Impact of Multiple Applications of Insecticides and Post-harvest Washing on Residues at Harvest and Associated Risk for Cherry Export

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**ABSTRACT**

Residue profiling was used to determine the degradation curves of four key insecticides registered for use in US tart cherries. Single and multiple application treatment regimens with minimum and maximum seasonal applications were tested for their effects on residue levels at harvest. The effects of the cherry washing procedure were also tested. The results were assessed using the US Environmental Protection Agency’s (EPA) fungicide and insecticide residue database. Fenpropathrin, cyantraniliprole, phosmet, and spinetoram were relative low risk for US tart cherry growers to use when exporting to the US to most prospective international markets. Fenpropathrin exceeded the European Union’s MRL at harvest for single or multiple applications and unwashed or washed treatments, making fenpropathrin a moderate risk for export to the EU.

**KEYWORDS**

Maximum residue levels; insecticide; Residue; cherry; export

**Introduction**

The United States (US) is a major cherry-producing country. According to the USDA National Agriculture Statistics Service (NASS), the state of Michigan is a national production leader of tart cherries, producing 75% of the nation’s cherries with 26,200 bearing acres (www.nass.usda.gov).

Meeting market standards for infestation-free fruit depends upon the judicious use of pesticides (Wise and Whalon, 2009), while maintaining chemical residues at acceptable levels for export markets. This is challenging, especially with new invasive pests, such as the spotted wing drosophila (Drosophila suzukii) (SWD). Growers use multiple applications of insecticides from the time that fruit starts to change color (Bellamy et al., 2013; Lee et al., 2011) through harvest, which increases the risk of fruit rejection in export markets. The intensity of SWD spray programs has shifted traditional integrated pest management in a way that makes it very difficult to reduce pesticide sprays near harvest. The high number of sprays used by growers can also lead to other pests and beneficial insect populations being variable across years (Rodriguez-Saona et al., 2019).

The Food Quality Protection Act (FQPA) of 1996 (Schierow, 1999) and the Green Movement (Lehman, 1993) have also created additional challenges for the cherry industry to retain pesticide options. Maximum residue limits also change frequently, which creates a challenge for growers to make seasonal pest management plans. Therefore, cherry producers must be aware of global standards for MRLs if they intend to trade in export markets. Many export countries use their own pesticide residue calculation system(s) to set MRLs and some use the OECD (Organization of Economic
Cooperation and Development) MRL calculator or just MRL calculator (Handford et al., 2015). This can result in un-harmonized global MRLs, which can pose a significant risk to specialty crop growers who desire access to international export markets. Wise (unpublished) proposed a disparity index to measure MRL differences, calculated as the US MRL divided by the lowest foreign MRL. This calculated value provides a simple way to identify which compounds are at the highest risk for growers targeting global export markets. It creates a single value instead of having to compare two values to explain how such differences affect the marketplace.

In the United States, fenpropathrin (Danitol) with a 3-day PHI, cyantraniliprole (Exirel) with a 3-day PHI, phosmet (Imidan) with a 7-day PHI, and spinetoram (Delegate) with a 7-day PHI are insecticides registered for use in cherries and recommended for control of late season insect pests in Michigan (Wise et al., 2016). These compounds are commonly used as late season options to control direct insect pests, such as SWD, cherry fruit fly, *Rhagoletis cingulata*, plum curculio (PC), *Conotrachelus nenuphar* (Herbst), and the oblique-banded leafroller, *Choristoneura rosaceana* (Harris). Near-harvest pest control is particularly challenging for cherry growers because the ripening fruit is highly susceptible to injury from insect pests, while the final sprays must be applied within the labeled pre-harvest intervals (PHIs).

With the need for late-season insecticides, and the risk of residue levels exceeding global MRLs, there is a need to understand the influence of grower pre- and post-harvest practices on pesticide residue levels at harvest. Therefore, the objectives of this study were to: 1) determine the residue levels of four key insecticides following either single or multiple applications to tart cherry trees, and 2) determine insecticide residue levels on tart cherries following post-harvest water washing treatments versus no washing.

**Materials and Methods**

**Study Design and Setup**

The 2014 fieldwork was conducted at the MSU Northwest Michigan Horticultural Research Station (NWMHRS), in Traverse City, MI, USA (44.8831, −85.6777). Plots were established in a 20-year-old 'Montmorency' (Sare Montmorency) cherry planting at NWMHRS, tree height 5.7 m and tree crown width 4.5 m, total planting size one row and six trees/row (between tree spacing was 4.6 m and between row spacing was 6.1 m), total area = 0.01 ha. The total experimental area was 2,357 sq m. Plot size is considered the area of the planting that was treated with insecticide. Untreated plots were the same size, but without insecticide treatment. Plots within this area were created using three consecutive trees (13.7 m within the row) with plots separated by six trees (total of 2 plots within a row). Treatment rows alternated with non-treated rows to create a buffer to further separate the plots in the event of drift. Treatments were replicated 3 times and applied to plots in a randomized complete block (RCB) design.

The 2015 fieldwork was conducted at the MSU Trevor Nichols Research Center (TNRC) in Fennville, MI, USA (42.5951, −86.1561). Plots were established in a six-year-old 'Balaton' tart cherry planting at TNRC, tree height 2.7 m and tree crown width 3.0 m, total planting size one row and 10 trees/row (between tree spacing was 4.6 m and between row spacing was 6.1 m), total area = 0.02 ha. The total experimental area was 7,576 sq m. Plots within this area were created using 10 consecutive trees (46 m within the whole row) with plots separated by 15.2 m (total of 1 plot within each row). Treatment rows alternated with different active ingredient rows to create a buffer to further separate the plots in the event of drift. Treatments were replicated 3 times and applied to plots in a randomized complete block (RCB) design. More trees were used per plot than in 2014 to build a larger confidence in spray accuracy.

**Applications**

All experimental plots were maintained throughout the year with insect, disease, and weed control preventative sprays, excluding any materials of similar AI as treatment compounds.
Table 1. List of active ingredients, trade name, manufacturer, rate, and field rate for products tested on tart cherry in 2014 and 2015 in Michigan, USA.

| Active ingredient | Chemical class | Trade name | Manufacturer | Ai. rate | Field rate |
|-------------------|----------------|------------|--------------|----------|------------|
| Cyantraniliprole  | Diamide        | Exirel 0.83 SE | DuPont Crop Protection, Wilmington, DE | 0.15 kg Al ha$^{-1}$ | 20.5 fl oz acre$^{-1}$ |
| Phosmet           | Organophosphate | Imidan 70 WP | Gowan Company, Yuma, AZ | 1.67 kg Al ha$^{-1}$ | 2.125 lb acre$^{-1}$ |
| Fenpropanthrin    | Pyrethroid     | Danitol 2.4 EC | Valent U.S.A., Walnut Creek, CA | 0.06 kg Al ha$^{-1}$ | 21.3 fl oz acre$^{-1}$ |
| Spinetoram        | Spinosyn       | Delegate 25 WG | DOW AgroSciences | 0.12 kg Al ha$^{-1}$ | 7.0 oz acre$^{-1}$ |

*Mixed with the buffer TriFol L, Aliphatic Polycarboxylate.

In 2014, each of the four insecticides was applied only once on 22 July at the maximum label rate for stone fruit prior to fruit harvest (Table 1). These insecticides, cyantraniliprole (Exirel 0.83SE), phosmet (Imidan 70 W), fenpropanthrin (Danitol 2.4EC), and spinetoram (Delegate 25WG), were selected from currently registered materials for stone fruits, each one representing a distinct chemical class (Table 1). A buffering agent to stabilize the pH was used with phosmet as per the label directions for use (Table 1). Test materials were applied with an FMC 1229 airblast sprayer (Jonesboro, AK, USA) calibrated to deliver diluent at 561 L ha$^{-1}$ (60 gallons per acre), 1.3 m per second (3.0 miles per h), and a 37.8 L tank mix of the insecticide, buffer (only phosmet), and water (10.0 gallons). This research sprayer has a tank capacity of 151.4 L (40.0 gallons).

In 2015, each of the four insecticides was applied (either singly or multiple times) using the maximum label rate for stone fruit prior to fruit harvest (Table 1). Treatments applied multiple times were done in accordance with the maximum rate and stated spray intervals. Applications of the various treatments were timed to ensure adequate time for harvesting and processing of the fruit at the end of the season Single applications of cyantraniliprole, phosmet, fenpropanthrin, and spinetoram were made on 7 July. Three applications of cyantraniliprole, phosmet, and spinetoram occurred on 24 June, 29 June, and 6 July, and spinetoram was applied twice, on 26 June and 6 July. Test materials were applied with an FMC 1029 airblast sprayer calibrated to deliver diluent at 935 L ha$^{-1}$ (100 gallons per acre), 1.1 m per second (2.5 miles per h), and a 94.6 L (25.0 gallons) tank mix of insecticide, buffer (only phosmet), and water. This research sprayer has a tank capacity of 105.9 L (28.0 gallons).

Cherry Washing and Insecticide Residues

All residue samples were collected and prepared, and the parent active ingredients were recovered using methods based on US EPA standards for GLP field residue studies (USEPA 40 CFR 160). One labeled gallon Ziploc$^*$ (SC Johnson, Racine, Wisconsin) bag was used to collect 0.9 kg (2 lbs, approximately 160 cherries) total fruit per bag for each washed and unwashed replicate sample. The cherries were selected randomly from each cardinal direction side of the tree, low/middle/high, and shielded/exposed portions of the tree crown. The specifics of each location are as follows: Low – below 1.2 m (4 ft) of tree, Middle – at 1.2 m height, and High – above 1.2 m of the tree canopy. Shielded location: Fruit at least 60.9 cm (24 in) inside of the tree crown. Exposed location: Fruit at least 60.9 cm (24 in) to the outside of the tree crown. Samples were collected on the specific day after treatment (DAT) or the day after the last treatment and ± 1 day (Table 2). The 2014 season samples were collected from all treatments at 1 DAT (23 July), 3 DAT (25 July), 7 DAT (29 July), 14 DAT (5 Aug), 21 DAT (12 Aug), and 28 DAT (19 Aug). The 2015 season sampling dates are listed in Table 2.
Table 2. Day after treatment (DAT) sampling dates of tart cherries for residue analysis during 2015 in Michigan, USA.

| Treatment/ Formulation | Sample DAT number |
|------------------------|-------------------|
|                       | 1     | 3     | 7     | 14    | 21    | 28    |
| UTC                   | 7-Jul | 9-Jul | 13-Jul| 20-Jul| 27-Jul| 3-Aug |
| Cyantraniliprole, Single Appl. | 8-Jul | 10-Jul| 14-Jul| 21-Jul| 28-Jul| 4-Aug |
| Cyantraniliprole, Multiple Appl. | 7-Jul | 9-Jul | 13-Jul| 20-Jul| 27-Jul| 3-Aug |
| Phosmet, Single Appl.  | 8-Jul | 10-Jul| 14-Jul| 21-Jul| 28-Jul| 4-Aug |
| TriFol L              | 7-Jul | 9-Jul | 13-Jul| 20-Jul| 27-Jul| 3-Aug |
| Phosmet, Multiple Appl.| 8-Jul | 10-Jul| 14-Jul| 21-Jul| 28-Jul| 4-Aug |
| Fenpropathrin, Single Appl. | 7-Jul | 9-Jul | 13-Jul| 20-Jul| 27-Jul| 3-Aug |
| Fenpropathrin, Multiple Appl. | 8-Jul | 10-Jul| 14-Jul| 21-Jul| 28-Jul| 4-Aug |
| Spinetoram, Single Appl.| 7-Jul | 9-Jul | 13-Jul| 20-Jul| 27-Jul| 3-Aug |
| Spinetoram, Multiple Appl. | 7-Jul | 9-Jul | 13-Jul| 20-Jul| 27-Jul| 3-Aug |

Treatments including more than one application, DAT refers to days after the final application.

Washing

After the initial cherry sampling from the field, the cherries were brought back to the water washing location located at the TNRC fruit barn. In 2014 and 2015, each insecticide underwent a water washing procedure. In 2014, the washed cherries were compared to the unwashed cherries and in 2015, all the cherries were washed. The water washing procedure simulates the standard industry methods for tart cherries modified from Cargill et al. (1969). The industry generally dumps all the harvested cherries into 946.3 L (250 gal) cooling tanks, which run water at 30.2–37.8 L (8–10 gal) per minute for approximately two hours at approximately 60 degrees Fahrenheit to chill the fruit in preparation for pitting. The water is naturally cool, coming from a well, with new cool water continuously flowing in and warmer water flowing out of the tanks. Then, the rate slows to 15.1–22.7 L (4–6 gal) per minute and finally the cherries sit in cooling tanks for approximately 2 h. Study methods followed the industry protocol, but on a smaller, research-scale.

The research-scale washing method was calibrated 3 times using a timer and sprinkler valves before each use. The flow rate was timed to reach the graduated gallon marks on 18.9 L (5 gal) buckets.

The research-scale washing system used a 4-way splitter allowing four 18.9 L (5 gal) buckets to be used simultaneously. Flow rate was regulated with an in-line sprinkler valve positioned before the bucket. Mesh screens were placed over the top of each bucket to prevent the cherries from floating out of the bucket during the washing treatment. Each 0.9 kg (2 lb) cherry sample was washed separately in different buckets to prevent cross contamination. The entire 0.9 kg (2 lb) cherry sample was placed into clean buckets and rinsed for 2 hrs ± 15 min at 18.9 L (5 gal) per minute in 2014 and 7.5 L (2 gal) per minute flow rate for the 2015 season. Variation in flow rate was due to differing water pressure at the tap. Just like the industry, the well water continuously flows in and out cooling the warming water that is exposed to the warm summer air. After the cold-water rinse, the cherries were placed back into their labeled Ziploc® (SC Johnson) bags. The cherries were then taken out of their labeled bags one repetition at a time and one treatment at a time to prevent cross contamination. The cherries were then pitted with a sanitized Leifheit® single cherry pitter (Leifheit, Nassau, Germany).

Insecticide Residue Analysis

All equipment was sanitized with acetone and gloves changed between each repetition and treatment to prevent cross contamination. Once pitted, the cherries were weighed (in the Ziploc bag) and stored in a −20°C chest freezer (Kenmore®, Hoffman Estates, Ill.) and monitored to ensure temperature ranges did not rise above −5°C for storage until processed.

Six-hundred grams of dry ice were then added to each 0.9 kg (2 lb) sample prior to processing to prevent softening. Samples were processed for 5 minutes in a commercial Hobart® food processor (Hobart Corporation, Troy, OH), beginning with the latest sample
date (28 DAT) and working toward the earliest DAT. This order of processing protects against cross contamination and ensures that the samples with the least potential residue levels were handled first, and the samples with potentially greater residue levels last. A homogenous ground subsample was taken from all four quadrants of the processing bowl. These subsamples were poured into clean labeled 120 ml jars (Qorpak Bottle Beakers®, Berlin Packaging, Chicago IL). The sample jars were then placed back into the freezer for 24–36 h when a second subsample (10 g) was removed from each jar and placed into new clean jars. Next, 4 g of magnesium sulfate, 1 g of sodium chloride, and 15 ml of dichloromethane were added. Also, samples were then refrigerated for 2 days to extract active ingredients (in solution) from the fruit tissue. The samples were shaken and then decanted through 12 g of reagent-grade anhydrous sodium sulfate (EMD Chemicals, Inc.) to remove water for an hour. The samples were reconstituted with 2 ml of acetonitrile and transferred into a 2 ml vial for HPLC analysis. Residue analysis was done using the QuEChERS method for multiple pesticide residue analysis for a variety of different sample types (Kong et al., 2016). The HPLC level of quantification for cyantraniliprole, spinetoram, and phosmet was 0.050 parts per million (ppm) of a.i., and level of detection was 0.015 ppm. The HPLC level of quantification for fenpropathrin was 0.010 ppm of a.i., and level of detection was 0.003 ppm.

The residue data for each compound were analyzed with mixed models using the MIXED procedure in SAS 9.4 (SAS Institute, Cary, NC, 2013). The fruit residues were analyzed with repeated measures best adjusted using an unstructured and a first-order heterogeneous autoregressive covariance structure. Replicates and treatments were used as subjects of repeated measurements. When the main effects or their interactions were statistically significant (P < .05), slicing of interactions within the main effects was performed, F-tests (Aćimović et al., 2014) were conducted, and pairwise or specific time or treatment comparisons were conducted using t-tests (α = 0.05).

Results

Residue Profiles-2014 Washed and Unwashed Cherries

Fenpropathrin was detected throughout the 28-day residue profile with a relatively flat decline curve for the washed and unwashed treatments (Figure 1). There were significantly more residues on the unwashed fruit 21 DAT, but not on other individual dates, nor in the overall dataset. For unwashed and washed treatments, mean residue values were below the US MRL for all sample dates. Fenpropathrin residues exceeded the EU and India’s default MRL. Residue fell below Mexico, Canada, China, Japan, Australia, Singapore, Korea, and Taiwan’s MRL (Table 3). There is no CODEX MRL for fenpropathrin and no default MRLs, thus must assume no detectable residues.

Cyantraniliprole was detected throughout the 28-day residue profile with a gradual decline in residue levels for the unwashed and washed treatments (Figure 1). There were significantly more residues on unwashed fruit than washed fruit at 1, 3, 7, 21, and 28 DAT. Mean residue levels following unwashed and washed regimes fell below the US MRL for the 3-day PHI. Internationally, unwashed or washed treatments fell below Korea, EU, Mexico, Canada, Singapore, India default, Taiwan, China, Japan, and Australia’s MRL (Table 3).

Phosmet was detected throughout the 28-day residue profile with a rapid decline in residue levels for the unwashed and washed treatments (Figure 1). Washing caused significant reductions in detectable residues 1 and 3 DAT, and in the overall dataset. Mean residue values following the unwashed and washed regimes were below the US MRL for all sample dates. Internationally, there is no CODEX MRL for phosmet and residues following unwashed and washed treatments and fell below Korea, EU, Mexico, India default, Singapore, Canada, China, Japan, Australia, and Taiwan’s MRL (Table 3).
Spinetoram was detected throughout the 28-day residue profile with rapid declines in residue levels for the unwashed and washed treatments (Figure 1). There were no significant differences in detectable residues between the unwashed and washed treatments for the overall sample set, or for any individual sample date after partitioning. Mean residue values following an unwashed or washed treatment were below the US MRL for all sample dates. Internationally, spinetoram residues following an unwashed or washed spinetoram treatment were below the EU, Mexico, Canada, Singapore, China, Korea, Japan, India default, Australia, and Taiwan’s MRL (Table 3).

Table 3. MRL values in ppm for the countries and compounds studied in 2014 and 2015.

|               | Fenpropathrin | Cyantraniliprole | Phosmet  | Spinetoram |
|---------------|---------------|------------------|----------|------------|
| US            | 5             | 6                | 10       | 0.3        |
| EU            | 0.01          | 6                | 1        | 2          |
| Mexico        | 5             | 6                | 10       | 0.3        |
| Canada        | 5             | 6                | 7        | 1          |
| China         | 5             | 6                | no MRL or default | 0.09 |
| Japan         | 5             | 6                | 0.1      | 0.5        |
| Australia     | 5             | 6                | 0.05     | 0.2        |
| Singapore     | 1             | 6                | no MRL or default | 0.09 |
| India Default | 0.01          | 0.01             | 0.01     | 0.01       |
| Korea         | 5             | 6                | 0.05     | 0.2        |
| Taiwan        | 5             | no MRL or default | 2        | 0.2        |
Residue Profiles-2015 Single and Multiple Applications

Fenpropathrin was detected throughout the 28-day residue profile with a gradual decrease in residue levels for the single and multiple application treatments (Figure 2). Residue levels were higher in multi-sprayed than in single-sprayed treatments on all evaluation dates and for the overall dataset. Mean residue levels for single and multiple application regimes were below the US MRL for all sample dates. Internationally, single or multiple applications would exceed EU’s default MRL for all sample dates. Fenpropathrin concentrations fell below Mexico, Canada, China, Japan, Australia, Singapore, India default, Korea, and Taiwan’s MRL (Table 3).

Cyantraniliprole was detected throughout the 28-day residue profile with a rapid decrease in residue levels for the single and multiple application treatments in the first 3 days, followed by a gradual decline (Figure 2). There were no significant differences in detectable residues between the single and multi-sprayed treatments for the overall sample set, or for any individual sample date after partitioning. Mean residue levels following single and multiple application regimes fall below the US MRL for all sample dates. Internationally, single and multiple application treatments fall below Korea, EU, Mexico, Canada, Singapore, India default, China, Taiwan, Japan, and Australia’s MRL (Table 3).

Phosmet was detected throughout the 28-day residue profile with a gradual decrease in residue levels for the single and multiple application treatments (Figure 2). Residue levels were higher in multiple-sprayed than single-sprayed treatments on 7, 14, 21, and 28 DAT. Mean residue values

Figure 2. a) Fenpropathrin, b) Cyantraniliprole, c) Phosmet (only one measured in ppb), and d) Spinetoram residue decline profiles measured 1, 3, 7, 14, 21, and 28 days after treatment (DAT) in 'Balaton' tart cherry fruit comparing single and multiple spray treatments sampled during 2014 in Michigan, USA. Concentration means within one date followed by different letters are significantly different (t-tests p < .05). Error bars represent standard error of the mean (SEM).
following a single or multiple application regimes were below the US MRL for all sample dates. Internationally, residues following single and multiple application treatments were also under Korea, EU, Mexico, Canada, China, Singapore, Japan, India default, Australia, and Taiwan’s MRL (Table 3). Spinetoram was detected throughout the 28-day residue profile with rapid declines in residue levels in the first seven days for the single and multiple application treatments (Figure 2). Residue levels were higher in multiple-sprayed than in single-sprayed treatments on all evaluation dates and for the overall dataset. Mean residue levels following a single or multiple application regimes were below the US MRL for all sample dates. Spinetoram concentrations fell below the EU, Mexico, Canada, China, Korea, Japan, Singapore, India default, Australia, and Taiwan’s MRL (Table 3).

Discussion

This research contributes important new information on pesticide residue levels at harvest, following grower pre- and post-harvest practices. The results show how post-harvest washing procedures and a number of applications for certain compounds can influence residue levels on cherry fruit at harvest.

In this study, compounds of the organophosphate and pyrethroid classes showed the greatest disparity of residue levels between single and multiple applications, and secondarily the spinosyns. There are several factors that could influence this phenomenon. One factor may be the differing plant penetration attributes of the compounds. Diamides and spinosyns have plant penetrative attributes allowing mobility into and beneath the plant cuticle (Bostanian et al., 2012; Wise et al., 2017a). Organophosphates and pyrethroids remain largely on the plant surface, with limited cuticle penetration. Another factor may be the persistence of the compound. In our study, compounds known to have greater persistence were more likely to show the greatest disparity in residue levels between single and multiple applications (Wise and Whalon, 2009).

The results also showed the organophosphate and diamide compounds to be more sensitive to wash-off from the water washing procedure. These factors appear to have the greatest influence on the likelihood of higher or lower residue concentrations at harvest under our treatment regimes.

Fenpropathrin, like most pyrethroids, has limited cuticular penetration, but like lipophilic compounds has a natural affinity for cuticular waxes. This is likely one of the factors responsible for the moderate rainfastness recorded for pyrethroids in another study (Hulbert et al., 2011). Fenpropathrin is relatively unstable and degrades rapidly in normal environmental conditions (Akhtar et al., 2004). This may indicate that with a single application, fenpropathrin will fall quickly after each application, such that multiple applications are needed if the goal is to maintain residue levels that are efficacious for pest control purposes, without exceeding MRLs. Residue levels for pyrethroids (fenpropathrin) were shown to be more variable and have greater persistence than spinosyns (spinetoram), with residue levels ranging from 0.89 to 2.93 at 3 DAT as shown in Haviland and Beers (2012). Haviland and Beers (2012) compared 3 different pyrethroids (lambda-cyhalothrin, zeta-cypermethrin, and fenpropathrin), which all followed the greater persistence conclusion as in this study. Andika et al. (2019) similarly demonstrated greater persistence of the pyrethroid zeta-cypermethrin on cherry following simulated rainfall.

The factors responsible for the differences between the Haviland and Beers (2012) study and this study may include the rainfall levels, crop type, post-harvest washing procedures, and application timing. The average rainfall for the California cherry growing season (February-May) is approximately 136 mm (5.35 in.) (www.intellicast.com) and the average seasonal (April-July) precipitation in Michigan approximates 380+ mm (15.06 in.) (www.enviroweather.msu.edu). This difference in rainfall levels for the two US growing regions indicates that fenpropathrin residue levels in California should be higher than levels expected in Michigan and the US Great Lakes region. Another difference between the two studies is fruit type, where the Haviland and Beers (2012) study used sweet cherries, which have thicker skins than tart cherries. Additionally, tart cherries undergo a post-harvest cold water washing procedure, whereas sweet cherries do not. These factors likely contribute to why
fenpropathrin residues were higher in the Haviland and Beers (2012) study than in the current Michigan study. There is also an important similarity in this study compared to the Haviland and Beers (2012) study in that the levels of fenpropathrin are consistent.

This study suggests that fenpropathrin (with unwashed or washed and single or multiple applications and a 3-day PHI) would be low risk in export markets in most prospective countries, as most of these markets are well harmonized with US MRLs. Since there is not a CODEX MRL for fenpropathrin, there would be significant risk for export to Colombia, Guatemala, Jordan, Nicaragua, and Philippines (Bryant Christie Inc, 2021) because they do not have default MRLs, thus must assume no detectable residues. Also, internationally, unwashed and washed treatments would be low risk for export to most importing countries with a 3-day PHI (Bryant Christie Inc Global MRL database, 2019).

In this study, residues exceeded the EU’s MRL of 0.01 ppm and thus would be unacceptable for export to the EU at the current 3-day PHI. For Michigan cherry growers to safely target international trade with the EU, one mitigation strategy could be to artificially extend the PHI by seven days. According to the levels in this study, this would likely reduce the fenpropathrin residues at harvest below the EU’s MRL. The EU has an extreme difference of 500-fold lower MRL for fenpropathrin when compared with the US; therefore, export must be done mindfully (Haviland and Beers, 2012).

Cyantraniliprole is moderately persistent in normal environmental conditions (Dong et al., 2011), and like most diamides, it has translaminar penetration in plant tissues, thus forming a “reservoir” from direct environmental exposure (Bostanian et al., 2012). There were eight rain events within the duration of the 2014 trial, the highest being near 15.2 mm (0.6 in.). While diamides are known to be moderate rainfast (Andika et al., 2019; Wise et al., 2017a), the disparity shown in this study between washed and unwashed treatments of cyantraniliprole suggests that post-harvest washing procedures can have a high impact on residues at harvest. This study suggests cyantraniliprole with unwashed or washed and single or multiple application regimes and a 3-day PHI would be low risk for export to many prospective countries. Most countries are well harmonized with US MRLs. The single spray unwashed residue profile in 2014 includes a spike at 21 d, which does not fit the overall decline curve well. This may have been a result of the 0.6 in rainfall event, causing the pesticides to be washed off with the rainfall event. Therefore, cherry growers should feel confident if exporting internationally to most prospective markets.

Phosmet, like most organophosphates, is known to be highly susceptible to rain wash off, as most of the active ingredients remain on the surface of the plant (Andika et al., 2019; Wise et al., 2017a). This study shows similarly that post-harvest washing procedures have a high impact on phosmet residues at harvest. This likely explains why residue profiles for phosmet in this study showed very similar concentrations in 2014 and 2015, even though there was more total rainfall in 2015 than in 2014. Phosmet residues fell below the US MRL of 10 ppm and would be accepted for domestic trade. Since there is not a CODEX MRL for phosmet, there would be significant risk for export to Colombia, Guatemala, Israel, Jordan, Nicaragua, Philippines, and Singapore, who do not have default MRLs, thus must assume no detectable residues. Phosmet, being generally more persistent than other materials, explains the tendency to accumulate with multiple applications, leading to higher residues at harvest. This study suggests that unwashed or washed cherries and single or multiple application regimes and 7-day PHI would be low risk for export to many prospective countries.

Spinetoram, like most spinosyns, has translaminar penetration in plant tissues, thus forming a “reservoir” from direct environmental exposure (Bostanian et al., 2012). This likely contributes to the moderate rainfastness documented for this compound (Andika et al., 2019; Wise et al., 2017a). A similar pattern was observed in this study, as the washing procedure had a minimal effect on residues. The effect of the treatment difference was not lost as residue profiles rapidly declined, yet it still resulted in significantly higher residues for the multiple-sprayed treatment. The rapid decrease in spinetoram in this study is similar to patterns documented in other studies (Andika et al. 2019)). Haviland and Beers (2012) similarly showed spinetoram residue levels on sweet cherries ranged from
nondetectable to 0.19 ppm at 0, 3, 7 and 21 DAT. Haviland and Beers also compared a second spinosyn (Spinosad), which also had similar results in spinetoram. These combined data can help inform cherry growers using conventional insecticides as well as those intending to export organically produced fruit.

The spinetoram residues on cherry fruit following all of the treatment regimes in this study would be acceptable for most prospective markets. Internationally, residues following a single or multiple application of spinetoram would fall below the EU’s MRL of 0.05 ppm, making it low risk for export to the EU. Since there is not a CODEX MRL for spinetoram, there would be significant risk for export to Colombia, Guatemala, India, Israel, Jordan, Nicaragua, Philippines, and Singapore, who do not have default MRLs. Therefore, this study’s results for spinetoram suggest that unwashed or washed and single or multiple-spray and 7-day PHI would be low risk for export to most prospective countries, as well as the markets that are well harmonized with US MRLs.

It is noteworthy to see in this study the range of insecticide residue levels measured in 2014 versus 2015. In the 29-day study period of 2014, there was a total of 49.7 mm (2.0 in) of rain and 8 precipitation events, while in the parallel study period of 2015 there was a total of 97.5 mm (3.8 in) of rain and 10 precipitation events. Thus, there was 47.7 mm (1.9 in) more rain in 2015 than 2014, and yet there were generally higher residue concentrations measured in 2015 for all compounds, except spinetoram, which was similar for both years (www.enviroweather.msu.edu). Therefore, weather does not explain the differences in residues from year to year, but as mentioned previously, there are several other factors, which may have contributed to these differences. Tree size (canopy size, structure, and density) and spray volume may have played a role in residue differences between 2014 and 2015 (Hall, 1991). The 2014 ‘Montmorency’ cherry trees were older with a very dense canopy structure and size standing 5.7 m tall. The 2015 ‘Balaton’ cherry trees are approximately half the canopy size and an open canopy structure standing 2.7 m tall. The spray volume in 2014 was 561 L.ha-1 (60 gallons per acre) and in 2015 was 935 L.ha-1 (100 gallons per acre). The larger tree size along with lower spray volume in 2014 may have reduced pesticide deposition onto fruit with more shielded portions of the canopy. The influence of spray volume on canopy penetration was similarly documented in grapes (Wise et al., 2010).

These data can contribute to developing spray programs and assist growers in management decisions related to potential export markets. Knowing when the different insecticides reach specific residue levels at specific times and spray rates can be used to develop valuable spray programs for pest control. The current driver of insect management programs near harvest is SWD. SWD management typically requires multiple sprays for tart cherry production. Sprays often occur from the time that fruit starts changing color until harvest. This period lasts approximately 4 weeks. Growers also need to rotate chemistries while considering resistance. Therefore, according to our studies, fenpropathrin has a short PHI and a long residual, so it provides a good fit at the front end of a program. Spinetoram has a longer PHI and shorter residuals, so it fits best closer to harvest.

Trials to evaluate multi-spray programs were conducted for SWD in Michigan tart cherries (Wise et al., 2016, 2017; Wise et al., 2020). These reports show that programs can be effective but require multiple sprays. In their 2016, 2017 and 2020 Arthropod Management Test reports, researchers evaluated programs for SWD that included products in this study. The programs, which proved effective against SWD, were sprayed weekly and began at first fruit color and continued until harvest. Our studies on residues, in combination with efficacy data by Wise et al. and others suggest that tart cherry growers can successfully implement single or multiple spray programs while qualifying fruit for export. Growers who use the information found in this manuscript can identify programs that can be used safely with regard to MRL tolerances for export-bound fruit while avoiding programs that may be of higher risk.

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**Literature Cited**

Aćimović, S.G., A.H. VanWoerkom, P.D. Reeb, C. Vandervoort, T. Garavaglia, B.M. Cregg, and J.C. Wise. 2014. Spatial and temporal distribution of trunk-injected imidacloprid in apple tree canopies. Pest Manage. Sci. 70(11):1751–1760. doi: 10.1002/ps.3747.

Akhtar, S., S.T.S. Gilani, and N. Hasan. 2004. Persistence of chlorpyrifos and fenpropathrin alone and in combination with fertilizers in soil and their effect on soil microbes. Pak. J. Bot. 36(4):863–870. Accessed 24 February 2016. http://www.pakbs.org/pjbot/PDFs/36(4)/PJB36(4)863.pdf.

Andika, I.P., C. Vandervoort, and J.C. Wise. 2019. Rainfastness of insecticides used to control spotted-wing drosophila in tart cherry production. Insects 10(203):1–15. doi: 10.3390/insects10070203.

Bellamy, D.E., M.S. Sisterson, S.S. Walse, and A.W. Shingleton. 2013. Quantifying host potentials: Indexing postharvest fresh fruits for spotted wing drosophila, *Drosophila suzukii*. PLoS ONE 8(4):e61227–e61227. doi: 10.1371/journal.pone.0061227.

Bostanian, N.J., J.C. Wise, and R. Isaacs. 2012. Insecticides and their use in vineyard pest management, p. 505. In: N. J. Bostanian, R. Isaacs, and C. Vincent (eds.). Arthropod management in vineyards. Springer Publishing Ltd, Dordrecht.

Bryant Christie Inc Global MRL database. 2019. 22 March. 2016. https://www.globalmrl.com

Cargill, B.F., J. George Mcmanus Jr, S. Bolen, and R.T. Whittenberger. 1969. Cherry cooling stations and handling practices for quality production of red tart cherries. Michigan State Univ. Ext. Bull. 659: 1–3.

Dong, F., X. Liu, J. Xu, J. Li, Y. Li, W. Shan, W. Song, and Y. Zheng. 2011. Determination of cyantraniliprole and its major metabolite residues in vegetable and soil using ultra-performance liquid chromatography/tandem mass spectrometry. Biomed. Chromatogr. 26:377–383. doi: 10.1002/bmc.1669.

Hall, F.R. 1991. Influence of canopy geometry in spray deposition and IPM. HortScience 26(8):1012–1017. doi: 10.2127/HORTSCIE.26.8.1012.

Handford, C.E., C.T. Elliott, and K.K. Campbell. 2015. A review of the global pesticide legislation and the scale of challenge in reaching the global harmonization of food safety standards. Integr. Environ. Assess. Manage. 9999 (9999):1–12. doi: 10.1002/ieam.1635.

Haviland, D.R., and E.H. Beers. 2012. Chemical control programs for drosophila suzukii that comply with international limitations on pesticide residues for exported sweet cherries. J. Integr. Pest Manage. 3(2):1–6. doi: 10.1603/IPM11034.

Hulbert, D., R. Isaacs, C. Vandervoort, and J.C. Wise. 2011. Rainfastness and residual activity of insecticides to control Japanese beetle (Coleoptera: Scarabaeidae) in grapes. J. Econ. Entomol. 104(5):1656–1664. doi: 10.1603/EC11077.

Kong, W.-J., Q.T. Liu, D. Kong, Q.-Z. Liu, X.-P. Ma, and M.-H. Yang. 2016. Trace analysis of multi-class pesticide residues in Chinese medicinal health wines using gas chromatography with electron capture detection. Nat. Publ. Group. 1–13. doi: 10.1038/srep21558.

Lee, J.C., D.J. Bruck, H. Curry, D. Edwards, D.R. Haviland, R.A. Van Steenwyk, and B.M. Yorgey. 2011. The susceptibility of small fruits and cherries to the spotted-wing drosophila, *Drosophila suzukii*. Pest Manage. Sci. 67 (11):1358–1367. doi: 10.1002/ps.2225.
Lehman, H. 1993. New directions for pesticide use, p. 3–9. In: D. Pimentel, and H. Lehman (eds.). The pesticide question: Environment, economics and ethics. Routledge: Chapman and Hall, Inc. 1993. doi: 10.1007/978-0-585-36973-0_1.

Rodriguez-Saona, C., C. Vincent, and R. Isaacs. 2019. Blueberry IPM: Past successes and future challenges. Annu. Rev. Entomol. 64(1):95–114. doi: 10.1146/annurev-ento-011118-112147.

Schierow, L.J. 1999. Pesticide residue regulation: Analysis of food quality protection act implementation. Risk Health Safety Environ. 10(4):281–288. Accessed 12 January 2015. https://scholars.unh.edu/cgi/viewcontent.cgi?article=1409&context=risk.

USEPA. 40 CFR, Part 160. Federal insecticide, fungicide, and rodenticide act. Good Laboratory Practices Standards; Final Rule. Office of the Federal Register, National Archives and Records Administration. U.S. Government Printing Office. Washington, D.C.

Wise, J.C., L.J. Gut, R. Isaacs, G.W. Sundin, B. Zandstra, R. Beaudry, and G. Lang. 2016b. 2017 Michigan fruit management guide. Michigan State University, East Lansing, (MSUE Bulletin E-154).

Wise, J.C., P.E. Jenkins, A.M.C. Schilder, C. Vandervoort, and R. Isaacs. 2010. Sprayer type and water volume influence pesticide deposition and control of insect pests and diseases in juice grapes. Crop Prot. 29(4):378–385. doi: 10.1016/j.cropro.2009.11.014.

Wise, J.C., A.H. VanWoerkom, and L.J. Gut. 2016a. Spotted wing drosophila control in tart cherries, 2015. Arthropod Manage. Tests. 40. doi: 10.1093/amt/tsw102.

Wise, J.C., A.H. VanWoerkom, and L.J. Gut. 2017a. Control of spotted wing drosophila in tart cherry, 2016. Arthropod Manage. Tests. 42(1). doi: 10.1093/amt/tsx065.

Wise, J.C., and M. Whalon. 2009. A systems approach to IPM integration, ecological assessment and resistance management in tree fruit orchards, Chapter 13, pp. 325–345. In I. Ishaaya and A. Rami Horowits (eds.). Biorational control of arthropod pests: Application and resistance management. Springer Publishing Ltd, Dordrecht, Heidelberg, London, New York.

Wise, J.C., C.E. Wheeler, A.H. VanWoerkom, and L.J. Gut. 2020. Control of spotted wing drosophila in tart cherry, 2019. Arthropod Manage. Tests. 45(1). doi: 10.1093/amt/tsaa042.