Application of fungicides to foliage through overhead sprinkler irrigation – a review

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Abstract: Articles on chemigation with fungicides targeting foliage have been reviewed. They included 23 fungicides tested on 10 crops. Many studies compared chemigation to a check treatment, while others also included conventional methods. Chlorothalonil, followed by mancozeb, fentin hydroxide and captafol were the most studied fungicides, while peanut (*Arachis hypogaea*), potato (*Solanum tuberosum*), tomato (*Lycopersicon esculentum*), and dry beans (*Phaseolus vulgaris*) were the most studied crops. Center pivot, followed by solid set, were the irrigation systems most frequently used. The minimum volume of water applied by some center pivots (25 000 litre ha^{-1}) is 25 times the maximum volume of water used by conventional ground sprayers. The reduction of fungicide residue on foliage caused by the very large volume of water used by chemigation might be offset by the following factors: (1) fungicide application at the time of maximum leaf wetness when fungi are most active, (2) complete coverage of plants, (3) reducing greatly the inoculum on plant and soil surface, (4) better control of some soil pathogens, and (5) more uniform distribution of fungicides by center pivot. Furthermore, chemigation avoids mechanical damage and soil compaction. Additionally, some systemic fungicides seem to be absorbed rapidly by the leaves, by root uptake from the soil, or by both. In general, all fungicides applied through irrigation water can lessen disease severity. However, when compared to conventional methods, chemigation with fungicides can be less, equally or more effective depending on crop, pathogen, disease severity, fungicide and volume of water. For *Cercosporidium personatum* control on peanuts, application of protectant fungicides through irrigation water is less effective than conventional methods, but the results with some systemic fungicides mixed with non-emulsified oil and applied through a relatively low volume of water (2.5 mm) are encouraging. Important diseases of potato and tomato can be controlled nearly as well by chemigation as by conventional methods without impairing yield. The main advantage of chemigation for these crops is avoiding a large number of tractor trips through the field and reduced costs of fungicide application. Chemigation has also been shown to be a good option for control of white mold [*Sclerotinia sclerotiorum*] on dry beans.

Keywords: chemigation; foliar fungicides; disease control; overhead sprinkler

1 INTRODUCTION

The concept of applying chemicals by sprinkler irrigation (chemigation) began with nitrogen fertilizer over 35 years ago.[1] The application of plant protectants through irrigation systems appears to have begun in the 1960s,[2] and the first report of the application of fungicides by sprinkler irrigation was made by McMaster and Douglas.[3]

Irrigation systems can generally be classified into sprinkler, surface, and drip.[4] During chemigation the chemical reaches only where the irrigation water falls. Therefore, surface and drip systems can be used successfully only for soil application. Sprinker irrigation is more flexible because both ground and foliar chemical applications are possible. Sprinkler irrigation includes hand move, solid set, lateral roll, traveling gun, center pivot, and linear move systems. A continuously moving sprinkler system such as the center pivot and the linear move achieves a coefficient of uniformity (CU) of 0.9 when properly calibrated and operated. However, many solid set and periodic lateral move systems achieve a CU of only 0.70 to 0.75 and a traveling gun usually achieves less than 0.70.[5] In addition, traveling guns are less effective because of the large amount of drift, and the high impact from one large nozzle washing chemicals off the leaves.[6]

Center pivot and linear move have another advantage over the solid set and periodic lateral move systems: the water in the pipe is moving at sufficiently high velocity to help keep the fungicides dispersed and the sprinklers can be mounted below the pipes. This combination of factors leads to low flushing times, prevents oil formulation from floating out

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Table 1. Some details of studies where plots treated via chemigation provided better disease control than in a non-treated control

Crop (*number of treatments or trials*)	*Fungicide* (*number of applications*, *formulation*)[a]	*Rate* (*kg ha*$^{-1}$)	*Pathogen*	*Disease severity on control*[a,b]	*Irrigation system* (*mm*)[a,c]	*Yield*[a,d]	*Reference* (*USA state*, *or country*)
Carrot (1)	Anilazine + copper resinate (12,W,E)	0.84 + 2.34	*Cercospora carotae* + *Alternaria dauci* + *Xanthomonas campestris* pv. *carotae*	M/S	ISH (0.4)	F > N	42 (MI)
Cucumber (1)	Captafol (9,F)	3.64	*Pseudoperonospora cubensis*	S	SS (2-4)	F = N	16 (GA)
Dry beans (1)	Benomyl (1,W)	1.12	*Sclerotinia sclerotiorum*	M	LR (NA)	F > N	43 (ID)
Dry beans (1)	Benomyl (4,W)	0.35	*Uromyces appendiculatus*	M/S	SS (3.0)	NA	44 (Brazil)
Dry beans (1)	Benomyl + mancozeb (3,W,W)	0.25 + 1.6	*Erysiphe polygoni*	L	CP (NA)	F = N	26 (Brazil)
Dry beans (1)	Bitertanol (4,W)	0.175	*U appendiculatus*	M/S	SS (3.0)	F > N	44 (Brazil)
Dry beans (1)	Chlorothalonil (3,NA)	1.5	*E polygoni*	L	CP (NA)	F = N	26 (Brazil)
Dry beans (1)	Mancozeb (4,W)	1.6	*U appendiculatus*	M/S	SS (3.0)	NA	44 (Brazil)
Dry beans (1)	Tebuconazole (3,E)	0.25	*E polygoni*	L	CP (NA)	F = N	26 (Brazil)
Dry beans (2)	Thiophanate-methyl (1,W)	1.1, 2.2	*S sclerotiorum*	M/S	CP (NA)	F > N	43 (ID)
Dry beans (1)	Thiophanate-methyl + chlorothalonil (3,NA,NA)	0.35 + 0.90	*E polygoni*	L	CP (NA)	F = N	26 (Brazil)
Dry beans (1)	Triforine (3,E)	0.285	*E polygoni*	L	CP (NA)	F = N	26 (Brazil)
Potato (1)	Anilazine (12,W)	1.12	*Phytophthora infestans*	M/S	ISH (0.4)	F > N	45 (MI)
Potato (1)	Captafol (7,S)	1.79	*Alternaria solani*	M/S	LM (2.5)	F > N	14 (MI)
Potato (1)	Chlorothalonil (2,W)	1.26	*A solani*	S	CP (8.0)	F = N	15 (CO)
Potato (2)	Chlorothalonil (2,F)	0.88	*A solani*	S	CP (8.0)	F = N	15 (CO)
Potato (1)	Chlorothalonil (6,F)	1.26	*A solani*	S	CP (4.8)	F = N	28 (WA)
Potato (1)	Chlorothalonil (2,F)	0.88	*A solani*	M	CP (8.0)	F = N	15 (CO)
Potato (1)	Chlorothalonil (4,F)	1.26	*A solani*	M	CP (5.6)	F = N	28 (WA)
Potato (1)	Chlorothalonil (4,F)	0.88, 1.17	*A solani*	L/M	CP (NA)	F = N	27 (UT)
Potato (1)	Chlorothalonil (12,F)	1.3	*P infestans*	M/S	ISH (0.4)	F > N	45 (MI)
Potato (2)	Fentin hydroxide (2,W)	0.33	*A solani*	M/S	CP (8.0)	F > N	15 (CO)
Potato (1)				M/S	CP (8.0)	F = N	
Potato (1)	Fentin hydroxide (7,NA)	0.33	*A solani*	M/S	LM (2.5)	F > N	14 (MI)
Potato (1)	Fentin hydroxide (4,W)	0.27	*A solani*	L/M	CP (NA)	F = N	27 (UT)
Potato (1)	Mancozeb (7,W)	1.79	*A solani*	M/S	LM (2.5)	F > N	14 (MI)
Rice (1)	Fentin hydroxide (5,NA)	0.75	*Pyricularia oryzae*	NA	SS (3,6,9)	F > N	46 (Brazil)
Rice (1)	Fentin hydroxide (5,W)	0.75	*P oryzae*	M/S	SS (3.0)	F > N	47 (Brazil)
Sugarbeet (2)	Benomyl (7,W)	0.28, 0.56	*Cercospora beticola*	M/S	SS (0.4)	NA	19 (MI)
Sugarbeet (2)	Benomyl (5,6,W)	0.28	*C beticola*	L/M	SS (0.4)	NA	19 (MI)
Sugarbeet (1)	Captafol (4,F)	2.24	*C beticola*	M	SS (0.4)	NA	19 (MI)
Sugarbeet (2)	Captafol + captan[e] (7,F,W)	(1.1 + 2.2) and (2.2 + 4.5)	*C beticola*	M/S	SS (0.4)	NA	19 (MI)
Sugarbeet (1)	Chlorothalonil (6,F)	1.46	*C beticola*	L/M	SS (0.4)	NA	19 (MI)
Sugarbeet (1)	Copper ammonium carbonate (5,F)	4.48	*C beticola*	L/M	SS (0.4)	NA	19 (MI)
Sugarbeet (1)	Copper hydroxide (7,W)	1.93	*C beticola*	M/S	SS (0.4)	NA	19 (MI)
Sugarbeet (1)	Copper hydroxide (4,W)	1.93	*C beticola*	M	SS (0.4)	NA	19 (MI)
Sugarbeet (1)	Copper hydroxide (5,W)	1.68	*C beticola*	L/M	SS (0.4)	NA	19 (MI)
Sugarbeet (1)	Copper resinate (7,E)	4.48	*C beticola*	M/S	SS (0.4)	NA	19 (MI)
Sugarbeet (1)	Copper resinate (4,E)	4.48	*C beticola*	M	SS (0.4)	NA	19 (MI)
Sugarbeet (1)	Copper resinate (5,E)	4.48	*C beticola*	L/M	SS (0.4)	NA	19 (MI)
Sugarbeet (1)	Fentin hydroxide (7,W)	0.33	*C beticola*	M/S	SS (0.4)	NA	19 (MI)
Sugarbeet (1)	Fentin hydroxide (4,W)	0.33	*C beticola*	M	SS (0.4)	NA	19 (MI)
Sugarbeet (2)	Fentin hydroxide (5,6,W)	0.33	*C beticola*	L/M	SS (0.4)	NA	19 (MI)

Table 1. *Continued*

Crop (*number of treatments or trials*)	*Fungicide* (*number of applications, formulation*)[a]	*Rate* (*kg ha*$^{-1}$)	*Pathogen*	*Disease severity on control*[a,b]	*Irrigation system* (*mm*)[a,c]	*Yield*[a,d]	*Reference* (*USA state, or country*)
Tomato (1)	Difolatan (10,F)	3.5	*A solani* + *Colletotrichum phomoides* + *Septoria lycopersici*	M/S M M	SS (0.4)	F > N	17 (MI)
Tomato (1)	Captafol + copper resinate (11,S,E)	2.69 + 2.11	*A solani* + *C phomoides*	M/S M	CP (NA)	F > N	10 (MI)
Tomato (1)	Captafol + copper resinate (14,S,E)	2.69 + 2.34	*A solani* + *C phomoides* + *S lycopersici* + *Xanthomonas campestris* pv *vesicatoria*	M L/M L/M L	CP (3.3)	F > N	13 (MI)
Tomato (1)	Chlorothalonil (10,F)	1.17	*A solani* + *S lycopersici* + *C phomoides*	M/S M/S M	SS (0.4)	F > N	17 (MI)
Tomato (1)	Chlorothalonil + copper resinate (10,F,E)	0.6 + 1.12	*A solani* + *S lycopersici* + *C phomoides*	M/S M/S M	SS (0.4)	F > N	17 (MI)
Tomato (1)	Iprodione (2,3,4,W)	0.75	*S sclerotiorum*	NA	CP (NA)	F > N	48 (Brazil)
Tomato (2)	Manzate 200 (10,W)	3.4	*A solani* + *S lycopersici* + *C phomoides*	M/S M/S M	SS (0.4)	F > N	17 (MI)
Tomato (1)	Mancozeb + copper sulfate (11,W,W)	2.69 + 2.37	*A solani* + *C phomoides*	M/S M	CP (NA)	F > N	10 (MI)
Tomato (1)	Manex + Super Cu (14,F,F)	5.62 + 4.68	*A solani* + *C phomoides* + *S lycopersici* + *X c* pv *vesicatoria*	M L/M L/M L	CP (3.3)	F > N	13 (MI)
Tomato (2)	Dithane FZ + copper sulfate (11,F,W)	5.62 + 2.37	*A solani* + *C phomoides*	M/S M	CP (NA)	F > N	10 (MI)
Tomato (1)	Dithane FZ + copper sulfate (14,F,W)	5.62 + 1.19	*A solani* + *C phomoides* + *S lycopersici* + *X c* pv *vesicatoria*	M L/M L/M L	CP (3.3)	F > N	13 (MI)
Tomato (1)	Metalaxyl (1,E)	1.12	*Phytophthora destructor*	M	CP (3.3)	F > N	21 (MI)
Tomato (1)	Metiram + Copper Count N (14,W,S)	2.69 + 4.68	*A solani* + *C phomoides* + *S lycopersici* + *X c* pv *vesicatoria*	M L/M L/M L	CP (3.3)	F > N	13 (MI)

[a] NA = information not available; E = emulsifiable concentrate, F = flowable, S = solution, W = wettable powder.
[b] L = low, M = moderate, S = severe.
[c] CP = center pivot, ISH = individual sprinkler head, LM = linear move, LR = lateral roll, SS = solid set.
[d] F = chemigation with fungicides, N = no fungicide treatment.
[e] Captafol was applied in the first four applications, captan in the last three.

Table 2. Some details of studies where plots treated *via* chemigation and plots with no fungicide did not differ from each other on disease severity

Crop (number of treatments or trials)	Fungicide (number of applications, formulation)[a]	Rate (kg ha^{-1})	Pathogen	Disease severity on control[b]	Irrigation system (mm applied)[c]	Yield[d]	Reference (USA state or country)
Dry beans (1)	Iprodione (4,W)	0.75	*Uromyces appendiculatus*	M/S	SS (3.0)	F = N	44 (Brazil)
Potato (1)	Chlorothalonil (2,W)	1.26	*Alternaria solani*	S	CP (8.0)	F = N	15 (CO)
Potato (1)	Chlorothalonil (2,F)	0.585	*A solani*	M	CP (8.0)	F = N	15 (CO)
Potato (1)	Fentin hydroxide (4,F)	0.30	*A solani*	M	CP (3.7)	F = N	28 (WA)

[a] F = flowable, W = wettable powder.
[b] M = moderate, S = severe.
[c] CP = center pivot, SS = solid set.
[d] F = chemigation with fungicides, N = no fungicide treatment.

of the pipes and prevents oil from settling from the water. A center pivot is preferable to a linear move because of easier management. Furthermore, a center pivot has most of the water going from the center to the border of the circle. Thus, there is a high water velocity over a longer length of pipe, which is preferable for the transport of chemicals.[6] Injection into center pivot systems is continuous because the irrigation lateral is continuously moving. On the other hand, chemicals can be applied at any moment of the irrigation with solid set or periodic lateral move systems, allowing the use of a smaller volume of water during the chemigation.

Another approach to the use of the center pivot or the linear move systems for chemical applications has come with the PASS (Pivot Agricultural Spray System). The PASS system utilizes a separate sprayer attached to a center pivot or lateral-move irrigation system that can apply pesticides in 1400 to 2800 litre ha^{-1} of water.[7] The lower volume of water applied by PASS minimizes wash-off and permits chemical application even when the soil is wet. Furthermore, applications by PASS do not require a special registration. The object of this paper is to review the literature on applying fungicides to foliage by sprinkler irrigation and the factors affecting the behavior of fungicides so applied.

2 GENERAL INFORMATION ABOUT THIS REVIEW

Twenty-three materials, pertaining to 10 groups of fungicides, have been reported. Chlorothalonil alone or combined with other fungicides, followed by mancozeb, fentin hydroxide and captafol, were the most frequent fungicides studied. In general, the fungicides were applied at recommended rates for both conventional methods and chemigation. Peanut (*Arachis hypogaea* L) with 11 articles, potato (*Solanum tuberosum* L) with nine, and tomato (*Lycopersicon esculentum* Mill) with seven were the most studied crops. In Brazil, most of the investigations were made with dry beans (*Phaseolus vulgaris* L). Center pivot irrigation was the most frequently used system. Diaphragm[8–10] and piston[11–15] metering pumps were used for injection of fungicides through this irrigation system. High,[14,16–20] medium,[7,20] and low pressure[8,10–13,21] center pivots were tested for fungicide distribution.

A summary of methodology and results from the articles that compare chemigation with fungicides (F) versus nontreated plots (N) are presented in Tables 1 and 2. In Tables 3, 4, and 5 results also include a comparison of chemigation with conventional methods (C) and PASS (P). Most of the conventional methods used for comparison to chemigation were ground applications. In some articles chemigation was compared to aircraft[11,12,15,18,20,22] and/or PASS application.[7,20,23–25] The volume of water used when fungicides were applied by ground sprayer varied from 94 to 561 litre ha^{-1}; for aircraft, it varied from 28 to 47 litre ha^{-1}. To eliminate the effects of irrigation on the results, in general plots with conventional methods were watered in advance with the same amount of water used in chemigation.

3 CHEMIGATION WITH FUNGICIDES VERSUS NON-TREATED CONTROL

Plots treated by chemigation were compared to non-treated plots for disease control in 18 articles (Tables 1 and 2). In most of the plots treated by chemigation there was less disease severity than in the control and yield was increased in 25 of 39 trials where this evaluation was reported (Table 1). In seven cases where chemigation did not increase yield[26,27] disease severity on the control was low or low/moderate and disease occurred late in the season. According to Franc *et al*,[15] overriding factors, such as Verticillium wilt and climate, masked the beneficial effects of early blight control with fungicides. In south central Washington,[28] early blight probably would not have been an economic problem in the absence of the other diseases, because it does not express itself on foliage in fields where there is not early die-back. Diseases controlled by chemigation include white mold [*Sclerotinia sclerotiorum* (Lib) de Bary], rust [*Uromyces appendiculatus* (Pers) Unger var. *appendiculatus*], and powdery mildew (*Erysiphe polygoni* DC) on dry beans; early blight (*Alternaria solani*

Table 3. Some details of studies where conventional methods are superior to chemigation in diseases control

Crop (number of treatments or trials)	Fungicide (number of applications, formulation)[a]	Rate (kg ha^{-1})	Pathogen	Disease severity on control[a,b]	Irrigation system (mm)[a,c]	Yield[a,d]	Reference (USA state, or country)
Cucumber (1)	Chlorothalonil (7,NA)	1.46	*Corynespora cassiicola* + *Pseudoperonospora cubensis*	S	SS (1-4)	C = F > N	49 (GA)
Cucumber (1)	Chlorothalonil (9,F)	2.33	*P cubensis*	S	SS (2-4)	C > F = N	16 (GA)
Cucumber (1)	Mancozeb (9,F)	1.79	*P cubensis*	S	SS (2-4)	C = F = N	16 (GA)
Cucumber (1)	Mancozeb (9,W)	1.79	*P cubensis*	S	SS (2-4)	C = F = N	16 (GA)
Dry beans (2)	Benomyl + captan (NA,W,NA)	0.25 + 1.2	*Phaeoisariopsis griseola*	NA	CP (NA)	C = F > N	50 (Brazil)
Dry beans (2)	Benomyl + chlorothalonil (NA,W,NA)	0.15 + 0.7	*P griseola*	NA	CP (NA)	C = F > N	50 (Brazil)
Dry beans (1)	Benomyl + mancozeb (3,W,W)	0.15, 0.25, 0.35 + 2.0	*Alternaria* spp	L	CP (4.9)	F > C = N	8 (Brazil)
Dry beans (2)	Benomyl + mancozeb (NA,W,W)	0.2 + 1.6	*P griseola*	NA	CP (NA)	C = F > N	50 (Brazil)
Dry beans (2)	Chlorothalonil (NA,NA)	1.0	*P griseola*	NA	CP (NA)	C = F > N	50 (Brazil)
Dry beans (1)	Thiophanate methyl + chlorothalonil (3,NA,NA)	0.28 + 0.7	*Alternaria* spp	L	CP (4.9)	F > C = N	8 (Brazil)
Peach (1)	Chlorothalonil (1,F + oil)	3.5	*Cladosporium carpophilum*	M	CP (2.5)	NA	25 (GA)
Peach (1)				M/S		NA	
Peanut (1)	Chlorothalonil (7,F)	1.25	*Cercosporidium personatum*	S	CP (1.8)	C > P > F = N	23 (GA)
Peanut (1)	Chlorothalonil (7,F)	1.25	*C personatum*	S	CP (7.6)	C > F = N	51 (GA)
Peanut (1)	Chlorothalonil (7,F)	1.24	*C personatum*	M/S	SC (4.0)	C = F > N	52 (GA)
Peanut (1)	Chlorothalonil (7,F)	1.25	*C personatum*	M/S	CP (1.8)	P = F ≥ C = N	23 (GA)
Peanut (1)	Chlorothalonil (7,F)	1.25	*C personatum*	M/S	CP (7.6)	C > F = N	51 (GA)
Peanut (1)				M/S		C = F = N	
Peanut (1)				M		C = F = N	
Peanut (1)	Chlorothalonil (7,NA)	1.24	*C personatum*	NA	CP (3.7)	C = F	53 (GA)
Peanut (1)	Chlorothalonil (6,NA)	0.84, 1.26	leaf spot[e]	S	SI (3.9)	C > P > F = N	7 (GA)
Peanut (1)	Chlorothalonil (NA,F)	2.49	leaf spot[e]	M/S	CP (NA)	C = F > N	30 (AL)
Peanut (1)				M	SG (NA)	C = F > N	
Peanut (1)	Diniconazole (7,NA)	0.061	*C personatum*	M	SC (4.0)	C > F > N	52 (GA)
Peanut (2)	Propiconazole (3,E)[f]	0.12	*C personatum*	NA	SI (2.5, 6.5)	F > C	39 (GA)
Peanut (2)	Tebuconazole (7,E)	0.252	*C personatum*	S	CP (2.5)	C = F > N	31 (GA)
Peanut (1)	Tebuconazole (7,E + oil)	0.252	*C personatum*	S	CP (2.5)	C = F > N	31 (GA)
Potato (1)	Captafol (2,F)	1.68	*Alternaria solani*	S	CP (8.0)	C = F > N	15 (CO)
Potato (1)	Captafol (12,F)	1.68	*A solani*	M/S	CP (8.6)	NA	20 (WI)
Potato (1)				M/S		C = F = N	
Potato (1)	Captafol (12,F)	1.68	*Phytophthora infestans*	S	CP (8.6)	NA	20 (WI)
Potato (1)	Chlorothalonil (2,F)	1.17	*A solani*	S	CP (8.0)	C = F = N	15 (CO)
Potato (1)	Chlorothalonil (9,F)	1.1	*A solani*	S	CP (8.6)	NA	20 (WI)
Potato (1)	Fentin hydroxide (12,W)	0.33	*P infestans*	S	CP (8.6)	NA	20 (WI)
Potato (1)	Fentin + mancozeb (11,W,F)	0.22 + 1.1	*A solani*	S	CP (8.6)	NA	20 (WI)
Potato (1)	Mancozeb (12,F)	1.81	*A solani*	M/S	CP (8.6)	NA	20 (WI)
Potato (1)	Mancozeb (9,F)	1.6	*A solani*	NA	CP (5.0)	C = F	20 (WI)
Potato (1)	Mancozeb (12,F)	1.81	*P infestans*	S	CP (8.6)	NA	20 (WI)
Tomato (1)	Mancozeb + tri-basic copper sulfate (12,F,W)	2.17 + 2.24	*Xanthomonas campestris* pv *vesicatoria*	L/M	CP (7.6)	C = F > N	11 (MI)
Wheat (1)	Propiconazole (NA,NA)	0.125,0.200	*Helminthosporium* sp	NA	CP (NA)	NA	22 (Brazil)

[a] NA = information not available, E = emulsifiable concentrate, F = flowable, W = wettable powder.
[b] L = low, M = moderate, S = severe.
[c] CP = center pivot, SC = sprinkler can, SG = stationary gun, SI = simulated irrigation, SS = solid set.
[d] C = conventional application, F = chemigation with fungicides, P = PASS, N = no fungicide treatment.
[e] Pathogen not specified.
[f] All plots were sprayed with chlorothalonil (1.26 kg ha^{-1}) on a 14-day schedule.

Sorauer) and late blight [*Phytophthora infestans* (Mont) de Bary] on potato; cercospora leaf spot (*Cercospora beticola* Sacc) on sugarbeet; and early blight [*Alternaria solani* Sorauer], Septoria blight (*Septoria lycopersici* Speg), and anthracnose [*Colletotrichum phomoides* (Sacc) Chester] on tomato.

Control of foliage diseases and yield may not be related if insects, weeds, nematodes, soil-borne pathogenic fungi, plant nutrition, edaphic and climate factors, or cultural practices are uncontrolled variables influencing crop production. Also, if epidemics of foliage diseases develop late in a crop cycle, the foliar pathogens may have a negligible effect on crop yield and quality.

In the few cases in which chemigation did not provide disease control (Table 2), other extraneous factors were responsible for these results rather than the method of fungicide application. Iprodione was not effective for rust control on dry beans, because this fungicide has little or no activity against rust.[29] Chlorothalonil formulation or rate was responsible for the lack of early blight control on potato. Chlorothalonil as a wettable powder (1.26 kg AI ha^{-1}) did not control the disease,[15] but when this fungicide was applied as an sc, at rates of 0.88 or 1.17 kg AI ha^{-1}, disease severity decreased. Chlorothalonil sc did not provide early blight control at 0.585 kg AI ha^{-1},[15] but it was efficient at 0.88 or 1.17 kg ha^{-1}. However, regardless of either formulation or rate, yield was not increased by the fungicide applications.

Table 4. Some details of studies where conventional methods and chemigation were both efficient for disease control when compared to a non-treated control

Crop (number of treatments or trials)	Fungicide (number of applications, formulation)[a]	Rate (kg ha^{-1})	Pathogen	Disease severity on control[b]	Irrigation system (mm)[a,c]	Yield[a,d]	Reference (USA state, or country)
Carrot (1)	Chlorothalonil + copper ammonium carbonate (12,F,S)	1.32 + 4.68	*Cercospora carotae* + *Alternaria dauci* + *Xanthomonas campestris* pv. *carotae*	M/S L L	ISH (0.4)	C = F > N	42 (MI)
Cucumber (1)	Chlorothalonil (3,F)	2.33	*Mycosphaerella melonis* + *Corynespora cassiicola*	M/S	SS (2-4)	C = F > N	16 (GA)
Dry beans (1)	Benomyl (1,W)	1.12	*Sclerotinia sclerotiorum*	M	CP (NA)	C = F = N	43 (ID)
Dry beans (2)	Benomyl (3,W)	0.5	*S sclerotiorum*	NA	CP (3.5)	C = F > N	54 (Brazil)
Dry beans (2)	Benomyl + captan (NA,W,NA)	0.25 + 1.2	*S sclerotiorum* + *Uromyces appendiculatus*	NA	CP (NA)	C = F > N	50 (Brazil)
Dry beans (2)	Benomyl + chlorothalonil (NA,W,NA)	0.15 + 0.7	*S sclerotiorum* + *U appendiculatus*	NA	CP (NA)	C = F > N	50 (Brazil)
Dry beans (2)	Benomyl + iprodione (3,W,W)	0.5 + 0.37	*S sclerotiorum*	NA	CP (3.5)	C = F > N	54 (Brazil)
Dry beans (2)	Benomyl + mancozeb (NA,W,W)	0.2 + 1.6	*S sclerotiorum* + *U appendiculatus*	NA	CP (NA)	C = F > N	50 (Brazil)
Dry beans (2)	Benomyl + mancozeb (3,W,W)	0.5 + 1.6	*S sclerotiorum*	NA	CP (3.5)	C = F > N	54 (Brazil)
Dry beans (2)	Chlorothalonil (NA,NA)	1.0	*S sclerotiorum* + *U appendiculatus*	NA	CP (NA)	C = F > N	50 (Brazil)
Dry beans (2)	Iprodione (3,W)	0.75	*S sclerotiorum*	NA	CP (3.5)	C = F > N	54 (Brazil)
Dry beans (2)	Thiophanate methyl (3,F)	1.5	*S sclerotiorum*	NA	CP (3.5)	C = F > N	54 (Brazil)
Peanut (1)	Chlorothalonil (7,NA)	1.24	Leaf spot[e]	NA	CP (4.0)	C = F > N	35 (GA)
Peanut (2)	Cyproconazole (7,S + oil)	0.112	*Cercosporidium personatum*	S	CP (2.5)	C = F > N	9 (GA)
Peanut (1)						C = F > N	
Peanut (1)	Tebuconazole (7,E + oil)	0.252	*C personatum*	S	CP (2.5)	C = F > N	31 (GA)
Potato (1)	Captafol (2,F)	1.68	*Alternaria solani*	M/S	CP (8.0)	C = F > N	15 (CO)
Potato (1)	Chlorothalonil (12,F)	1.68	*A solani*	M/S	CP (8.6)	F > C	20 (WI)
Potato (1)				M/S		N = F > C = N	
Potato (1)	Chlorothalonil (2,F)	1.9	*A solani*	M	LR (0.4)	NA	3 (ID)
Potato (1)	Chlorothalonil (1,F)	1.9	*A solani*	L/M	LR (0.4)	NA	3 (ID)
Potato (1)	Chlorothalonil (2,F)	1.9	*A solani*	M	SS (0.4)	NA	3 (ID)
Potato (1)	Chlorothalonil (2,F)	1.9	*A solani*	M	CP (6.5)	NA	3 (ID)
Potato (1)	Chlorothalonil (12,F)	1.26	*A solani*	M	SS (1.1)	C = F > N	33 (MI)
Potato (1)	Chlorothalonil (12,F)	1.26	*A solani* + *Botrytis cinerea*	M L/M	SS (1.1)	C = F > N	33 (MI)
Potato (1)	Chlorothalonil (12,F)	1.68	*Phytophthora infestans*	S	CP (8.6)	NA	20 (WI)
Potato (1)	Fentin hydroxide (12,W)	0.33	*A solani*	M/S	CP (8.6)	NA	20 (WI)
Potato (1)	Fentin hydroxide (1,NA)	0.56	*A solani*	M	LR (≥0.4)	NA	3 (ID)
Potato (1)	Fentin hydroxide (12,W)	0.33	*P infestans*	M/S	ISH (0.4)	F > C > N	45 (MI)
Potato (1)	Mancozeb (12,F)	1.81	*A solani*	M/S	CP (8.6)	N = C > F = N	20 (WI)
Tomato (1)	Chlorothalonil[f] + copper resinate (10,F,E)	1.32 + 2.24	*A solani* + *Septoria lycopersici* + *Colletotrichum phomoides* + *Xanthomonas campestris* pv *vesicatoria*	M/S M/S M L/M	CP (2.5)	C = F > N	12 (MI)
Tomato (1)	Chlorothalonil + copper resinate (12,F,E)	2.34 + 2.24	*C phomoides* + *S lycopersici*	M/S M	CP (7.6)	C = F > N	11 (MI)
Tomato (1)	Mancozeb + tri-basic copper sulfate (12,W,W)	1.79 + 2.24	*A solani* + *C phomoides* + *S lycopersici* + *X c* pv *vesicatoria*	M/S M/S M L/M	CP (7.6)	C = F > N	11 (MI)
Tomato (1)	Mancozeb + tri-basic copper sulfate (12,F,W)	2.17 + 2.24	*A solani* + *C phomoides* + *S lycopersici*	M/S M/S M	CP (7.6)	C = F > N	11 (MI)
Tomato (1)	Mancozeb + tri-basic Cu (10,F,W)	2.9 + 2.24	*A solani* + *S lycopersici* + *C phomoides* + *X c* pv *vesicatoria*	M/S M/S M L/M	CP (2.5)	C = F > N	12 (MI)

[a] NA = information not available, E = emulsifiable concentrate, F = flowable, S = solution, W = wettable powder.
[b] L = low, M = moderate, S = severe.
[c] CP = center pivot, ISH = individual sprinkler head, LR = lateral roll, SS = solid set.
[d] C = conventional application, F = chemigation with fungicides, N = no fungicide treatment.
[e] Pathogen not specified.
[f] After 6th, spray rate of chlorothalonil increased to 2.34 kg ha^{-1}.

According to Easton and Nagle,[28] lack of early blight control on potato with fentin hydroxide may be explained by the fungicide having been applied before the presence of *A. solani* spores. In summary, if a fungicide had known efficacy on a foliage pathogen when applied by conventional methods, it usually provided disease control when applied by chemigation.

4 CHEMIGATION WITH FUNGICIDES VERSUS CONVENTIONAL METHODS

In 46 trials or treatments, conventional methods provided superior disease control to chemigation (Table 3); in 45 trials, chemigation and conventional methods were equally efficient (Table 4); and in 11 trials, chemigation was superior to conventional methods (Table 5). Diseases that were better con-

Table 5. Some details of studies were chemigation was superior to conventional methods in disease control

Crop (number of tests or treatments)	Fungicide (number of applications, formulation)[a]	Rate (kg ha^{-1})	Pathogen	Disease severity on control[b]	Irrigation system (mm)[a,c]	Yield[a,d]	Reference (USA state, or country)
Dry beans (1)	Benomyl + mancozeb (3,W,W)	0.15, 0.25, 0.35 + 2.0	*Erysiphe polygoni*	M	CP (4.9)	F > C = N	8 (Brazil)
Dry beans (1)	Thiophanate methyl + chlorothalonil (3,NA,NA)	0.28 + 0.7	*E polygoni*	M	CP (4.9)	F > C = N	8 (Brazil)
Peanut (1)	Chlorothalonil (NA,F)	1.24	Leaf spot[e]	M/S	CP (NA)	F > C > N	30 (AL)
Peanut (1)	Cyproconazole (7,S + oil)	0.112	*Cercosporidium personatum*	S	CP (2.5)	C = F > N	9 (GA)
Potato (1)	Chlorothalonil (2,F)	1.17	*Alternaria solani*	S	CP (8.0)	C = F = N	15 (CO)
Potato (1)	Chlorothalonil (2,F)	1.17	*A solani*	M	CP (8.0)	C = F = N	15 (CO)
Potato (1)	Chlorothalonil (12,F)	1.26	*Botrytis cinerea*	M	SS (1.1)	C = F > N	33 (MI)
Potato (1)	Fentin hydroxide (12,W)	0.33	*A solani*	M/S	CP (8.6)	N = C > F = N	20 (WI)
Potato (1)	Fentin hydroxide (14,W)	0.33	*A solani* + *B cinerea*	M L/M	SS (0.4)	F ⩾ C ⩾ N	18 (MI)
Potato (1)	Mancozeb (12,F) + metalaxyl (6,E)[f]	1.81 + 0.84	*A solani*	M/S	CP (8.6)	C = F = N	20 (WI)
Tomato (1)	Chlorothalonil + copper resinate (12,F,E)	2.34 + 2.24	*A solani* + *Xanthomonas campestris* pv *vesicatoria*	M/S L/M	CP (7.6)	C = F > N	11 (MI)

[a] NA = information not available, E = emulsifiable concentrate, F = flowable, S = solution, W = wettable powder.
[b] L = low, M = moderate, S = severe.
[c] CP = center pivot, SS = solid set.
[d] C = conventional application, F = chemigation with fungicides, N = no fungicide treatment.
[e] Pathogen not specified.
[f] Mancozeb weekly plus metalaxyl bi-weekly.

trolled by conventional methods included downy mildew [*Pseudoperonospora cubensis* (Berk & Curt) Rostov] on cucumber, angular leaf spot [*Phaeoisariopsis griseola* (Sacc) Ferraris] and Alternaria leaf spot (*Alternaria spp*) on dry beans, late leaf spot [*Cercosporidium personatum* (Berk & Curt) Deighton] on peanut, and early and late blight on potato (Table 3). However, in only six trials (one with cucumber and five with peanut) did fungicides applied by conventional methods result in yields higher than those obtained by chemigation. On the other hand, chemigation provided higher yield in three trials with peanuts despite less disease control. The higher yield of dry beans with chemigation[8] occurred due to the superior control of powdery mildew provided by this method of application in comparison to ground sprayer (Table 5). PASS provided superior leaf spot control and yield to chemigation with chlorothalonil but it was inferior in relation to conventional methods.[7,23]

Control of leaf spot, primarily late leaf spot, is difficult because pathogens produce spores in large numbers on the lower leaf surface, and it is difficult to apply fungicides on the underside of the leaves even with a well-designed ground sprayer.[30] Chemigation has been tested as an alternative with the advantage over the conventional methods of providing total wetting of the leaves. However, it seems that a high concentration of fungicide on foliage is necessary in addition to total wetting of the leaves. The exact density of chlorothalonil needed on peanut foliage to prevent infection by *Cercosporidium* spores is unknown.[24] The fungicide levels probably vary depending upon genotype, growth stage, environmental conditions, and uniformity of distribution of fungicide on the leaf surface. Under Georgia conditions,[24] it seems that 1–2 µg of chlorothalonil per cm^2 of leaf area (if deposited uniformly) is required to ensure protection of peanut cv. Florunner. That density on leaves is not achieved when commercial formulations of chlorothalonil are applied by chemigation even with the lowest volume of water that can be applied by a center pivot irrigation system. An alternative to improve foliar retention of fungicide applied by irrigation water might be the mixture of a non-emulsifiable oil with the fungicide before injection into the water. Depositions of chemigated chlorothalonil applied as Bravo 500, Bravo 720, or Bravo 720 plus either an emulsifiable vegetable oil or a non-emulsifiable petroleum oil have been tested.[24] Both the non-emulsifiable and the emulsifiable oil increased the initial deposition of chlorothalonil, particularly in the upper canopy. However, residues of the fungicide apparently had less affinity for the peanut foliage and decreased at a higher rate than residues from application of either commercial formulation alone. According to the authors, detrimental interactions between the oils and the formulation adjuvants could enhance weathering of chlorothalonil residues. They also postulated that co-application of oil with chlorothalonil results in enhanced formation of conjugates or complexes that reduce the availability of chlorothalonil *per se* to the stripping solvent (toluene) used in the research.

Chemigation with systemic fungicides, however, is promising for late leaf spot control on peanut (Tables 4 and 5). According to Culbreath *et al*,[9] cyproconazole may be absorbed rapidly by the foliage or salvaged from the soil by root uptake and these factors could be an advantage in a year with frequent heavy rainfall. Application of SoyOil with cyproconazole *via* chemigation may also have enhanced control compared to cyproconazole applied by ground sprays. Use of oil as the diluent also increased the activity of tebuconazole against leaf spot.[31] Oil could increase the activity of systemic compounds due to improved penetration of the lipid layer of foliage as a result of altering the partition coefficient. Alternatively, the addition of oil could increase the efficacy of the fungicide by reducing its dispersion in the large volume of water applied as well as increasing its affinity for the plant surface.[31]

The number of successes with protectant fungicides applied through sprinkler irrigation for early blight control on potato (Tables 4 and 5) is higher than number of failures (Table 3). In general, when environmental conditions were favorable for development of a severe epidemic, the level of control provided by chemigation was inferior to that with conventional methods, but yield did not differ between the application methods. There were some indications that chlorothalonil and fentin hydroxide performed better in chemigation than captafol and mancozeb for early blight control on potato.

Applications of captafol and mancozeb in large volumes of water provided less late blight control on potato than did conventional application (Table 3). Fentin hydroxide was efficient only when applied in a small volume of water and disease was not severe (Tables 3 and 4). Chlorothalonil, however, was efficient even when applied in a large volume of water and disease was severe (Table 4). Captafol and mancozeb are more soluble in water (1.4 and 6.0 mg $litre^{-1}$, respectively) than fentin hydroxide (1.0 mg $litre^{-1}$) and chlorothalonil (0.6 mg $litre^{-1}$).[32] This difference among fungicides in water solubility might influence efficacy when they are applied through high volumes of irrigation water.

Influence of water volume on early and late blight control on potato by chemigation seems to depend, in part, on disease severity. Application in a large volume of water (8.6 mm) may have been responsible for lack of disease control when environmental conditions were favorable for a severe epidemic (Table 3).

In Michigan, control of Botrytis blight on potato with chlorothalonil or fentin hydroxide was equal to or better by chemigation with 1.1 mm of water than by ground sprayer (Tables 4 and 5). Apparently the good distribution of fungicide around the base of the plants provided by chemigation favored disease control.[33]

Aircraft have become widely used for fungicide applications on potato since overhead irrigation systems interfere with ground sprayer applications. Furthermore, tractor applications are associated with reduction of yield of potato in wheel rows.[33] On the other hand, ground spraying permits deeper fungicide penetration into the plant canopy than aircraft application, so protecting the lower leaves that are more susceptible to infection.[34] Chemigation, however, is superior to a ground sprayer in distribution of fungicide into the plant canopy[24] and does not have its disadvantages. Therefore, application of protectant fungicides through low volume of irrigation water for disease control on potato is promising, primarily in regions not prone to severe early and late blight.

Benomyl alone or combined with another fungicide, thiophanate methyl, and iprodione were efficient for white mold control on dry beans regardless of application method (Table 4). In general, attack by *S sclerotiorum* begins on the senescent flower parts. For this reason, an initial application is made during early bloom and, if conditions continue to be favorable for the disease, an additional application may be necessary. Application by aircraft is unsatisfactory since fungicides do not penetrate deeply into the plant canopy to protect the lower flowers. Fungicide application by tractor is impaired by the closure of rows when plants achieve the reproductive phase. Therefore, chemigation is also a practical method for white mold control on dry beans. Application of benomyl, vinclozolin, procymidone and fluazinan through center pivot is widely used in Brazil for white mold control on dry beans.

A few tests showed that rust control on dry beans by chemigation is promising (Table 4). Application of benomyl plus mancozeb or thiophanate-methyl plus chlorothalonil through a center pivot or by ground sprayer were equivalent for powdery mildew control on dry bean leaves, but chemigation was superior to ground sprays in controlling the fungus on pods. Consequently, in the chemigation treatments, seeds were heavier and had fewer spots caused by the pathogen (Table 5).

Studies carried out in Michigan showed that diseases of tomato could successfully be controlled by protectant fungicides applied *via* center pivot in 2.5 or 7.6 mm of water (Tables 4 and 5). Even in one situation when the conventional method was superior to chemigation for bacterial leaf spot (*Xanthomonas campestris* pv *vesicatoria* (Doidge) Dye) control, yields achieved did not differ between the two application methods and were superior to the control (Table 3). In summary, if a fungicide had known efficacy on a foliage pathogen when applied by conventional methods, it has usually provided disease control when applied by chemigation.

5 POSSIBLE EXPLANATIONS FOR EFFECTIVENESS OF CHEMIGATION WITH FUNGICIDES

Under conventional ground or aerial application, fungicides are normally applied in 30 to 1000 litre ha^{-1} of water. By chemigation, on the other hand, the minimum volume of water applied by some center pivots is 2.5 mm (25 000 litre ha^{-1} of water), which exceeds by at least 25 times the maximum volume of water used by conventional ground sprayers. Consequently, residues remaining on the foliage immediately after fungicide application[24] or one or two days later[3] are much greater when fungicide is ground-sprayed[3,24,35] and aircraft-applied[3] than when it is distributed through sprinkler systems.[3,24,35] However, the difference of residue density between methods tends to decrease with time. McMaster and Douglas[3] showed that two and 10 days after fungicide application through stationary systems (4200 litre ha^{-1}) or aircraft (28 litre ha^{-1}), chlorothalonil residues on foliage were 0.1 and 0.1 $\mu g\,cm^{-2}$ and 5.5 and 0.1 $\mu g\,cm^{-2}$, respectively. For ground spray (234 litre ha^{-1}), fungicide residues dropped from 5.8 to 1.4 $\mu g\,cm^{-2}$ in that period. One irrigation was done before the second residue evaluation. Moreover, according to Brenneman *et al*,[24] although chemigation (17 800 litre ha^{-1}) resulted in deposition of less chlorothalonil than ground spray (120 litre ha^{-1}) or PASS (1700 litre ha^{-1}), the differences were not as great as might be expected on the basis of spray volume alone. For example, the amount of water used for chemigation was 148 times the amount used for ground spray. Therefore, assuming that most of the water for chemigation runs off the plants, it might be theorized that there should be 148 times more chlorothalonil deposited with the ground spray than by chemigation. However, it was found that the actual differences were 27.5, 15.3 and 5.0 fold for the upper, middle and lower canopy layers, respectively. It was suggested that there may be partitioning of chlorothalonil to the leaf surface when it is applied in higher volumes of water. In addition, some systemic fungicides seem to be able to offset the potential of being washed from foliage when applied through chemigation by rapid absorption by plants and/or by root uptake from the soil.[9] Nevertheless, it is desirable to reduce the washing of fungicide from plants. For this reason, fungicide properties and formulation are the keys to the success of this technology. These factors must interact in order to minimize the removal of chemicals from the target. One approach that has shown promise in reducing the washing of fungicide from foliage involves the dilution of fungicides in a non-emulsified oil before injection into the irrigation water. The fungicide–oil, being insoluble in the water phase, is distributed through the water phase as discrete droplets. These droplets have a higher affinity for the plant than the water phase and are therefore removed from the water on contact with plants.[36] Also oil–fungicide droplets may improve penetration into the lipid layer of foliage.[9,31] Although little research has been focused on the oil–fungicide mixture, increase of efficacy of insecticides applied as non-emulsified oil formulations or as emulsified formulations applied with non-emulsified oil additives has been reported in some studies.[36,37] Additionally, adequate insect control was obtained with these non-emulsified formulations at one-quarter and one-eighth of recommended rates of the insecticides. These studies also suggested that volume of water used for application of oil–insecticide formulations does not affect insect control for volumes ranging up to 60 mm ha^{-1}.[2]

It seems that reduction of fungicide residue on foliage caused by the large volume of water used by chemigation might usually be offset by the following factors: (1) the fungicide is applied at the time of maximum leaf wetness when the fungus is most active; (2) nearly complete coverage is achieved due to redistribution on the leaf with successive droplets; (3) there is a great reduction of inoculum in the field by complete coverage of plants and plant residues on the soil surface;[38] (4) some fungicides applied by chemigation can provide better control of soilborne pathogens than when applied by ground sprayer;[39] and (5) fungicides applied through continuously moving lateral sprinkler systems can generally be more uniformly distributed, since those systems apply water with high uniformity (CU = 80 to 90%). The CU for applications of water from a ground-based sprayer ranges from 50 to 92%, while the CU by aircraft is approximately 70%.[40] Furthermore, mechanical damage to the crop that can predispose plants to diseases,[13,23,33] and soil compaction by tractor tires that can reduce crop yield,[18,33,35] are avoided when fungicides are applied in irrigation water.

Prescription application, reduced application costs, and reduced operator hazards are important advantages of chemigation. If pesticides are applied through an irrigation system, savings of 29–78% in application costs may result.[41] On the other hand, this technique has disadvantages that include the following: results of research are limited, chemigation is not viable for control of all diseases, chemigation can be more hurtful to antagonistic micro-organisms in the soil, both irrigation and fungicide application must be needed simultaneously to take maximum advantage of chemigation with fungicides, and more time is required to apply fungicide by irrigation water than by aircraft. Moreover, certain safety factors must be considered, and a high level of management is required, but the benefits of chemigation should outweigh the disadvantages for many growers.

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