BSF and Imidacloprid, the flow capacity of emitters affected the distribution uniformity of the other test agents throughout driplines. Among the three emitters tested, EPF had the highest DU at the 2.0-L h^{-1} flow rate. The uniformity of SF and nematode distribution throughout driplines increased as the flow capacity of emitters increased. For the emitters with flow rates ranging from 2.0 to 6.9 L h^{-1}, DU averaged over 0.95 for BSF, over 0.80 for nematodes, over 0.75 for Imidacloprid, ranged from 0.44 to 0.68 for SF, and ranged from 0.33 to 0.56 for EPF.

Emitter size and flow capacity affected the recovery rates of Imidacloprid and SF discharged throughout the dripline, but not of BSF, EPF, and nematodes. The recovery rates greatly varied with the physical properties of the individual product formulation. For the emitters with flow rates ranging from 2.0 to 6.9 L h^{-1}, the recovery rate was below 9.5% for EPF, 21% for SF, 50% for nematodes, and 78% for Imidacloprid.

These results demonstrated that drip irrigation could be a viable alternative method for water-soluble pesticide applications. However, the use of drip irrigation systems for the delivery of suspended powders and granular agents, e.g. EPF and SF, for pest control may be limited because of their poor uniformity and low recovery rates throughout driplines. Any materials with sizes larger than the width or depth of emitter flow paths would clog emitters and should not be applied through drip irrigation systems.

ACKNOWLEDGEMENTS

The authors greatly acknowledge Adam Clark and Keith Williams for setting up the experimental irrigation system, Betsy Anderson, and Michelle Baker, Yu Chen, Erin Lowe, Barry Nudd, Mollie Sheron, Alex Sigler for collecting water samples, Jackie Hammel, Anthony Karcher and Leslie Morris for analyzing samples of fluorescence and Imidacloprid, and Leona Horst for analyzing samples of microbial pesticides.

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