Efficacy of OMRI-certified fungicides and chitosan for managing early blight caused by *Alternaria solani* and Septoria leaf spot in tomato[1,2]

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ABSTRACT

Field studies to evaluate the efficacy of OMRI-certified fungicides and other materials for control of early blight caused by *Alternaria solani* and Septoria leaf spot of tomato were conducted in Lexington, Kentucky during 2009 and 2010. Nine fungicides as well as ammonium bicarbonate and chitosan were evaluated in an organic production system. The most effective fungicides for managing Septoria leaf spot and early blight of tomato were copper based. None of the biological-based products (Sonata® and Serenade Max®), plant-based extracts (Trilogy® and Regalia® SC), chitosan, ammonium bicarbonate nor horticultural lime sulfur provided a significant (P>0.05) reduction in disease severity. However, despite significant (P<0.05) disease control in plots treated with copper-based products, no significant (P>0.05) improvement in yield over the untreated control was observed during the first two experiments in which the initial symptoms of foliar disease were observed after fruits were set. In the third field trial, in which initial symptoms were observed before fruit set, Serenade Max®, Bordeaux mixture, Regalia® SC, water-soluble chitosan and lime sulfur improved yield, although none provided significant disease control. These results suggest that, when necrotrophic foliar disease develops after fruit set, fungicides may have no effect on yield. In addition, some OMRI-certified fungicides may improve tomato yields by unknown mechanisms that do not involve disease control.

Keywords: *Solanum lycopersicum*, *Septoria lycopersici*, *Alternaria solani*

RESUMEN

Eficacia de fungicidas certificados por OMRI y quitosano para el manejo del tizón temprano causado por *Alternaria solani* y la mancha foliar de Septoria en tomate

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En 2009 y 2010, se realizaron estudios de campo para evaluar la eficacia de materiales certificados por OMRI y otros productos para el control del tizón temprano causado por *Alternaria solani* y la mancha foliar de Septoria en tomate en Lexington, Kentucky. Se evaluaron nueve fungicidas, así como bicarbonato de amonio y quitosano en un sistema de producción orgánica. Los fungicidas más efectivos para controlar la mancha foliar por *Septoria* y el tizón temprano del tomate fueron los fungicidas a base de cobre. Ninguno de los productos de base biológica (Sonata® y Serenade Max®), los extractos de origen vegetal (Trilogy® y Regalia® SC), el quitosano, el bicarbonato de amonio ni el azufre de cal hortícola proporcionaron una reducción significativa ($P>0.05$) en la severidad de la enfermedad. Sin embargo, a pesar del control significativo ($P<0.05$) de la enfermedad en las parcelas tratadas con productos a base de cobre, no se observó una mejoría significativa ($P>0.05$) en el rendimiento sobre el control no tratado durante los primeros dos experimentos, en los que los síntomas iniciales de enfermedad foliar se observaron después del cuajado de frutos. En la tercera prueba de campo, en la que se observaron los síntomas iniciales antes del cuajado de frutos, Serenade Max®, caldo bordelés, Regalia® SC, quitosano soluble en agua y azufre de cal mejoraron el rendimiento, aunque ninguno proporcionó un control significativo de la enfermedad. Estos resultados sugieren que, cuando la enfermedad foliar necrotrófica se desarrolla después de la fructificación, el fungicida puede no tener efecto sobre el rendimiento. Además, algunos fungicidas certificados por OMRI pueden mejorar los rendimientos de tomate por mecanismos desconocidos que no involucran el control de enfermedades.

Palabras clave: *Solanum lycopersicum*, *Septoria lycopersici*, *Alternaria solani*

INTRODUCTION

Tomatoes (*Solanum lycopersicum* Mill.) are considered among the top three vegetables in terms of area harvested and total production in the USA (USDA, National Agricultural Statistics Service, 2021). In Kentucky, fresh-market tomatoes are among the most valuable vegetables grown, with approximately 405 hectares cultivated for wholesale and farmers' markets (Coolong et al., 2009). Given this region's warm and humid summers, foliar fungal diseases are among the main production constraints favored by such weather conditions. Early blight, caused by *Alternaria solani* (Ellis & Martin) Jones & Grout, and Septoria leaf spot, caused by *Septoria lycopersici* Speg., are two of the most common and important foliar diseases of tomatoes (*Solanum lycopersicum* Mill.) in Kentucky (Quiterio-Gutiérrez et al., 2019; Kumar et al., 2018; Coolong et al., 2008). Both diseases are favored by humid, rainy weather and mild temperatures between 24 and 29 °C (Rotem, 1994; Jones et al., 1991; Coolong et al., 2008; Nash and Gardner, 1988). Early blight typically begins in the lower canopy and progresses to the middle and upper canopy as fruit sets, while Septoria leaf spot usually appears on the lower leaves after the fruits are set (Rotem, 1994; Jones et al., 1991; Madden et al., 1978; Coolong et al., 2008).

Management of necrotrophic foliage-attacking fungi is a challenge due to their wide host ranges, capacity to grow as saprophytes and the ability to attack young, weak, or senescent tissue (Schumann and D'Arcy, 2006). These necrotrophic fungi are controlled primarily through crop rotation, the use of resistant varieties, pathogen-free seed, and fungicide applications (Agrios, 2005; Madden et al., 1978; Rowell et al., 2010-11; Jones et al., 1991). Most tomato cultivars currently grown are susceptible to Septoria leaf spot and early blight. Managing these diseases often depends on the use of fungicides such as strobilurins and chlorothalonil to prevent yield losses (Rowell et al., 2010-11). Even so, certified organic growers are not permitted to use these synthetic fungicides. Only OMRI (Organic Material Review Institute) listed products are allowed for use on certified organic farms of fresh market tomatoes. Several products are registered and approved for managing foliar disease in organic agriculture in the United States. However, data on the efficacy of these products for managing foliar necrotrophic fungi like *A. solani* and *S. lycopersici* under field conditions are limited (Wszelaki and Miller, 2005; Zitter et al., 2005; Seaman et al., 2004). Also, experiments performed under one set of environmental conditions are often not predictive of results in other environments. With the rapid increase in organic food production and the relative lack of research on this topic, the objective of this project was to test the efficacy of OMRI-certified materials as well as other potentially certifiable materials to manage early blight and Septoria leaf spot under field conditions.

MATERIALS AND METHODS

Field plots. Field trials were conducted at the University of Kentucky Horticultural Research Farm on a Maury silt loam soil type. Plots were established on land in transition from conventional to organic practices. The cultivar used was 'Paragon OG', a determinate type with resistance to *Fusarium* wilt races 1 and 2 and *Verticillium* wilt (Johnny's Selected Seeds, Winslow, ME)[5]. Five-week-old seedlings were transplanted to the field on 18 June 2009 and 2010 for experiments I and II, respectively, and on 5 July 2010 for experiment III. For all field experiments a randomized complete block design with four replicates was used. Plots consisted of single rows 6.1-m long covered with black plastic mulch and with 46 cm between plants and 3 m be-

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[5] Company or trade names in this publication are used only to provide specific information. Mention of trade names does not constitute an endorsement by the Agricultural Experiment Station of the University of Puerto Rico, nor is this mention a statement of preference over other equipment or materials. Products evaluated for disease control in this publication are used for experimental purposes, and the results of experiments performed under one set of environmental conditions do not predict the results in other environments.

tween rows, with drip irrigation and fertigation; plants were staked and trellised. Pre-plant fertilization was done with nitrogen at 13.6 kg/ha. Fertigation was delivered at 14-day intervals using 4.7 L/ha of Phytamin® Fish Plus 5-1-1 (California Organic Fertilizers, Inc.™, Hanfor, CA). All materials tested were applied in a spray volume of 374 L/ha and increased up to 935 L/ha through the season to increase foliar coverage as plants grew. All treatments were sprayed at 7-day intervals using a CO_2 backpack sprayer fitted with hollow-cone nozzles (R&D Sprayer, Bellspray, Inc.) operating at 276 kPa. The positive control, Quadris®(azoxystrobin), was used at 7-day intervals to conform to the spray program, taking into consideration the possible development of resistance (Adhikari et al., 2017; Rosenzweig et al., 2008). The sprayer was calibrated to deliver 0.2 L in 30.5 m^2 (plot size). A total of 0.4 L was applied to each plot (0.2 L on each side of the plot) during the first three applications using a single hollow-cone nozzle spraying a 45.7 cm swath. From the fourth application through the last, 0.8 L was applied to each plot (0.4 L per side) using two hollow-cone nozzles spraying a 66.0 cm swath and spaced at 45.7 cm. For all experiments, the initial application was made three weeks after transplanting and continued throughout the season for a total of nine (experiments I and II) or eight (experiment III) applications. Table 1 describes all treatments and the rates applied in each experiment. Weeds were controlled using a small tractor-pulled field cultivator and by manual removal throughout the season in all experiments. Each plot consisted of 13 to 14 plants from which the seven plants in the middle of the plot were selected for assessments of disease severity and yield. Fresh ripe tomatoes were manually harvested four times in experiments I and III and five times in experiment II. After harvest, tomato fruits were separated into marketable (free of rot, adequate size) and non-marketable categories and weighed. Yield data were analyzed by analysis of variance and the least significant differences (LSD) to separate means ($P < 0.05$) using INFOSTAT Statistical Software Version 2014 (InfoStat, FCA, Córdoba, Argentina).

Disease severity assessment and data analysis. Severity of foliar necrosis caused by early blight and Septoria leaf spot was evaluated in all experiments. Both diseases together were evaluated as foliar necrosis. Disease severity was assessed by canopy position (lower, middle, and upper canopy) and then averaged for the whole plot. Disease severity was estimated visually (four times in experiment I and three times in experiments II and III) at each of three canopy positions in each plot. A scale from 0 to 7 (0= 0%; 1= 1 to 14 %; 2= 15 to 29 %; 3= 30 to 49 %; 4= 50 to 69 %; 5= 70 to 84 %; 6= 85 to 95 %; and 7= >96%) was used to estimate disease severity (Little and Hills, 1978). The stan-

TABLE 1.—*Materials evaluated in field trials to manage early blight caused by* Alternaria solani *and Septoria leaf spot in tomatoes.*

Material or product tested[a]	Active Ingredient	Rate of application
Sonata®	1.38% *Bacillus pumilus*	9.4 L/ha
Serenade Max®	14.6% *Bacillus subtilis*	3.4 kg/ha
Bordeaux mixture	12.5% Copper hydroxide, copper sulfate	30 g/L
Kocide®2000	53.8% Copper hydroxide	2.6 kg/ha
Kocide®3000	46.1% Copper hydroxide	1.12 kg/ha
Trilogy®	70% Neem oil	2% v/v
Regalia® SC	5% Giant Knotweed	4.7 L/ha
Ammonium bicarbonate	Ammonium bicarbonate	7.7% v/v
Acid soluble chitosan	86% chitosan	0.01% w/v
Water-soluble chitosan	85% chitosan	1-2% w/v
Acetic acid	4% acetic acid	0.5% v/v
Quadris® 50WG	50% Azoxystrobin	224 g/ha
Lime sulfur	26% Calcium polysulfide	25.8 ml/L

[a] Materials applied at 7-day intervals.

dardized area under the disease progress curve (sAUDPC) was determined to express the cumulative disease severity occurring over the 43-, 49-, and 74-day period of experiment I, II, and III, respectively, using the mid-point or trapezoidal method (Madden et al., 2007). The data for sAUDPC and final disease severity were analyzed by ANOVA, and treatments were compared with the LSD test. Weather data (temperature, precipitation, and relative humidity) were measured daily by the University of Kentucky Agricultural Weather Center (Table 2).

RESULTS

Field trial I. During the field trial of 2009 (experiment I), based on symptoms and microscopic observations, the predominant disease observed was Septoria leaf spot, and less than 10% of the foliar necrosis observed on plants was caused by early blight. Septoria leaf spot symptoms were first detected seven weeks after transplanting, when the tomato fruits were already set, while early blight symptoms were initially observed 10 weeks after transplanting (Figure 1A), when fruits were ripening. An epidemic of bacterial spot (*Xanthomonas euvesicatoria* pv. *euvesicatoria* (syn. *Xanthomonas campestris (axonopodis)* pv. *vesicatoria*), confirmed by PCR using previously published primers (Obradovic et al., 2004), was observed during the final few weeks of the growing season, affecting mainly tomato fruits and therefore, marketable yields.

TABLE 2.—*Weather conditions for the tomato trials during the growing seasons of 2009 and 2010.*

		Temperature (°C)			Precipitation (cm)	Relative Humidity		
Months	Year	Max	Min	Avg	Total Accum.	Max	Min	# hours ≥ 90 %
June	2009	28	18	23	13.1	86	50	40
	2010	30	20	25	11.7	87	48	53
July	2009	27	18	22	19.2	88	49	81
	2010	31	21	26	15.4	87	50	62
August	2009	28	18	23	11.5	90	51	76
	2010	32	19	26	2.0	86	41	31
September	2009	25	16	21	15.0	88	53	104
	2010	29	14	22	1.6	81	31	11
October	2009	16	8	12	14.7	89	53	68
	2010	22	8	15	3.2	74	27	0

Among the treatments evaluated, Sonata®, ammonium bicarbonate, Trilogy®, and acid-soluble chitosan provided no disease control (Table 3). By contrast, copper-based products (Bordeaux mixture and Kocide® 2000) provided a significant ($P = 0.0001$) reduction in disease severity compared with the unsprayed control. Efficacy was equivalent to that provided by the positive control (Quadris® 50WG). In this and the other trials reported here, plants treated with Bordeaux mixture had leaf curling symptoms that were not observed in any other treatment. This physiological effect has been reported previously on tomato plants treated with Bordeaux mixture and may be associated with the use of this material under warm conditions (Wszelaki and Miller, 2005). Regardless of the disease control provided by the copper-based products and the positive control, no difference ($P = 0.7421$) was observed in total yield or marketable yield among treatments. Across all treatments, more than 40% of the total yields were classified as unmarketable due to symptoms of disease on fruit (predominantly bacterial spot).

Field trial II. In the second field trial, the overall disease pressure was lower than in the first trial (Table 4; Figure 1B). The lower disease pressure may have been caused by the unfavorable weather conditions during the growing season (Table 2). Both diseases were initially detected after fruit set, 48 days after transplanting, in the lower canopy position, resulting in a 49-day epidemic. As in the first experiment, microscopic examination of symptomatic leaves indicated that Septoria leaf spot was the predominant disease, with early blight causing approximately 20% of the lesions observed on plants.

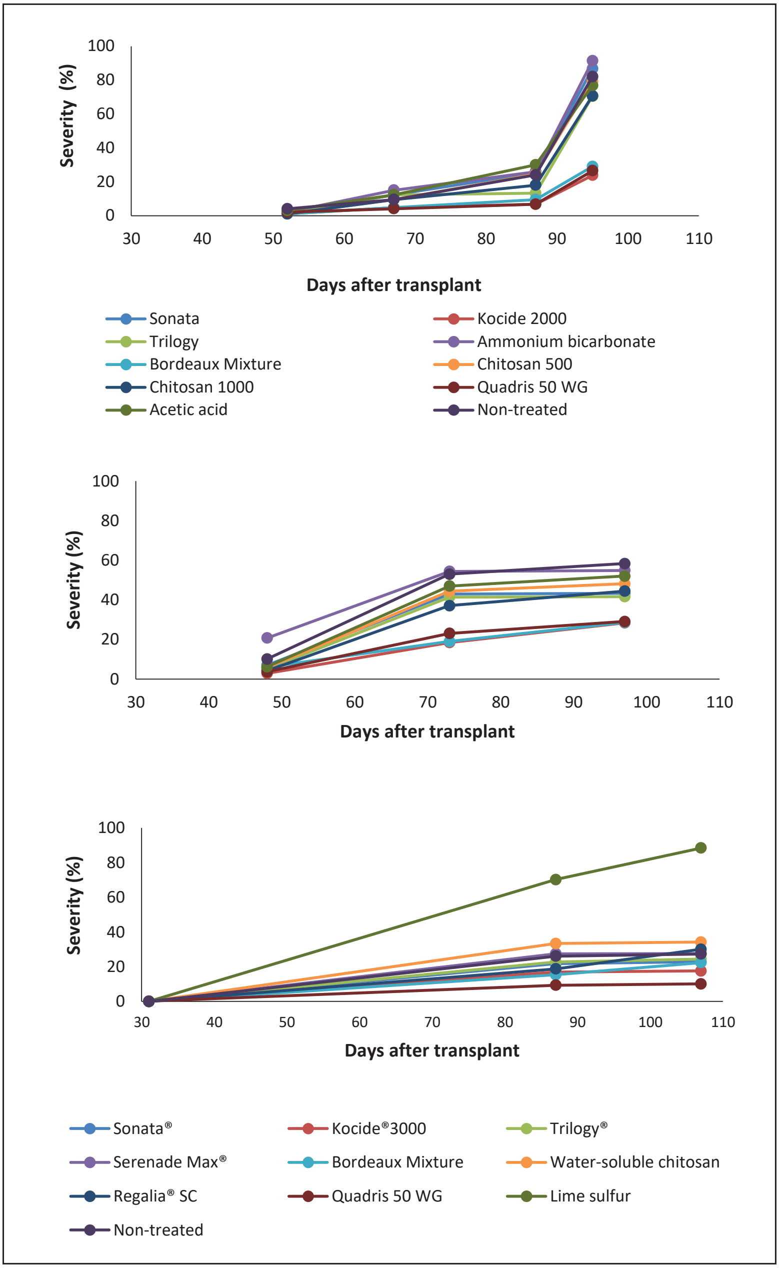

FIGURE 1. Foliar necrosis progress curves measure disease severity of *Septoria lycopersici* and *Alternaria solani* in tomato (%), from 30 to > 100 days after transplant. A) Experiment I, B) Experiment II and C) Experiment III.

TABLE 3.—*Effect of foliar fungicide application on severity of Septoria leaf spot and early blight and tomato yields, Experiment I.*

Treatments[a]	Final disease[b] severity (%)	sAUDPC[c]	Yields (kg/m^2)[d]	Marketable yields (kg/m^2)[d]
Sonata®	86.7 bc[e]	26.9 bc	37.1 a	15.4 a
Bordeaux Mixture	29.0 a	11.1 a	37.9 a	15.7 a
Kocide®2000	23.6 a	8.9 a	36.1 a	16.3 a
Trilogy®	70.4 b	29.6 c	31.1 a	14.3 a
Ammonium bicarbonate	91.3 c	20.1 b	34.9 a	15.4 a
Acid-soluble chitosan	70.7 b	20.5 b	38.7 a	16.9 a
Acetic acid	76.8 bc	28.4 bc	34.1 a	14.5 a
Quadris® 50 WG	26.5 a	9.2 a	35.8 a	15.5 a
Unsprayed control	82.1 bc	25.1 bc	36.0 a	14.3 a

[a] Treatments applied at 7-day intervals. Acetic acid was included as negative control for acid-soluble chitosan; Quadris® 50 WG was included as positive control.

[b] Disease assessed 95 days after transplanting; foliar necrosis caused by *Septoria lycopersici* and *Alternaria solani*.

[c] Area under disease progress curve standardized for a 43-day epidemic.

[d] Values are the means (kg/m^2) of four replicate plots after four weeks of harvesting.

[e] Values are the means of four replicate plots. Means within a column followed by the same letter are not significantly different according to Fisher's least significant difference ($P = 0.05$).

As observed in the first trial, except for the copper-based products, none of the OMRI-certified treatments (Sonata®, Serenade Max®, Trilogy®, Regalia® and lime sulfur) provided a significant ($P < 0.05$) decrease in disease severity (Table 4). Likewise, water-soluble chitosan failed to provide significant disease control. As in experiment I, even with a significant reduction in disease severity provided by the copper-based products, no effect on yield or marketable yield ($P > 0.05$) was observed among treatments.

Field trial III. In the third field trial, both diseases (Septoria leaf spot and early blight) were detected four weeks after transplanting (Figure 1C), resulting in a 74-day epidemic. Both diseases were present in similar proportions on symptomatic leaves, but they progressed slowly and remained at relatively low levels throughout the growing season. Concentric brown rings characteristic of early blight and small water-soaked spots with dark brown margins characteristic of Septoria leaf spot were observed on the same leaves and in coalescent lesions.

In contrast to results obtained during the first two trials, none of the treatments, including copper-based products, provided disease control over the unsprayed control in the third trial ($P > 0.05$) (Table 5). At the end of the season, horticultural lime sulfur had disease severity and sAUDPC significantly higher ($P < 0.05$) than the unsprayed control (Table 5; Figure 1). Total yields were comparatively lower in this trial

TABLE 4.—*Effect of foliar fungicide application on severity of Septoria leaf spot and early blight and yields, Experiment II.*

Treatments[a]	Final disease[b] severity (%)	sAUDPC[c]	Yields (kg/m²)[d]	Marketable yields (kg/m²)[d]
Sonata®	43.3 ab[e]	46.2 abcd	28.4 a	21.8 a
Serenade Max®	54.9 b	64.5 d	34.8 a	26.3 a
Bordeaux Mixture	28.6 a	24.3 ab	33.0 a	25.9 a
Kocide®3000	28.4 a	22.2 a	31.0 a	22.1 a
Trilogy®	41.6 ab	43.7 abcd	31.6 a	24.3 a
Regalia®SC	44.5 ab	40.7 abcd	33.5 a	25.2 a
Water-soluble chitosan	48.1 ab	47.8 bcd	29.0 a	21.7 a
Lime sulfur	52.0 b	50.9 cd	29.8 a	21.7 a
Quadris 50 WG	29.1 a	26.2 abc	34.9 a	25.9 a
Unsprayed control	58.8 b	58.9 d	31.6 a	24.3 a

[a] Treatments applied at 7-day intervals. Quadris® 50 WG was used as positive control.

[b] Disease assessed 97 days after transplant and caused by *Septoria lycopersici* and *Alternaria solani*.

[c] Area under disease progress curve standardized for a 49-day epidemic.

[d] Values are the means (kg/m²) for four replicate plots after four weeks of harvesting.

[e] Values are the means of four replicate plots. Means within a column followed by the same letter are not significantly different according to Fisher's least significant difference ($P = 0.05$).

than in the previous trials, but marketable yields were higher than the first trial and similar to the second. An improvement in total yield and marketable yield was obtained with spray applications of Serenade Max®, Bordeaux mixture, Regalia®, water-soluble chitosan and lime sulfur compared with the non-treated plants ($P<0.05$).

TABLE 5.—*Effect of foliar fungicide application on severity of early blight and Septoria leaf spot and yields, Experiment III.*

Treatments[a]	Final disease[b] severity (%)	sAUDPC[c]	Yields (kg/m²)[d]	Marketable yields (kg/m²)[d]
Sonata®	21.7 abc[e]	18.7 ab	22.4 ab	19.2 abc
Serenade Max®	27.6 abc	22.7 ab	26.1 bcd	23.4 bcd
Bordeaux mixture	22.4 abc	13.9 ab	28.5 d	25.2 d
Kocide®3000	17.0 ab	14.4 ab	25.1 abcd	21.4 abcd
Trilogy®	24.5 abc	22.7 ab	23.0 abc	18.7 ab
Regalia®SC	30.1 bc	17.3 ab	28.7 d	25.3 d
Water-soluble chitosan	34.2 c	27.7 b	27.6 cd	24.0 cd
Lime sulfur	88.5 d	60.9 c	29.1 d	25.6 d
Quadris 50 WG	10.2 a	7.9 a	25.9 bcd	22.2 abcd
Unsprayed control	26.1 abc	22.4 ab	20.6 a	18.3 a

[a] Treatments applied at 7-day intervals. Quadris® 50 WG was used as positive control.

[b] Disease assessed 107 days after transplant and caused by *Alternaria solani* and *Septoria lycopersici*.

[c] Area under disease progress curve standardized for a 74-day epidemic.

[d] Values are the means (kg/m²) of four replicate plots after four weeks of harvesting.

[e] Values are the means of four replicate plots. Means within a column followed by the same letter are not significantly different according to Fisher's least significant difference ($P = 0.05$).

DISCUSSION

Among the materials tested, we found that copper-based fungicides were the only effective treatments for managing Septoria leaf spot and early blight of tomato in an organic production system. Despite the disease control obtained by copper-based fungicides that included Kocide® 2000, Kocide® 3000 and Bordeaux mixture, no yield improvement was obtained by these products in any trial. In numerous other trials testing the efficacy of organic certified materials, copper-based products provided the best results in disease management but produced inconsistent results in yield improvement. For example, Seaman et al. (2004) also showed that the copper-based fungicide Champion® WP (a.i., copper hydroxide) was the only treatment that significantly reduced foliar symptoms caused by *S. lycopersici* and *A. solani* compared with the untreated control in tomato. In that trial, none of the OMRI-certified materials evaluated (Plantshield, Mycostop, Trilogy®, $CaCO_3$, SW-3 Seaweed, Humega) produced a significant reduction in disease. In addition, results similar to ours were reported in an Ohio study where a significant reduction in disease severity was obtained with Champion® WP, but no improvement in tomato yields was observed (Wszelaki et al., 2003). In a study conducted in Iowa, copper fungicide-treated plants had low disease severity, which was associated with a yield increase of over 60% above the negative control (Joslin and Taber, 2003). While copper fungicides have often provided better foliar disease control than other OMRI-certified products in the field, there are instances where disease control provided was poor or inconsistent. In the Ohio study mentioned previously (Wszelaki et al., 2003), the Bordeaux mixture did not provide a significant reduction in disease in 2002 whereas significant disease control was observed with the same product in 2003. In another example of trial-to-trial inconsistency, plants treated with Champion WP, which was effective in previous studies (Joslin and Taber, 2003; Wszelaki et al., 2003), showed no difference in disease control compared with the untreated plants (McGrath, 2007).

In our trials, it is possible that the reduction in AUDPC and disease severity by copper-based fungicides was not sufficient to allow an expression of yield benefits. Their lack of effect on yields might be related to the timing of the onset of the disease. In the first two trials, in which copper-based fungicides showed significant disease control but no yield benefit, the initial symptoms of disease were detected after fruit set. Previous field trials had shown no effect of fungicide applications for managing early blight or Septoria leaf spot on yields, regardless of disease control and detection timing (Brammall, 1993; Ferrandino and Elmer, 1992). Septoria leaf spot (the predominant disease in the first two trials) is commonly first detected after fruit set (Rotem, 1994; Jones et al., 1991; Madden et al., 1978; Coolong et al., 2008). This fact suggests that when necrotrophic foliar disease develops after fruit set, fungicide application may have little or no effect on yield. It is important to point out that these results might not apply to tomato cultivars with indeterminate growth, which continue growing and setting fruit throughout the growing season until frost, versus the determinate growth tomato used in the present study, which produce all their fruit in a relatively short period of time. Furthermore, all three trials were conducted under weather conditions that were not as humid and/or rainy as the most extreme disease-conducive conditions possible in Kentucky's humid climate.

Copper-based products are recommended for managing fungal and bacterial foliar diseases in conventionally and organically produced tomatoes. However, one of the main concerns is the potential buildup of copper in the soil to levels that are toxic to plants, soil fauna and soil microbiota, as well as to aquatic ecosystems receiving runoff from treated fields (Van Zwieten et al., 2004; Streit, 1984; Wszelaki and Miller, 2005; EPA, 2006). According to OMRI, copper fungicides are listed as synthetics and are permitted in organic crop production only in a manner that minimizes copper accumulation in the soil. Nevertheless, the relatively poor efficacy of alternatives to copper may create conflicts for organics producers wanting to control fungal diseases of foliage while protecting their soil from copper accumulation.

Except for the copper-based products, none of the materials tested provided a significant reduction in disease severity in any of the field trials. These include biological-based products (Sonata® and Serenade Max®), plant-based extracts (Regalia®SC and Trilogy®), ammonium bicarbonate, horticultural lime sulfur and chitosan. In other tests, biological-based products like Sonata® (a.i., *Bacillus pumilus*) and Serenade Max® (a.i., *Bacillus subtilis*) have been evaluated alone and in combination with other OMRI-certified materials but provided no disease control (Wszelaki and Miller, 2005; McGrath and Moyer, 2003). Plants treated with combinations of Sonata® plus Kocide® 2000 showed more damage from early blight than the water control or each fungicide used alone (Wszelaki and Miller, 2005). In the same trials, Sonata® applied alone showed more foliar damage caused by *A. solani* compared with the water control. In another trial, no effect on Septoria leaf spot severity was obtained by the application of Sonata® alone nor in combination with compost tea, as compared with the untreated control (McGrath and Moyer, 2003). Field evaluations of Serenade Max® for disease control have also produced conflicting results. Combinations of Serenade Max® with Champion WP had provided a reduction in disease severity caused by *A. solani* and *S. lycopersici*, compared with the water control, but not with the use of Serenade Max® and Champion WP alone (Wszelaki and Miller, 2005). In another trial, Serenade Max® applied with Kocide® 2000 showed the same levels of early blight as the untreated control (Lewis et al., 2004). A combination of Serenade Max® with Champion WP and Biotune had no effect on disease severity of early blight (Zitter and Drennan, 2005). Trilogy®, an OMRI-certified material labeled as fungicide/miticide/insecticide, was evaluated in three consecutive trials and showed no effect in disease control in any of the trials presented here. Our results agree with Wszelaki et al. (2002) who showed that Trilogy® had no effect on early blight and Septoria leaf spot disease control.

In addition to failing to provide disease control, some OMRI-certified materials described did not improve yield or they were inconsistent. In the results presented here we were unable to establish any correlation between disease severity and yield. In a two-year study, Sonata® showed as much or more disease than the water control but surprisingly produced higher marketable yields than the water control (Wszelaki and Miller, 2005). This suggests that Sonata® sometimes improves yields by a mechanism independent of disease control. However, this effect is inconsistent because in all three of our trials, Sonata® showed the same levels of disease as the unsprayed plants and no improvement of yield. Similarly, Trilogy® also failed to provide either disease control and/or yield improvement in our study or in those of others (Wszelaki and Miller, 2005; Zitter et al., 2005; Lewis et al., 2004).

While some products showed no disease control or yield improvement, others improved yields by an unknown mechanism as seen in our third trial (Table 5). In the presence of low disease pressure during this trial, improvement in total yield and marketable yield was obtained with Serenade Max®, Bordeaux mixture, Regalia®SC, water-soluble chitosan, and lime sulfur, although none provided measurable disease control. Regalia®SC is labeled as a "plant immune system booster" against fungi and bacteria, but the role of this plant-based extract in yield improvement beyond disease control has not been investigated.

Horticultural lime sulfur also improved yields even though disease severity was higher than in the unsprayed control. In soil nutrition, sulfur acts as a soil conditioner to reduce sodium content and nitrogen-fixing (Salem et al., 2016). In plants, sulfur is an important structural element of proteins, amino acids, enzymes, vitamins, and chlorophyll. Previous research has shown that tomato plants treated with sulfur nanoparticles improve the growth of tomato roots and shoots (Salem et al., 2016). Recent field trials of foliar-treated plants with nano sulfur increased marketable tomato yield up to 3.3~3.4-fold compared to controls and reduced disease severity of *Fusarium oxysporum* f. sp. *lycopersici* (Wang et al., 2022).

In our studies, chitosan also provided no disease control in all three trials but did improve yield in the third trial. Chitosan (β 1,4-, linked glucosamine), a deacetylated form of chitin, is a natural compound derived from the outer shell of crustaceans which displays antimicrobial activity against fungi and bacteria (Liu et al., 2004; Park et al., 2002). Two biological roles have been attributed to this compound against fungal pathogens: first, antifungal activity at certain concentrations and second, acting as a potent elicitor enhancing plant resistance and promoting plant growth (El Ghaouth et al., 1994; Shalom et al., 2003). This latter property of chitosan might be responsible for the observed increase in yields in our experiments in the absence of disease control. However, limited research has been done under field conditions to evaluate the effect of chitosan on yield improvement. In orchids, accelerated growth and development of meristemic tissue were observed in plants treated with chitosan (Uthairatanakij et al., 2007).

The results demonstrate an inconsistency in disease control between trials and/or failure to provide disease control or improvement of yields by unknown mechanisms of some of the OMRI-certified products we tested here. This outcome highlights the need for additional research to develop more effective materials or to identify conditions that might improve the efficacy of these materials. With the rapid growth of the organic industry more data on the efficacy of OMRI-certified products is required to provide effective options for organic growers.

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