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Research Article

Suppression of Leaf Spot Disease in Peanut (*Arachis hypogaea*) with Chlorothalonil, Copper Salts of Fatty Acid Rosins, and Microionized Sulfur

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Abstract

Concern over evolved resistance to fungicides that are quinone outside inhibitors (QOI), demethylation inhibitors (DMI), and succinate dehydrogenase inhibitors (SDHI) and possible restrictions on the use of the multi-site fungicide chlorothalonil for resistance management have increased the need to develop alternatives to current fungicide programs designed to protect peanut (*Arachis hypogaea* L.) from late leaf spot disease [caused by *Nothopassalora personata* (Berk. & M.A. Curtis) U. Braun, C. Nakash., Videira & Crous]. Research was conducted in North Carolina to determine the effectiveness of copper salts of fatty acid rosins and microionized sulfur in protecting peanut yield from canopy defoliation caused by late leaf spot disease. In one experiment, chlorothalonil was more effective in protecting peanut from leaf spot disease than copper salts of fatty acid rosins when these fungicides were applied five times on 14-day intervals during the cropping cycle when the pathogen was active. Chlorothalonil decreased defoliation caused by late leaf spot disease when co-applied with a diverse fungicide program consisting of prothioconazole plus tebuconazole, azoxystrobin, and pyraclostrobin compared with these fungicides without chlorothalonil. Copper salts of fatty acid rosins did not affect defoliation with the diverse fungicide program. In a second experiment, defoliation was similar when azoxystrobin or prothioconazole plus tebuconazole were applied alone or with microionized sulfur. Microionized sulfur provided similar protection from canopy defoliation compared with the more diverse fungicide programs.

Introduction

Late leaf spot disease [caused by *Nothopassalora personata* (Berk. & M.A. Curtis) U. Braun, C. Nakash., Videira & Crous] and southern stem rot disease (caused by *Athelia rolfsii* Sacc.) can reduce peanut *(Arachis hypogaea L.)* yield if control measures are not implemented in a timely manner and sustained through the period of time when epidemics of these diseases often occur [1,2]. During this period of time, beginning at the R-3 stage of peanut development [3], fungicides are often applied on 14-day intervals to prevent canopy defoliation and minimize infection and damage to stems and pods to avoid yield loss. Crop rotation sequence, cultivars expressing resistance to disease, and planting date also affect the risk of late leaf spot and southern stem rot in peanut [1,2].

Evolved resistance of fungicides used to control the pathogen that causes late leaf spot disease in peanut has been documented in North Carolina [4]. Fungicides that are demethylation inhibitors (DMI) and quinone outside inhibitors (QOI) are no longer effective against this pathogen in many areas of North Carolina. While fungicides that are succinate dehydrogenase inhibitors (SDHI) are still effective against this pathogen, current use patterns of these fungicides have increased concern over possible evolution of resistance [2,5]. Chlorothalonil affects multiple sites in the pathogen causing leaf spot disease and is not prone to development of resistance [2,5]. This fungicide has been used to protect peanut from leaf spot disease since its introduction more than 50 years ago. Chlorothalonil is the most frequently applied fungicide in peanut in North Carolina and Virginia [6] because of expense and management of resistance [2]. Chlorothalonil is often applied as the first and last sprays in a 5-spray program for resistance management [2,6]. However, this fungicide does not protect peanut from southern stem rot disease [2]. Although widely used in crop production systems in the United States, concern over negative environmental impact and human exposure to chlorothalonil have led to a ban on use by farmers in the European Union (EU) [7]. Although this fungicide continues to be used on a wide scale in US peanut production, restrictions on peanut imported into the EU could have an effect on use of chlorothalonil in peanut production systems. Developing alternatives to chlorothalonil for resistance management is needed in the event that this fungicide is no longer used because of marketing arrangements.

Protecting peanut from southern stem rot disease is important and can be achieved by using some of the fungicides that have evolved resistance to leaf spot disease [2]. For example, tebuconazole is no longer effective in protecting peanut from leaf spot disease but continues to provide protection from southern stem rot [2]. Co-application of chlorothalonil and tebuconazole is relatively common in fungicide programs in peanut in North Carolina [6]. Sulfur, a multi-site inhibiting fungicide [5], can be used to suppress pathogens including the causal pathogen for late leaf spot disease [2]. Culbreath et al. [8] reported that microionized sulfur applied with DMI fungicides increased suppression of this disease compared with DMI fungicides alone. Efficacy of microionized sulfur used in fungicide programs as an alternative to chlorothalonil in North Carolina has not been reported in the peer-reviewed literature. Copper salts of fatty acid rosins is also an alternative to chlorothalonilfor protection from leaf spot disease [9-11]. Chlorothalonil, copper salts of fatty acid rosins, and microionized sulfur are considered multi-site inhibitors of pathogens [2,5]. Given concerns over long-term sustainability of chlorothalonil and evolved resistance of fungicides that protect peanut from leaf spot disease, determining effectiveness of microionized sulfur and copper salts of fatty acid rosins would help farmers develop alternative fungicide programs for peanut. Therefore, research was conducted to compare protection of peanut from late leaf spot disease and maintenance of peanut yield when microionized sulfur or copper salts of fatty acid rosins were used in a manner similar to chlorothalonil.

Materials and Methods

Fungicide programs with copper salts of fatty acid rosins

The experiment was conducted in 2016 and 2017 in North Carolina at the Peanut Belt Research Station located near Lewiston-Woodville and at the Upper Coastal Plain Research Station located near Rocky Mount. The peanut cultivar Bailey [12] was planted in conventionally prepared raised seedbeds spaced 91-cm apart at a rate to establish 15 plants/m-row.

Treatments consisted of the following fungicide programs:

a) no-fungicide control
b) five sequential sprays of chlorothalonil (Bravo Weather Stik, Syngenta Crop Protection, Greensboro, NC) at 1.4 kg ai/ha spaced 14 days apart
c) five sequential sprays of copper salts of fatty acid rosins (Tenn-Cop 5E®, Griffin, Corp., Valdosta, GA) at 2.2 kg ai/ha spaced 14 days apart
d) five sequential sprays of prothioconazole plus tebuconazole (Provost, Bayer Crop Science) at 0.49 kg ai/ha, prothioconazole plus tebuconazole, azoxystrobin (Abound, Syngenta Crop Protection, Greensboro, NC) at 0.32 kg ai/ha, pyraclostrobin (Headline, BASF Corp, Research Triangle Park, NC) at 0.11 kg ai/ha, and chlorothalonil spaced 14 days apart
e) fungicide program d) co-applied with chlorothalonil
f) fungicide program d) co-applied with copper salts of fatty acid rosins (Table 1).

Table 1: Fungicide programs used to protect peanut yield from leaf spot disease with copper salts of fatty acid rosins.[a]

Fungicide Program	Spray 1	Spray 2	Spray 3	Spray 4	Spray 5
Chlorothalonil	Chlorothalonil	Chlorothalonil	Chlorothalonil	Chlorothalonil	Chlorothalonil
Copper salts of fatty acid rosins	Copper salts of fatty acid rosins	Copper salts of fatty acid rosins	Copper salts of fatty acid rosins	Copper salts of fatty acid rosins	Copper salts of fatty acid rosins
Diverse fungicide program	Prothioconazole plus tebuconazole	Prothioconazole plus tebuconazole	Azoxystrobin	Pyraclostrobin	Chlorothalonil
Diverse fungicide program co-applied with chlorothalonil	Prothioconazole plus tebuconazole plus chlorothalonil	Prothioconazole plus tebuconazole plus chlorothalonil	Azoxystrobin plus chlorothalonil	Pyraclostrobin plus chlorothalonil	Chlorothalonil
Diverse fungicide program co-applied with copper salts of fatty acid rosins	Prothioconazole plus tebuconazole plus copper salts of fatty acid rosins	Prothioconazole plus tebuconazole plus copper salts of fatty acid rosins	Azoxystrobin plus copper salts of fatty acid rosins	Pyraclostrobin plus copper salts of fatty acid rosins	Copper salts of fatty acid rosins

[a]Azoxystrobin, chlorothalonil, copper salts of fatty acid rosins, prothioconazole plus tebuconazole, and pyraclostrobin were applied at 0.32, 1.4, 2.2, 0.49, and 0.11 kg/ha, respectively.

Fungicide programs with microionized sulfur

The experiment was conducted in 2020 in North Carolina at the Peanut Belt Research Station located near Lewiston-Woodville and at the Border Belt Tobacco Research Station near Whiteville. The experiment was also conducted at the Peanut Belt Research Station in 2023. The peanut cultivar Bailey II [13] was planted in conventionally - prepared raised seedbeds spaced 91-cm apart at a rate to establish 15 plants/m-row.

Treatments consisted of the following fungicide program

a) no-fungicide control
b) four sequential sprays of chlorothalonil, prothioconazole plus tebuconazole, azoxystrobin, and chlorothalonil spaced 14 days apart
c) four sequential sprays of chlorothalonil, azoxystrobin, prothioconazole plus tebuconazole, and chlorothalonil spaced 14 days apart
d) four sequential sprays of chlorothalonil, prothioconazole plus tebuconazole plus microionized sulfur (Microthiol Disperss®, UPL, King of Prussia, PA) at 4.4 kg elemental sulfur/ha, azoxystrobin plus microionized sulfur, and chlorothalonil spaced 14 days apart
e) four sequential sprays of chlorothalonil, azoxystrobin plus microionized sulfur, prothioconazole plus tebuconazole plus microionized sulfur, and chlorothalonil spaced 14 days apart
f) four sequential sprays of microionized sulfur spaced 14 days apart (Table 2).

Table 2: Fungicide programs used to protect peanut yield from leaf spot disease with microionized sulfur.[a]

Spray 1	Spray 2	Spray 3	Spray 4
Chlorothalonil	Prothioconazole plus tebuconazole	Azoxystrobin	Chlorothalonil
Chlorothalonil	Prothioconazole plus tebuconazole plus microionized sulfur	Azoxystrobin plus microionized sulfur	Chlorothalonil
Chlorothalonil	Azoxystrobin	Prothioconazole plus tebuconazole	Chlorothalonil
Chlorothalonil	Azoxystrobin plus microionized sulfur	Prothioconazole plus tebuconazole plus microionized sulfur	Chlorothalonil
Microionized sulfur	Microionized sulfur	Microionized sulfur	Microionized sulfur

[a]Azoxystrobin, chlorothalonil, microionized sulfur, prothioconazole plus tebuconazole, and pyraclostrobin were applied at 0.32, 1.4, 4.4, 0.49, and 0.11 kg/ha, respectively.

Methods common to both experiments

Fungicide sprays were initiated in early July when peanut was in the R-3 stage of growth as defined by Boote [3]. Fungicides were applied in 145 L/ha aqueous solution at 275 kPa using 11002 flat fan nozzles (Teejet FF, Spraying Systems Co., Wheaton, IL) using a CO_2-pressurized backpack sprayer.

Percent canopy defoliation was recorded on a scale of 0 to 100% where 0 = no defoliation and 100 = complete defoliation within one week prior to digging pods and inverting vines. Pod yield was determined from the center two rows of the four-row plot and final yield adjusted to 8% moisture. The experimental design was a randomized complete block with treatments replicated four times. Data for canopy defoliation and pod yield were subjected to analysis of variance using the GLIMMIX procedure in SAS (SAS Institute, Cary, NC). Site-year combinations and replications were considered random effects. Fungicide programs were considered fixed effects. Means were separated using Fishers Protected LSD test at $\alpha = 0.05$ pooled over site-year combinations.

Results and Discussion

Fungicide programs with copper salts of fatty acid rosins

Peanut defoliation in absence of fungicides was 83% and exceeded that of all fungicide programs (Table 3). Applying chlorothalonil every 14 days was more effective than copper salts of fatty acid rosins (26% versus 68%). The more diverse fungicide program including two applications of prothioconazole plus tebuconazole followed by azoxystrobin, pyraclostrobin, and chlorothalonil was less effective than the program of chlorothalonil alone but more effective than the program of only copper salts of fatty acid rosins. When chlorothalonil was co-applied with each fungicide in the more diverse program, defoliation decreased from 55% to 23%. However, defoliation when fungicides were co-applied was not lower than when chlorothalonil was applied alone. Co-applying copper salts of fatty acid rosins with fungicides in the diverse program did not lead to greater protection from leaf spot than the diverse fungicide program without co-applied fungicide.

Applying the diverse fungicide program alone or with either chlorothalonil or copper salts of fatty acid rosins resulted in similar peanut yields that exceeded yield of the no-fungicide control (Table 3). Yield when chlorothalonil was applied every 14 days alone exceeded that of non-treated peanut and peanut treated with only copper salts if fatty acid rosins. The results from this research were not unexpected. Chlorothalonil continues to be highly effective in protecting peanut from leaf spot disease. Less effective protection by copper salts of fatty acid rosins compared with chlorothalonil has been reported previously [9-11]. Chlorothalonil is effective when applied on a 14-day schedule while copper salts of fatty acid rosins require applications on closer intervals to be effective [2]. The high percentage of canopy defoliation with the diverse fungicide program was also not unexpected. Inability of QOI fungicides to control the pathogen causing late leaf spot was observed at both of these locations in most fields at the time when these experiments were implemented [4]. While the combination of prothioconazole plus tebuconazole continues to be effective against leaf spot disease, azoxystrobin and pyraclostrobin, both QOI fungicides, are completely ineffective in controlling the pathogen. In essence, the diverse fungicide program had a gap is protection of 4 weeks during the peak of the leaf spot epidemic in this fungicide program. Chlorothalonil was an effective tank-mix partner for protecting peanut from leaf sot disease when azoxystrobin and pyraclostrobin were applied. While these results on the surface suggest that applying chlorothalonil only is the most effective approach, two caveats need to be considered. First, protection from southern stem rot disease is needed in many fields, and chlorothalonil offers no protection for this disease. Secondly, applying chlorothalonil this frequently can increase risk of inducing two-spotted spider mite *(Tetranychus urticae* Koch*)* [14] and Sclerotinia blight (caused by *Sclerotinia minor* Jagger) [15]. These data demonstrate that copper salts of fatty acid rosins is ineffective in protecting peanut from leaf spot disease when applied on a 14-day schedule and does not improve suppression when applied with fungicides with evolved resistance to the pathogen causing leaf spot disease.

Table 3: Peanut canopy defoliation within one week of digging pods and inverting vines and peanut yield with fungicide programs including chlorothalonil or copper salts of fatty acid rosins only and a diverse fungicide program applied alone or co-applied with chlorothalonil or copper salts of fatty acid rosins.[a,b]

Fungicide program	Peanut Defoliation	Peanut Pod Yield
	%	kg/ha
Non-treated control	83 a	3,130 c
Chlorothalonil	26 d	4,370 a
Copper salts of fatty acid rosin	68 b	3,590 bc
Diverse fungicide program	55 c	4,250 ab
Diverse fungicide program co-applied with chlorothalonil	23 d	4,350 a
Diverse fungicide program co-applied with copper salts of fatty acid rosins	51 c	4,380 a

[a]Diverse fungicide program consisted of sequential applications of prothioconazole plus tebuconazole, prothioconazole plus tebuconazole, azoxystrobin, pyraclostrobin and chlorothalonil. Azoxystrobin, chlorothalonil, copper salts of fatty acid rosins, prothioconazole plus tebuconazole, and pyraclostrobin, were applied at 0.32, 1.4,2.2, 0.49 and 0.11 kg/ha, respectively. [b]Means within a column followed by the same letter are not significantly different based on Fishers Protected LSD test at $\alpha = 0.05$. Data are pooled over four site-year combinations.

Fungicide programs with microionized sulfur

In absence of fungicides, canopy defoliation was 30%, and all fungicide programs minimized defoliation in a similar manner (Table 4). When fungicides were applied, canopy defoliation did not exceed 2% regardless of the sequence of prothioconazole plus tebuconazole and azoxystrobin or presence of microionized sulfur. These results were not unexpected because three of the four sprays (e. g., chlorothalonil applied twice and prothioconazole plus tebuconazole applied once) provided adequate protection even though azoxystrobin does not because of evolved resistance [2,4]. Unlike copper salts of fatty acid rosins in the other experiment, microionized sulfur provided effective control when applied on a 14-day schedule. Culbreath et al. [15] reported that microionized sulfur was effective in protecting peanut from leaf spot disease in peanut. Although the two fungicides were not compared in the same experiment, these results suggest that microionized sulfur is likely the most effective option for resistance management and substitution for chlorothalonil when comparing copper-based fungicide with sulfur-based fungicide.

Table 4: Peanut canopy defoliation within one week of digging pods and inverting vines and peanut yield with fungicide programs including microionized sulfur co-applied with axoxystrobin and prothioconazole plus tebuconazole.[a,b]

Fungicide Program	Peanut Defoliation	Peanut Pod Yield
	%	kg/ha
Non-treated control	30 a	4,880 c
Chlorothalonil then prothioconazole plus tebuconazole then azoxystrobin then chlorothalonil	0 b	5,540 a
Chlorothalonil then prothioconazole plus tebuconazole plus microionized sulfur then azoxystrobin plus microionized sulfur then chlorothalonil	0 b	5,340 ab
Chlorothalonil then azoxystrobin then prothioconazole plus tebuconazole then chlorothalonil	2 b	5,210 abc
Chlorothalonil then azoxystrobin plus microionized sulfur then prothioconazole plus tebuconazole plus microionized sulfur then chlorothalonil	2 b	5,330 ab
Microionized sulfur then microionized sulfur then microionized sulfur then microionized sulfur	1 b	5,020 bc

[a]Azoxystrobin, chlorothalonil, microionized sulfur, prothioconazole plus tebuconazole, and pyraclostrobin, were applied at 0.32, 1.4, 4.4, 0.49, and 0.11 kg/ha, respectively.
[b]Means within a column followed by the same letter are not significantly different based on Fishers Protected LSD test at $\alpha = 0.05$. Data are pooled over three site-year combinations.

Peanut yield was similar when prothioconazole plus tebuconazole or azoxystrobin were applied alone or with microionized sulfur and when microionized sulfur was applied alone (Table 4). Peanut receiving the program with prothioconazole plus tebuconazole followed by azoxystrobin without microionized sulfur yielded more than peanut receiving microionized sulfur alone. The difference in yield between these two fungicide programs may have been due in part to southern stem rot that may have been present but not evaluated. Of these fungicide programs, microionized sulfur does not protect peanut from southern stem rot [2,11].

Conclusion

Results from these experiments demonstrate the continued benefits of chlorothalonil for leaf spot control in peanut, especially in fields where resistance to QOI and DMI fungicides is present. Copper salts of fatty acid rosins did not appear to be a reasonable substitute for chlorothalonil when applied on 14-day intervals. The potential of microionized sulfur in protecting peanut from leaf spot is a positive finding and warrants closer evaluation, especially given concerns over long-term use of chlorothalonil for management of fungicide resistance.

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