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A comparative evaluation of post-infection efficacy of mefenoxam and potassium phosphite with protectant efficacy of azoxystrobin and potassium phosphite for controlling leather rot of strawberry caused by *Phytophthora cactorum*

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ABSTRACT

Leather rot, caused by *Phytophthora cactorum*, is one of the most important fruit-rotting diseases of strawberry worldwide. Efficacy of mefenoxam and potassium phosphite against leather rot, when applied in a post-infection fungicide program, made in response to rain events was evaluated over 3 years of testing. Post-infection treatments of potassium phosphite and mefenoxam were compared with calendar-based treatments of azoxystrobin or potassium phosphite sprayed weekly, starting at late bloom (fruit set). In order to obtain high-risk conditions for infection (splash dispersal of the pathogen and subsequent infection periods), plots were flooded until standing water was observed between the rows. Post-infection applications were made within 36 h after the initiation of a flooding event. Leather rot incidence in the untreated controls ranged from 15 to 66% over the 3 years. All fungicide treatments had significantly ($P < 0.001$) less leather rot incidence than in the untreated control. There were no significant differences in leather rot incidence between the different fungicide treatments. Percent control (the percentage reduction in incidence relative to the check) was as high as 100% with all fungicide treatments. Mefenoxam and potassium phosphite post-infection (after flooding) provided control equal to that obtained with a calendar-based spray program, but with from 1 to 3 fewer fungicide applications.

1. Introduction

Leather rot of strawberry, caused by *Phytophthora cactorum* (Lebert and Cohn) Scröt, is a common disease of strawberry (*Fragaria* × *ananassa*) in which fruits can become infected at all stages of development. On green fruits, dark brown areas covering the entire fruit may appear. Fruits appear leathery and eventually will dry down and mummify. On mature diseased fruits, symptoms may not be easy to recognize, and infected fruits can be inadvertently picked along with healthy fruits. Farmers have experienced complaints from "pick your own" costumers because of the characteristic bad taste and foul odor of infected fruits. The off-odor of diseased fruits is caused by compounds derived from phenolic acids, such as 4-ethyl-phenol and 4-ethyl-2-metoxy-phenol (Jelen et al., 2005). Losses due to leather rot can reach 50% under favorable conditions (Ellis and Grove, 1983).

Leather rot is favored by periods of heavy rainfall and saturated soils. Splashing of infective propagules by rainfall and wetness periods as short as 2 h are important components for the development of leather rot epidemics (Grove et al., 1985; Madden et al., 1991). Cultural practices such as avoiding saturated soils through proper site selection, improving soil drainage, and applying straw mulch between the rows are beneficial to disease control. Straw mulch prevents fruits from touching the soil and standing water, and reduces the splashing of water droplets containing sporangia and zoospores (Madden et al., 1991). However, under high disease pressure, cultural control may not be sufficient to provide satisfactory disease control. Fungicides have been reported to be highly effective for controlling leather rot (Ellis et al., 1998; Rebollar-Alviter et al., 2005). Protectant fungicides such as captan and thiram have been used for many years against leather rot; however, under high disease pressure they provide poor disease control

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(Wedge et al., 2007). The introduction of systemic and more efficacious fungicides has greatly improved chemical control of leather rot. Currently, azoxystrobin (Abound 22.9F, manufactured by Syngenta Crop Protection, P.O. box 18300, Greensboro, NC 27419, USA), potassium phosphite (AgriFos 45.8%, manufactured by Agrichem/ Liquid Fertiliser Pty. Ltd., 4–10 Chetwynd St., Loganholme, Queensland 4129, Australia) and mefenoxam (Ridomil Gold 4 EC, manufactured by Syngenta Crop Protection, Inc.) are registered in the USA for controlling leather rot of strawberry. According to the label, mefenoxam (the R-enantiomer of metalaxyl) is recommended for applications during pre-bloom and 30 days before harvest. A third application is recommended for supplemental control during the harvest season. Previous experiments with metalaxyl have shown that one application during bloom may provide sufficient protection for the entire season against leather rot in matted-row production systems (Ellis et al., 1998). Applications of azoxystrobin and phosphorous acid-based compounds are initiated at 10% bloom and with repeated applications at 7–10 day intervals as needed.

Several studies have been conducted on the physical mode of action of the QoI (strobilurin) fungicide azoxystrobin. Wong and Wilcox (2001) working with grapevine downy mildew (*Plasmopara viticola*), reported that azoxystrobin provided 100% control when applied 1–5 days before inoculation, but post-infection applications did not provide a satisfactory reduction of downy mildew incidence. Azoxystrobin provided excellent activity against leather rot under very high disease pressure in the field (Rebollar-Alviter et al., 2005). Rebollar-Alviter reported that azoxystrobin provided protectant activity against leather rot for up to 7 days before inoculation, but only slight curative activity when applied at 13 h after inoculation (Rebollar-Alviter et al., 2007). The strobilurin fungicides represent an important addition to currently used fungicides for control of leather rot. In addition to providing excellent protectant activity against *P. cactorum*, they are also in a different class of chemistry than mefenoxam and the phosphite fungicides. If used in alternating spray programs with mefenoxam and the phosphite fungicides, they should be useful in preventing or delaying the development of fungicide resistance in *P. cactorum*.

Mefenoxam is systemic and can be taken up by roots and leaves, and translocated via xylem following the transpiration stream (Gisi, 2002). Mefenoxam exhibits strong preventive and curative activity against several foliar, soil-borne and seed infecting oomycete pathogens (Gisi, 2002). For example, post-infection applications of metalaxyl to grapes have provided control of grape downy mildew for up to 48 h after inoculation and a substantial reduction in disease development for up to 5 days after inoculation (Kennelly et al., 2007; Wong and Wilcox, 2001).

Phosphite fungicides, on the other hand, are the only truly systemic fungicides that move through phloem from source to sink, and through xylem following the transpiration stream (Gisi, 2002). The mode of action of phosphite fungicides is not known but various reports suggest that phosphite fungicides act by interfering with several enzymes and with phosphorous metabolism (McDonald et al., 2001; Niere et al., 1990; Stehmann and Grant, 2000). In addition, phosphite fungicides have been associated with the stimulation of plant defense responses (Gisi, 2002; Guest and Grant, 1991; Jackson et al., 2000).

Mefenoxam and phosphorous acid are commonly used fungicides for post-infection control of oomycete pathogens on different crops. For instance, both fungicides provided protectant activity for up 12 days against *P. viticola*. Mefenoxam applied post-infection against the same pathogen provided up to 4 days of curative activity; whilst, fosetyl-al only provided 2 days of curative activity (Gisi, 2002; Wicks et al., 1991). Post-infection applications of phosphorous acid or mefenoxam against cankers caused by *P. cactorum* in almond reduced canker development between 36 and 88% (Browne and Viveros, 2004).

The curative activity of mefenoxam and phosphorous acid makes them potentially useful in post-infection fungicide programs where fungicides are applied in response to recorded or predicted infection periods. A disease forecasting system for leather rot has been developed by Reynolds et al. (1987). The influence of weather variables on sporulation, infection and dispersal of *P. cactorum*, and on disease progress, was previously investigated (Grove et al., 1985; Madden et al., 1991; Reynolds et al., 1988). Based on this information, Reynolds et al. (1987) developed a prototype forecasting system for leather rot using discriminant analysis; this forecaster classified weather conditions into categories corresponding to low, medium and high disease risk. From this analysis, the authors concluded that it was possible to predict disease hazards associated with individual rain events with a high degree of reliability, based on the amount of rainfall, an estimation of previous disease incidence, an index of sporulation and an inoculum-dispersal index. Because *P. cactorum* requires very short wetness periods over a wide range of temperatures to cause fruit infection (assuming that propagules are in contact with fruit), determining the occurrence of infection periods (independent of dispersal and high-sporulation events) would not be sufficient for accurately predicting infection periods used to schedule post-infection applications of fungicide. Rather, high risk (or hazard), as determined by individual rain storms and the amount of rainfall during critical periods, is a better indicator of the need to apply a fungicide, because this takes into account the dissemination of propagules to susceptible fruits (a requirement for infection to occur). However, fruit infection would have already occurred (or started) if fungicides were applied only after the high-risk periods, given the very short time needed for fruit infection during wet conditions (Grove et al., 1985). Therefore, fungicides used in this manner would need to have good post-infection or curative activity.

In Ohio, chemical control of leather rot is currently based on calendar-based spray program where prophylactic applications of fungicide are made on a 5–7 day protectant schedule with no regard to infection events. Previous experiments in the greenhouse to investigate the physical mode of action of mefenoxam and phosphorous acid showed that both fungicides provide excellent protectant activity against leather rot for at least 7 days as well as excellent post-infection (curative) activity for up to 36 h after inoculation with *P. cactorum* (Rebollar-Alviter et al., 2007). Since rainfall is a major component that drives the epidemic in this pathosystem, by favoring splash dispersal of primary and secondary inoculum (Madden et al., 1991), scheduling fungicide applications only after the occurrence of moderate to heavy rain events (Reynolds et al., 1987, 1988) could reduce fungicide applications in a leather rot management program. The objective of this research was to evaluate and compare the post-infection activity of mefenoxam and phosphorous acid and the protectant activity of azoxystrobin and phosphorous acid for control of strawberry leather rot in the field.

2. Materials and methods

2.1. Field trials and experimental conditions

Three field trials were established during spring of 2005, 2006 and 2007 in a commercial strawberry planting near Wooster, Ohio, where leather rot is a major problem. The land in all plantings was broadcast fumigated with TERR-O-GAS 67 (methyl bromide (67%) and chloropichrin (33%)), Manufactured by Great Lakes Chemical Corp., P.O. Box 2200, West Lafayette, IN 47996, USA. Fumigation was performed in the fall before the planting was established the