Post-Harvest Applications of Zoxamide and Phosphite for Control of Potato Tuber Rots Caused by Oomycetes at Harvest

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ABSTRACT

Potato storage tuber rots caused by the late blight and pink rot pathogens at harvest can cause severe economic losses, warranting the need for effective post-harvest fungicide applications. The purpose of this study was to evaluate the efficacy of select post-harvest fungicides in reducing tuber infections by the late blight and pink rot pathogens when applied at various post-inoculation time intervals. 'Russet Burbank' potatoes were inoculated by submersion in an aqueous suspension of *Phytophthora infestans* or *Phytophthora erythroseptica* zoospores at 0, 1, 2, 4, and 6 h prior to receiving a post-harvest treatment. Products evaluated were zoxamide (various rates and formulation), phosphite (335 g a.i./MT), and a hydrogen peroxide/peroxyacetic acid mixture (HPPA, 9 g a.i./MT), all applied at 2.08 L/MT of tubers as a low pressure spray prior to storage. Zoxamide and phosphite significantly reduced late blight and pink rot incidence and severity when applied immediately after inoculation. HPPA was less effective at controlling disease development. Phosphite was effective at reducing late blight development at all time intervals up to 6 h post-inoculation (7% vs 80% in untreated). Zoxamide appeared to have good post-harvest disease control if applied soon after inoculation. The maximum time intervals between inoculation and treatment where significant reductions in pink rot incidence were observed was 0 h for HPPA (28%), 2 h for zoxamide (55%; 64 g a.i./MT) and 6 h for phosphite (13%) compared to the untreated (73%). Phosphite provided consistent disease control even when applied several h after inoculation and has potential to be a reliable post-harvest fungicide for the potato industry.

RESUMEN

Las pudriciones de los tubérculos de papa en almacén, causados por los patógenos del tizón tardío y la pudrición rosada durante la cosecha, pueden causar pérdidas económicas cuantiosas, haciendo necesaria la aplicación de funguicidas después de la cosecha. El propósito de este estudio ha sido evaluar la eficacia de fungicidas selectos, aplicados después de la cosecha para reducir la infección de los patógenos antes mencionados a varios intervalos. Papa 'Russet Burbank' fue inoculada sumergiéndola en una suspensión acuosa de zoosporas de *Phytophtora infestans* o de *Phytophthora erythroseptica* por 0, 1, 2, 4, 6 horas antes de recibir el tratamiento de post-cosecha. Los productos evaluados fueron zoxamide (a varias dosis y formulaciones), phosphite (335g de i.a./T) y una mezcla de peroxido/ácido peroxiacético (HPPA, 9g de i.a./T) todo aplicado a 2.8 L/T de tubérculos como pulverización a baja presión antes del almacenamiento. Zoxamide y phosphite redujeron significativamente la incidencia de tizón tardío y de pudrición rosada cuando se aplicaron inmediatamente después de la inoculación. El HPPA fue menos efectivo en controlar el desarrollo de la enfermedad. El phosphite fue efectivo en reducir el desarrollo de tizón tardío en todos los tiempos de post-inoculación hasta las 6 horas (7% contra 80% de las no tratadas). Zoxamide parece ejercer buen control post-cosecha de la enfer-

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medad si se aplica lo más pronto después de la inoculación. Los máximos tiempos de intervalo entre la inoculación y el tratamiento donde se observó reducción significativa en la incidencia de pudrición rosada fue 0 h para HPPA (28%), 2 h para zoxamide (55%; 64g de i.a./T) y 6 h para phosphite (13%) comparado con el testigo no tratado (73%). Phosphite proporcionó un consistente control aún cuando se aplicó varias horas después de la inoculación y tiene el potencial para ser un funguicida confiable para ser usado después de la cosecha en la industria de papa.

INTRODUCTION

Pink rot caused by *Phytophthora erythroseptica* Pethybr. and late blight caused by *Phytophthora infestans* (Mont.) de Bary can be serious pre- and post-harvest diseases, causing significant rot of potato (*Solanum tuberosum* L.) tubers when plants become infected in the field (Erwin and Ribeiro 1996; Taylor et al. 2004). Pink rot has been traditionally associated with poorly drained, water-logged soils or in situations where the crop is exposed to high soil moisture late in the season (Goss 1949). Cultural control measures for managing this disease in the field have included crop rotation, planting in soils with good water drainage, avoiding over-irrigation, applying mefenoxam-based fungicides, establishing a good tuber skin set prior to harvest, and harvesting tubers when tuber pulp temperatures are below 18 C (Jones 1954; Lambert and Salas 2001; Salas et al. 2000b; Taylor et al. 2004). However, severe pink rot has been observed in eastern Idaho in sandy soils with low organic matter where drainage is good (Blodgett 1945). Additionally, insensitivity of *P. erythroseptica* populations to mefenoxam in eastern Idaho (Porter et al. 2004; Salas et al. 2000a) has made pink rot management more challenging. Even when employing cultural and chemical measures in the field, tubers infected with *P. erythroseptica* can still enter a storage facility, mandating disease management during the storage season.

Phytophthora infestans, another oomycete causing tuber rot, can also cause severe losses in the U.S. Pacific Northwest and many potato-growing regions in the world. Tuber losses in storage in the Columbia Basin due to tuber rot caused by *P. infestans* were estimated at $3 million and $1.4 million in 1995 and 1998, respectively (Johnson et al. 1997; Johnson et al. 2000). Tubers can become infected with *P. infestans* with minimal foliar infections (Miller et al. 2004). This dry, corky rot can lead to tuber disintegration in storage.

Tuber rot caused by infections of the pink rot and late blight pathogens at harvest can increase various production problems. It is possible that rotting tubers (pink rot) can disintegrate during the harvesting operation on harvester chains. Infected (*P. erythroseptica*) tuber pieces can easily adhere to healthy potatoes, providing a potential source of contamination and infection of healthy tubers during the harvesting process, or shortly after the tubers have been places in storage facilities (Salas et al. 2000b). Wounding of tubers during the harvesting operation would make tubers more susceptible to *P. erythroseptica* infection and subsequent disease development in storage. It is not known if the etiology for late blight in storage follows a similar pattern. Sporangia produced from infected seed tubers can contaminate and infect healthy seed tubers during the seed-cutting operation (Lambert et al. 1998), and a similar process could occur at harvest if tubers were damp or wet. Hypothetically, wounds generated during harvest could be susceptible to infection by *P. infestans*, since cut tuber surfaces are highly susceptible to infection, but this has not yet been demonstrated.

There is a need for safe post-harvest products that can provide consistent and effective control of pink rot and late blight that might occur during the harvest process where free water is limited, dirt and debris are present, and the product is applied as a low-volume spray prior to storage. Current products used in the potato industry include two disinfestants: chlorine dioxide and mixtures of hydrogen peroxide and peroxyacetic acid (HPPA). Disinfestants, or general biocides, have been evaluated previously for control of potato diseases that are initiated during harvest. Olsen et al. (2003) reported limited efficacy with chlorine dioxide applications using the current label rates and application methods. Hydrogen peroxide and peroxyacetic acid mixtures provided inconsistent control of potato diseases when applied to prevent disease development at harvest (Kimes 2002). Although there is limited research to substantiate the effectiveness of post-harvest applications of HPPA on potatoes to prevent pathogen infections occurring at harvest, it is commonly used in the potato industry and was used as a "standard" comparison in this study.

Zoxamide is a relatively new fungicide that has specific activity against oomycetes. Zoxamide functions by arresting nuclear division and destroying the microtubule cytoskeleton of oomycete organisms (Young and Slawecki 2001). This mode

of action makes zoxamide a potential product to be used as a direct post-harvest application spray on potatoes for control of pink rot and late blight disease. Zoxamide has been shown to inhibit lesion development of *Phytophthora nicotianae* on citrus bark (Matheron 2002). Several reports published in Fungicide and Nematicide Tests show that zoxamide in combination with mancozeb (Gavel® 75 DF, Dow Agrosciences, Indianapolis, IN) is effective in controlling foliar late blight (Alexander and Waldenmaier 2003; Cubeta and Cody 2002; Kirk et al. 2003; May et al. 2004; Olsen 2002). Control of pink rot with zoxamide has been inconsistent with trials showing both control (Ludy and Powelson 2003) and no control (Fitzpatrick and Lambert 2004; Stevenson et al. 2004).

Phosphite-based compounds are also effective in controlling oomycete pathogens. A review by Erwin and Ribeiro stated that phosphites had been used to control 19 species of *Phytophthora* (Erwin and Ribeiro 1996). Phosphites are systemic in both a basipetal and acropetal direction (Cohen and Coffey 1986), and this systemic property permits their use as a foliar spray for control of root rots caused by *Phytophthora* spp. and other oomycetes. Applications of phosphite to potato foliage provide protection against pink rot and late blight in tubers that can develop from pathogen infections in the field or at harvest (Cooke and Little 2001; Johnson et al. 2005). Phosphites have direct antifungal activity against mycelial growth (Fenn and Coffey 1984, 1985), and stimulate active host defense responses (Dunstan et al. 1990), however the antifungal activity is believed to be more important (Guest and Grant 1991; Guest 1984, 1986; Saindrenan et al. 1988). A study by Zainuri et al. (1997) evaluated mango pre- and post-harvest dips with phosphite prior to inoculation and showed no reduction in disease development. In this study, phosphite was not applied as a fungicide to stop infection, but to induce a plant-defense response. Minimal research on post-harvest application of phosphites has been performed on any agricultural commodity.

Several different names have been used to describe phosphate-based products, such as phosphorous acid, phosphonic acid, and phosphonate. According to the rules of the International Union of Pure and Applied Chemistry (IUPAC), phosphorous acid refers to an anhydrous solid (Coffey and Ouimette 1989). When this solid is dissolved in water, phosphonic acid is formed. The mixture of phosphonic acid with metal bases forms phosphite compounds. Phosphite derivatives of phosphonic acid are regarded as benign to the environment and exhibit very low mammalian toxicity (Guest and Grant 1991). These properties make phosphites an ideal candidate for a post-harvest product for protection of potato tubers against pink rot and late blight.

The purpose of this study was to evaluate the efficacy of post-harvest applications of zoxamide and phosphites in reducing potato tuber infections during harvest caused by *P. erythroseptica* and *P. infestans* when applied at various rates and post-inoculation time intervals.

MATERIALS AND METHODS

Certified cv Russet Burbank seed potatoes were grown according to University of Idaho recommendations (Stark and Love 2003) at Kimberly, ID, from 2001 to 2004. Vines were flailed 2 weeks prior to harvest (late September each year) and potatoes were stored at the Kimberly Potato Storage Research Facility. Harvested potatoes were cured at 12.8 C for 14 days and the storage temperature was decreased by 0.3 C per day to a final holding temperature of 7.2 C. All tubers (113 g to 340 g) used in the following tests were stored in this manner, but differed in days after harvest to the initiation of the trial. Tubers were washed and air-dried prior to inoculation.

Inoculum Production

Phytophthora infestans inoculum (US-8 genotype) was obtained from slices of infected tubers (cv Russet Burbank). Tuber slices were cut 1 cm thick and placed in 20 × 100-mm glass Petri dishes containing a 9-cm Whatman No. 1 filter paper moistened with 3 mL of distilled water. A *P. infestans* sporangial suspension was created by flooding a 2- to 3-week-old culture grown on rye extract agar with distilled water and scraping with a small spatula to dislodge sporangia. Three drops of the suspension were then placed on a tuber slice. Cultures were incubated at 18 C for 6 to 7 days in darkness. Sporangia were obtained by washing mycelia from infected tuber slices into a beaker. The suspension was strained through three layers of cheesecloth, and the sporangial suspension was adjusted to 1×10^4 sporangia/mL with distilled water using a hemacytometer. The sporangial suspension was then incubated at 4 C for 2 h to induce zoospore formation.

To prepare the *P. erythroseptica* inoculum, three 7-mm agar plugs were removed from the leading edge of an expanding colony grown on V8 agar and placed into a 15 × 100-mm plastic petri dish. Ten milliliters of V8 broth was added to each dish and cultures were incubated in the dark at 18 C for 4 days.

Cultures were then rinsed twice with 10 mL of autoclaved distilled water and refilled with 10 mL of autoclaved soil extract water and placed at 18 C for 2 days in the light. Cool white fluorescent lights (Sylvania deluxe L 40 W FT40DL/841/RS; Sylvania, Danvers, MA) were placed 30 cm above the cultures. Cultures were moved to 4 C for 1.5 h, and then placed at room temperature for 45 min to stimulate the release of zoospores. The soil extract water was collected from the cultures and the resulting zoospore suspension was adjusted to 3×10^4 zoospores/mL with soil extract water using a hemacytometer. Soil extract water was prepared by placing 200 g of a silt loam soil in 1000 mL of water, stirring the suspension for 20 min and allowing the soil to settle for 24 h. The suspension was screened through four layers of cheese cloth with care not to disturb the sediment at the bottom of the bottle and filtered through Whatman No. 1 filter paper. Distilled water was added to bring the total volume back to 1000 mL. The resulting extract was autoclaved for 20 min.

Tuber Inoculation

Tubers were dipped to complete submersion into the inoculum suspension. Timing between inoculation and treatment varied with the test. If the time duration between inoculation and treatment was greater than "immediately," inoculated tubers were placed in a sealed plastic bag at 15.5 C until the appropriate treatment time. A total of 15 tubers (subsamples) were used for each treatment, and treatments were replicated four times.

Post-Harvest Treatments and Storage

Three separate tests were conducted to meet the objectives of this study. Test 1 evaluated various rates of zoxamide (Zoxium 2F, Dow AgroSciences, Indianapolis, IN) against *P. infestans* and *P. erythroseptica* inoculated tubers. Prior to *P. erythroseptica* inoculation, the apical end of each tuber was abraded on nylon mesh material to incur slight wounding. Tubers were inoculated and immediately sprayed with distilled water (untreated), sodium hypochlorite (3% solution, (Sauer and Burroughs 1986)), and four rates of Zoxamide (100, 200, 300 and 400 g a.i./ MT of tubers). All treatments were applied to tubers using a Research Track Spray Cabinet (Devries Manufacturing, Hollandale, MN) with a Tee-Jet™ 8001 EVS nozzle (Tee-Jet, Spraying Systems Co., Loveland, CO). This approach was designed to simulate a post-harvest liquid product application with a low-pressure boom sprayer as potato tubers are being loaded into storage. The spray cabinet was calibrated to apply 2.08 L diluted product/MT of tubers. After treatment, tubers were placed by treatment into sealed plastic boxes (76 × 51 × 38 cm), and stored for 21 days at 8.9 C and 95% relative humidity (RH).

Test 2 evaluated phosphite (Phostrol™, mono- and dibasic sodium, potassium, and ammonium phosphates 53.6%; other ingredients 46.4%; Nufarm Americas Inc., Houston, TX), hydrogen peroxide/peroxyacetic acid (OxiDate™, hydrogen dioxide 27%; inert ingredients 73%; BioSafe Systems, Glastonbury, CT), and various rates of zoxamide (Zoxium® 80WP, Dow AgroSciences, Indianapolis, IN) against tubers inoculated with *P. infestans* and *P. erythroseptica*. Tubers were inoculated without wounding and immediately sprayed with distilled water (untreated), hydrogen peroxide/peroxyacetic acid (HPPA; 9 g a.i./MT of tubers), phosphite (335 g a.i./MT of tubers) and six rates of zoxamide (8, 16, 32, 64, 128, and 192 g a.i./MT of tubers). Tubers with *P. infestans* were stored as described in test 1. Tubers inoculated with *P. erythroseptica* were individually wrapped with a brown single fold paper towel (228.6 × 260.3 mm; Georgia-Pacific, Atlanta, GA) saturated with distilled water, placed in boxes described in test 1, and stored for 3 days at 15.5 C with 95% RH. The paper towels were removed, and the tubers were returned to the storage for 17 additional days.

Test 3 evaluated the interval time between inoculation and application of zoxamide, HPPA, and phosphite for disease control of *P. infestans* and *P. erythroseptica*. Tubers were inoculated as described above and treated with distilled water (untreated), HPPA (9 g a.i./MT of tubers), phosphite (335 g a.i./MT of tubers) and three rates of zoxamide (16, 32, and 64 g a.i./MT of tubers) at 0, 1, 2, 4, and 6 h after inoculation. Tubers were stored and evaluated similarly to test 2 except smaller sealed plastic boxes (53 × 39 × 31 cm) were used for storage and tubers inoculated with *P. erythroseptica* were stored wrapped for 5 days and then unwrapped and stored for an additional 9 days.

Tuber Evaluation

Tubers inoculated with *P. erythroseptica* were cut in half longitudinally and incubated at room temperature for 30 to 60 min. Incidence (the percentage of inoculated tubers with pink rot symptoms) and severity (average percentage of cut tuber surface with pink rot symptoms) was visibly assessed for each tuber. Tubers inoculated with *P. infestans* were peeled and the

TABLE 1—*Effect of post-harvest applications of zoxamide and NaOCl on tubers inoculated with* P. infestans *(cause of late blight) and* P. erythroseptica *(cause of pink rot) (test 1).*

	P. infestans[a]		*P. erythroseptica*
Treatment (rate)[b]	Incidence[c]	Severity[d]	Incidence[c]
Untreated	85 a	76 a	21 a
Zoxamide (100)	32 b	18 b	0 b
Zoxamide (200)	21 c	9 c	0 b
Zoxamide (300)	7 d	2 d	1 b
Zoxamide (400)	4 d	2 d	0 b
NaOCl (3% soln.)	1 d	1 d	0 b

[a]Values (least square means) in the same column followed by the same letters are not significantly different as determined by Fisher's LSD ($P > 0.05$).
[b]Product rates listed as grams of active ingredient applied per metric ton of tubers. Zoxamide formulated as Zoxium® 2F.
[c]Percentage of inoculated tubers resulting in infection.
[d]Average percentage of peeled tuber surface area showing disease symptoms.

TABLE 2—*Effect of post-harvest applications of HPPA, zoxamide and phosphite on tubers inoculated with* P. infestans *(cause of late blight) and* P. erythroseptica *(cause of pink rot) (test 2).*

Treatment	*P. infestans*[a]		*P. erythroseptica*	
(rate)[b]	Incidence[c]	Severity[d]	Incidence[c]	Severity[d]
Untreated	64 a	24 a	88 a	82 a
HPPA (9)[e]	44 a	15 b	57 b	53 a
Zoxamide (8)	NT[f]	NT	36 bc	30 ab
Zoxamide (16)	4 b	8 bc	21 cd	18 b
Zoxamide (32)	3 bc	6 c	7 ef	5 cd
Zoxamide (64)	0 c	0 c	11 def	4 cd
Zoxamide (128)	0 c	0 c	16 de	7 c
Zoxamide (192)	0 c	0 c	NT	NT
Phosphite (335)	1 c	1 c	7 f	2 d

[a]Values (least square means) in the same column followed by the same letters are not significantly different as determined by Fisher's LSD ($P > 0.05$).
[b]Product rates listed as grams of active ingredient applied per metric ton of tubers. Zoxamide formulated as Zoxium® 80WP and Phosphite formulated as Phostrol®.
[c]Percentage of inoculated tubers developing infection. Analysis performed on log(x+1) values for late blight and arcsin (square root) transformed values for pink rot. Back transformed values given in the table.
[d]Average percentage of peeled tuber surface area (late blight) or internal tuber tissue area showing disease symptoms (pink rot). Analysis performed on log(x+1) values for late blight. Back transformed values given in the table.
[e]HPPA = hydrogen peroxide/peroxyacetic acid formulated as Oxidate™.
[f]NT = treatment was not tested.

incidence and severity (percentage of peeled surface area with late blight symptoms) were visually assessed. If late blight symptoms were not observed, additional cuts were made to ensure the tuber was not infected. Average severity was calculated for all symptomatic and asymptomatic tubers to obtain a measure of the total amount of rot for each treatment. In this study, disease severity was an estimate of the volume of infected tissue of all tubers exposed to a pathogen while disease incidence was the percentage of tubers infected.

Data for disease incidence and disease severity were analyzed by analysis of variance (ANOVA) using the PROC GLM procedure of SAS (SAS institute, Inc., Cary, NC). Mean separation was performed using the Fisher's protected least significant difference (LSD) test when the F test was significant ($P < 0.05$) for a test factor. If assumptions for ANOVA were not met, appropriate transformations were made and back-transformed values given in the tables. Test 3 was conducted as a split-plot design with treatment as the main plot effect and interval as the sub-plot effect.

RESULTS

In test 1, post-harvest applications of zoxamide significantly reduced incidence of pink rot and late blight and severity of late blight (Table 1, pink rot severity not scored) when simulating infection occurring at harvest. Lower zoxamide rates (100 and 200 g/MT) were not as effective as higher rates (300 and 400 g/MT) or the sodium hypochlorite (NaOCl) dip in reducing the incidence or severity of late blight tuber infection. Of the lower rates, 200 g/MT was more effective than 100 g/MT for both incidence and severity of late blight. All rates of zoxamide and the sodium hypochlorite dip resulted in a significantly lower incidence of pink rot compared to the untreated control (Table 1). Application of this zoxamide formulation (Zoxium® 2F) resulted in a chalky, white residue that remained on tubers when applied at the higher rates (data not shown).

Due to the issues concerning residues encountered in test 1, a different formulation of zoxamide was evaluated in test 2 (Zoxium® 80WP). In addition, phosphite was added to this test. As in test 1, the incidence and severity of late blight from simulated at-harvest inoculations was significantly lowered by all rates of zoxamide compared to the untreated control (Table 2). Zoxamide also reduced late blight compared to the standard HPPA treatment. Phosphite performed similarly to higher

TABLE 3—*Effect of post-inoculation interval and post-harvest treatment on incidence and severity of late blight (caused by* P. infestans*) on Russet Burbank tubers (test 3).*

Treatment (rate)[a]	Post-inoculation interval (h)[b]									
Incidence	0		1		2		4		6	
Untreated	80 a[b]	xy[b]	73 a	x	77 a	xy	93 a	y	80 a	xy
HPPA (9)[c]	10 b	x	33 b	y	40 b	y	63 b	z	72 ab	z
Zoxamide (16)[d]	2 c	w	7 c	wx	18 c	x	40 bc	y	60 abc	z
Zoxamide (32)	0 c	w	8 c	wx	18 c	xy	30 c	yz	43 c	z
Zoxamide (64)	0 c	x	7 c	x	7 cd	x	27 c	y	52 bc	z
Phosphite (335)[e]	0 c	x	0 c	x	2 d	x	0 d	x	7 d	x
Severity										
Untreated	40 a	xy	37 a	x	37 a	x	45 a	y	47 a	y
HPPA (9)	16 b	x	24 b	xy	28 ab	xy	28 b	y	42 a	z
Zoxamide (16)	9 bc	x	11 c	x	15 bc	x	17 c	x	37 ab	y
Zoxamide (32)	0 c	x	4 cd	x	16 bc	x	20 bc	xy	28 bc	y
Zoxamide (64)	0 c	x	6 cd	x	11 c	x	14 c	x	25 c	y
Phosphite (335)	0 c	x	0 d	x	6 c	x	0 d	x	8 d	x

[a]Product rates listed as grams of active ingredient applied per metric ton of tubers.
[b]Values (least square means) in the same column followed by the same letters (a-d) or values in the same row followed by the same letters (w-z) are not significantly different as determined by Fisher's LSD ($P > 0.05$). Incidence defined as the percentage of inoculated tubers developing symptoms and severity defined as the average percentage of cut tuber surface area showing disease symptoms.
[c]HPPA = Hydrogen peroxide/peroxyacetic acid formulated as Oxidate™.
[d]Zoxamide formulated as Zoxium® 80WP.
[e]Phosphite formulated as Phostrol®.

TABLE 4—*Effect of post-inoculation interval and post-harvest treatment on incidence and severity of pink rot (caused by* P. erythroseptica*) on Russet Burbank tubers (test 3).*

Treatment (rate)[a]	Post-inoculation interval (h)[b]									
Incidence	0		1		2		4		6	
Untreated	87 a[b]	x[b]	92 a	x	88 a	x	90 b	x	100 a	y
HPPA (9)[c]	43 b	x	85 ab	y	87 ab	y	98 a	z	95 a	yz
Zoxamide (16)[d]	17 bc	x	67 c	y	80 ab	y	95 ab	z	97 a	z
Zoxamide (32)	7 c	x	68 bc	y	85 ab	z	93 ab	z	97 a	z
Zoxamide (64)	3 c	x	70 bc	y	72 b	y	92 b	z	97 a	z
Phosphite (335)[e]	0 c	x	3 d	x	3 c	x	22 c	y	29 b	y
Severity										
Untreated	73 a	x	84 a	x	80 a	x	79 a	x	92 a	x
HPPA (9)[c]	28 b	x	69 a	y	76 a	yz	89 a	yz	93 a	z
Zoxamide (16)[d]	9 c	w	51 b	x	66 ab	xy	86 a	yz	88 a	z
Zoxamide (32)	3 c	x	50 b	y	71 a	z	80 a	z	91 a	z
Zoxamide (64)	2 c	x	49 b	y	55 b	y	83 a	z	91 a	z
Phosphite (335)[e]	0 c	x	1 c	x	1 c	x	8 b	y	13 b	y

[a]Product rates listed as grams of active ingredient applied per metric ton of tubers.
[b]Values (least square means) in the same column followed by the same letters (a-d) or values in the same row followed by the same letters (w-z) are not significantly different as determined by Fishers LSD ($P>0.05$). Incidence defined as the percentage of inoculated tubers developing symptoms and severity defined as the average percentage of cut tuber surface area showing disease symptoms. Analysis performed on the arcsine of proportion values (x/100) for incidence and square root transformed values for severity. Back transformed values given in the table.
[c]HPPA = Hydrogen peroxide/peroxyacetic acid formulated as Oxidate™.
[d]Zoxamide formulated as Zoxium® 80WP.
[e]Phosphite formulated as Phostrol®.

rates of zoxamide (32 g a.i./MT tuber and greater). Phosphite and all zoxamide-treated tubers had significantly lower late blight severity ratings than HPPA-treated tubers except tubers that were treated with zoxamide at 16 g a.i./MT of tubers. No late blight was observed in any tubers that received at least 64 g a.i./MT zoxamide.

Pink rot incidence from simulated at-harvest inoculation in test 2 was also reduced by all products tested (Table 2). As the zoxamide concentration increased to 32 g a.i./MT, the incidence of pink rot decreased. Increasing zoxamide rates above 32 g a.i./MT did not improve pink rot control as measured by incidence or severity. Pink rot severity was not significantly reduced by HPPA or a zoxamide rate of 8 g a.i./MT. Phosphite-treated tubers had the lowest pink rot incidence and severity of all treatments.

When tubers were inoculated and then treated with fungicide treatments at different intervals, all treatments significantly reduced late blight incidence compared to the untreated control when applied within 4 h of inoculation (Table 3). Phosphite and all rates of zoxamide were significantly more effective than HPPA when applied 0 to 2 h after inoculation. Zoxamide applied at 32 g a.i./MT or at higher rates resulted in lower incidence of late blight compared to HPPA applied at 4 and 6 h after inoculation. The phosphite treatment resulted in the lowest disease incidence when applied 4 and 6 h after inoculation.

Generally, late blight incidence increased as the time interval from inoculation to treatment increased (Table 3). With the exception of HPPA, all treatments reduced late blight incidence equally at 1 h after inoculation compared to the 0-h treatment. Late blight incidence was greater when treatments were applied 4 h after inoculation as compared to 2 h for HPPA and zoxamide (16 and 64 g a.i. rates). Delaying treatment with phosphite for up to 6 h did not reduce the efficacy in reducing late blight incidence.

Results for late blight severity were similar to incidence (Table 3). Late blight severity was reduced by all treatments at 0-, 1-, and 4-h intervals compared to the untreated control (Table 3). All rates of zoxamide resulted in reduced late blight severity when applied within 4 h of inoculation compared to the untreated control. Application of zoxamide rates above 32 g a.i./MT resulted in significantly less late blight severity than the untreated control at all intervals tested. Tubers receiving phosphite had significantly lower late blight severity values than all other treatments for the 4- and 6-h post-inoculation treatments. Phosphite and zoxamide applications at 64 g a.i./MT always resulted in significantly lower disease severity compared to the HPPA treatment.

Similar to incidence, late blight severity generally increased as the time interval from inoculation to treatment increased (Table 3). Treatment with HPPA at 4 and 6 h after inoculation was not as effective as treating immediately after inoculation. For all zoxamide rates, late blight incidence was significantly greater when product was applied 6 h after inoculation as compared to 0 to 4 h after inoculation. As with incidence, late blight severity was not influenced by the time interval (at least up to 6 h) from inoculation to treatment with phosphite.

As with previously mentioned tests, all post-harvest products significantly reduced pink rot incidence when applied immediately after inoculation (Table 4). Zoxamide at 32 g a.i./MT and higher and phosphite were significantly more effective than HPPA when applied immediately after inoculation and phosphite continued to be significantly more effective than HPPA at all intervals tested. When products were applied 1 h after inoculation, significant disease reductions were only observed with zoxamide and phosphite compared to the untreated control and phosphite provided a significantly greater reduction in pink rot incidence than zoxamide. All rates of zoxamide performed similarly at each time interval. By 2 h after inoculation, only the high rate of zoxamide and the phosphite treatments provided significant disease control compared to the untreated control, with phosphite exhibiting greater disease reduction than zoxamide. At 4- and 6-h post-inoculation intervals, only phosphite provided significant disease control.

Pink rot incidence generally increased as the time interval from inoculation to treatment increased for HPPA and all zoxamide treatments. For HPPA, pink rot incidence was greater at 1 and 2 h after inoculation compared to the 0-h treatment. Additionally, disease incidence at 4 and 6 h was greater than at the other intervals. Efficacy of zoxamide was greatest at the 0-h interval. For all rates of zoxamide, pink rot incidence was less at 1 h compared to the 4- and 6-h intervals. Pink rot incidence was greater at 4 and 6 h after inoculation than at 0 to 2 h for the phosphite treatment.

Pink rot severity followed a similar pattern to incidence since all treatments significantly reduced the severity of pink rot if applied immediately after inoculation (Table 4). The phosphite and all the zoxamide treatments significantly

reduced the severity of pink rot when applied 1 h after inoculation compared to the untreated control and HPPA treatment. The high rate of zoxamide and phosphite showed less pink rot severity at 2 h after inoculation than the HPPA and untreated control treatments, and only phosphite consistently showed a reduced severity of pink rot at 4- and 6-h post-inoculation compared to the untreated control, HPPA, and zoxamide. The effect of time interval for pink rot severity was similar to that observed for pink rot incidence.

DISCUSSION

There is limited availability of post-harvest products labeled for pink rot and late blight control that can be applied as a direct spray on tubers going into storage. General disinfestants such as chlorine dioxide and HPPA were previously shown to provide limited or inconsistent control of potato diseases when applied to prevent disease development occurring from infections at harvest (Klimes 2002; Olsen et al. 2003). Sodium hypochlorite (NaOCl) was used as a disinfestant in test 1 due to its documented disinfesting properties (Sauer and Burroughs 1986), although the use of this product is not an industry practice. Subsequent experiments included HPPA since this compound is commonly used in the potato industry.

Dipping harvested products in hydrogen peroxide alone or hydrogen peroxide stabilized with silver ion has shown some specific disease control in agricultural crops such as eggplant and sweet red peppers (Fallik et al. 1994), and mushrooms (Brennan et al. 2000). Afek et al. (2001) has shown the possibility of controlling silver scurf (*Helminthosporium solani*) on potatoes with stabilized hydrogen peroxide fogged into a storage facility. Peroxyacetic acid, or peracetic acid, has also been shown to control brown rot when stone fruits are dipped for extended periods of time (Mari et al. 1999). HPPA was only moderately effective in reducing oomycete infections of tubers at harvest in this study. Efficacy was greater for controlling *P. infestans* than *P. erythroseptica* based on the results of test 3. Late blight incidence and severity were significantly reduced when HPPA was applied as long as 4 h after inoculation. In comparison, pink rot incidence and severity was only reduced when HPPA was applied immediately after inoculation.

The rationale behind post-harvest applications of fungicides for late blight and pink rot control in potato is the assumption that healthy tubers become exposed to pathogen inoculum during the harvest operation. This exposure may occur as tubers are lifted from the soil on the belt of commercial potato harvesters, as tubers bump together on the harvester belt, as tubers are piled into trucks for transportation, or when tubers are delivered from trucks to storages, packing, or processing plants. Healthy tubers can become wounded during any of these phases, increasing tuber susceptibility to pathogen infection. Inoculum in soil adhering to tubers or from infected tubers may be present in the form of viable spores or mycelium and may be transferred to healthy tubers during these processes. Post-harvest fungicides are aimed at reducing the viability of these potential inoculum sources on the surface of the healthy tubers prior to infection. In tests 1 and 2, post-harvest applications were made immediately after inoculation. In reality, post-harvest treatments may not be applied immediately to tubers following exposure to pathogens in the field or during the transportation process. A couple of hours may elapse between inoculation and post-harvest treatment.

Foliar applications of zoxamide have exhibited foliar and tuber protection against *P. infestans* in potatoes (Alexander and Waldenmaier 2003; Cubeta and Cody 2002; Kirk et al. 2003; Olsen 2002) and in one study against *P. erthyrospetica* (Ludy and Powelson 2003). Zoxamide applied in an aqueous solution to potatoes prior to storage significantly reduced late blight and pink rot disease development after tubers were exposed to the pathogens. Zoxamide formulated as Zoxium® 2F was effective in decreasing potato tuber infection by both *P. infestans* and *P. erythroseptica*. However, a chalky, white residue remained on the tuber surface. The residue was greatest when Zoxium® 2F was applied at the higher rates that were required to attain nearly complete control for late blight. This residue would make tubers unmarketable. Zoxamide formulated as Zoxium® 80WP was more effective than the 2F formulation at lower rates at decreasing the incidence and severity of late blight and pink rot when applied immediately after inoculation. Application of the 80WP formulation did not leave visible residues on potato tubers, making it more acceptable as a potential post-harvest product. Zoxamide applied at a rate of 32 g a.i./MT of tubers appeared to be adequate for both late blight and pink rot control.

Phosphite-based products applied as a foliar spray to potatoes have shown efficacy in protecting tubers from oomycetes in the field (Cooke and Little 2001; Johnson et al. 2005). Phosphites have been used for oomycete disease con-

trol in other crops (Wicks et al. 1990). The results from this study indicate post-harvest application of phosphite to potatoes just after harvest and prior to storage can be highly effective in decreasing disease development upon exposure to *P. infestans* and *P. erythroseptica* inoculum at harvest.

Post-harvest applications were generally more effective against late blight than pink rot. For late blight, zoxamide at the high rate could be applied as long as 2 h after inoculation without a significant reduction in disease control. Phosphite applications were equally effective at all of the time intervals tested. Zoxamide and HPPA were not as effective in controlling pink rot, however, unless they were applied immediately after inoculation. Phosphite was the exception as it showed significant control of pink rot even 6 h after inoculation. This process of evaluating post-inoculation interval and application of post-harvest treatments on disease management of storage rots should be implemented as a standard testing procedure when assessing any post-harvest product due to the decline in product efficacy over time as demonstrated by zoxamide and HPPA in this study.

This research indicates that phosphites are highly effective post-harvest management tools for controlling late blight and pink rot for an industry where there is a paucity of effective products to use. Zoxamide was less effective as the interval between inoculation and treatment increased. Additionally, visible residues on the surface of the tuber may limit the use of this product. Phosphite was highly effective against pink rot and late blight even 6 h after inoculation. The systemic properties and lack of food safety concern (Guest and Grant 1991) make phosphite an ideal candidate for a post-harvest product. Post-harvest applications of phosphite, when used in conjunction with proper storage management, will be lessen the impact of late blight and pink rot decay in potato storages.

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