Meta-Analytical Approaches to Assess the Efficacy of Organic Foliar Treatments for Management of Black Rot in Cabbage

Ariana A. Abbrescia

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Abstract

Brassica black rot (*Xanthomonas campestris pv. campestris*) is widely considered one of the biggest pathological threats to cabbage production worldwide. In order to inform recommendations for best management practices in organic systems, we conducted a scoping review of web-based efficacy studies and performed multiple three-level multivariate meta-analyses to synthesize available report data on the comparative efficacy of organic foliar treatments in managing black rot disease severity, as well as subgroup analyses of potentially moderating effects. We extracted data from 12 available reports published in the online *Plant Disease Management Reports* (PDMR) database that assessed treatment efficacy in managing black rot on cabbage, which took place across the central and eastern United States between 2007 and 2020. Foliar treatments, including copper-based compounds, biologicals, extracts, oils, biopesticides, and sulfur-containing compounds, were grouped by Fungicide Resistance Action Committee (FRAC) Codes and Modes of Action (MOA). Moderator variables included year, variety, region, number of applications, and total precipitation, and average temperature.

Our scoping review of web-based databases yielded an insufficient number of records suitable for inclusion in a meta-analysis, but provided a model for future investigations to explore products in research and development, as well as potential topics for meta-analyses of disease management in topics with more robust data availability. Our meta-analysis of PDMR reports provided information about the overall, comparative, and moderating effects of treatment efficacy in this pathosystem. The application of organic foliar treatments significantly reduced disease severity overall, and resulted in an estimated mean reduction in disease severity of 41.7%. Coppers showed the most consistent and significant reduction in

disease severity, while multimodal Bacillus spp. were categorized as among the highest efficacy estimates as well as having the greatest variability across efficacy rankings. Further investigation of treatment efficacy and associated trends, given the addition of trial data including multiple treatment groups, could be used to validate and build upon the findings of this study.

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Chapter 1: Organic Management of Brassica Black Rot on Cabbage: A Literature Review

1.1 Cabbage

1.2 Cabbage Overview

The Brassicaceae family, containing 338 genera and over 3,7000 species, includes multiple agriculturally-significant species in cultivation worldwide (Al-Shehbaz, Beilstein, and Kellogg 2006). The most widely cultivated vegetable crop in the Brassicaceae family is *Brassica oleracea*, which includes broccoli, Brussels sprouts, cabbage, cauliflower, and kale (Golicz et al. 2016). Of these crops, cabbage (*Brassica oleracea* L. *var. capitata*) is one of the most popular culturally and economically-important staples globally, providing a host of health benefits and an affordable food source to consumers (Moreb et al. 2020).

In 2021, the United States was the tenth-largest producer of cabbage in the world, with a fresh market production value of over $433 million (USDA NASS 2022). Out of all state cabbage producers, Wisconsin ranked fourth in 2021, producing 8.7% of the U.S. supply (USDA 2021). In the past decade, both the United States and Wisconsin have seen an increase in organic cabbage production. The US acreage dedicated to organic cabbage production has more than doubled from 1,534 acres in 2011 to 3,187 acres in 2021 (USDA 2011). In Wisconsin, the acreage and number of operations producing organic cabbage is also increasing; 205 acres of organic cabbage were harvested in 2021, compared to just 46 acres in 2011. Across the state, the amount of certified organic operations harvesting cabbage also increased from 26 to 112 operations between 2011 and 2021.

1.3 Cabbage Production Challenges in the United States

There are several challenges that impact cabbage production in the United States. Drought conditions and soil saturation can reduce cabbage biomass production and affect nutritional quality (Barber and Müller 2021). Both of these conditions have been and will continue to become increasingly common in certain regions across the country as a result of climate change (Rohde 2023). Cabbage plants are sensitive to soil compaction, which can reduce both biomass and marketable yield in affected fields (Wolfe et al. 1995). Weed competition for moisture and nutrients can also reduce cabbage growth and yields (Abernethy and Mitchell 1992).

Cabbage production is also impacted by several pests and diseases of concern. Caterpillar pests, aphids, flea beetles, and thrips can cause significant damage to a field if left unmanaged (Colquhoun et al. 2022). Cabbage plants are also susceptible to a number of fungal, bacterial, and viral diseases that can widely impact quality and yield.

2.1 Brassica Black Rot

2.2 Black Rot Overview

Of the many diseases of brassica, Brassica black rot (*Xanthomonas campestris pv. campestris)* is considered to be one of the most important diseases worldwide (Williams 1980). Black rot is a disease caused by *Xanthamonas campestris pv. campestris* (XCC), a gram-negative bacterium. It affects a variety of brassica species, with *Brassica oleracea* serving as its most economically important host (Vicente and Holub 2013). Black rot progression in a field can threaten production and returns, resulting in yield loss via premature defoliation and a reduction in head quality (Gupta, Vikram, and Bharat 2013). Early infection can also significantly decrease seedling biomass and photosynthesis (Vega-Álvarez, Francisco, and Soengas 2021). Without proper management, significant losses can occur; one early report from Florida estimates reductions in marketable yield between 50 and 70 percent (Jorgensen and Walter 1954).

The disease was first described in 1894 on cabbage in Kentucky, USA (Garman 1894), and was first formally reported in Wisconsin in 1898 after causing significant damage in the southeastern portions of the state (Russell 1898; Smith 1898). By 1904, black rot presence was reportedly widespread east of the Mississippi river (Harding, Stewart, and Prucha 1904). In the century since, black rot has continued to spread and is now identified globally on brassica crops (J. G. Vicente et al. 2001). Black rot became a more significant issue in the Midwest in the 1960s and 1970s, when the use of untreated and untested seed in transplant production led to more widespread outbreaks (Lange 2010). There was a

particularly notable and major outbreak of black rot in Wisconsin in 1973, when the pathogen spread from infected early season transplants to main crop seedbeds (Williams 1980). Today, black rot is both present and of significant concern in Wisconsin; in a 2019 DATCP report, 46% of cole crop samples across four Wisconsin counties were infected with black rot (Wisconsin Department of Agriculture, Trade and Consumer Protection 2019). The disease has been identified as one of the most significant disease threats to cabbage in the state, with the potential to infect and affect entire fields (Delahaut 2003; O'Rourke, Delahaut, and Hutchinson 2003).

2.3 Black Rot Epidemiology

Cabbage seedlings can be infected systemically by being grown from infected seed, or secondarily transmitted during production. During transplant production, bacteria can enter the plant through the stomates of the cotyledons (Lange 2010). In seedlings, infection can first appear as stem stunting, blackening of the cotyledons, yellowing of leaves, or blackening of veins, and eventually can cause wilting or death (Dániel-Gómez, Reeves, and Meadows 2022).

Figure 1: Foliar lesions associated with XCC in cabbage (Gerald Holmes 1998)

In mature plants, there are two primary methods of infection. If the bacteria enters and infects the plant through the hydathodes, openings on the leaf edges, the first sign of disease is yellowing on the leaf margins, which will progress to V-shaped lesions with yellow edges and dry, brown interiors (Fig. 1) (Pape 2021). If the plant is infected through wounds to the vascular system, including insect damage, mechanical wounding, root injury, or hail, leaf yellowing and wilting may precede marginal lesions (Carisse et al. 1999).

As the vascular infection progresses, the veins, stems, and roots of a plant can become black as the bacteria produces xanthan, an exopolysaccharide essential to *Xanthomonas* infectivity through several methods, including xylem plugging, biofilm formation and suppressing callose deposition (Sutton and Williams 1970; Yun et al. 2006; Bianco et al. 2016). In later stages of disease, cabbage plants can become stunted, chlorotic, wilted, or die (Dániel-Gómez, Reeves, and Meadows 2022). Secondary soft-rotting infections from *Pseudomonas* and *Erwinia* species can occur in progressed cases of black rot (Rimmer, Shattuck, and Buchwaldt 2007), and these diseases can often be observed as a complex of co-infecting pathogens in later stages of production.

In cabbage grown for seed, the seeds can also become infected through the flower stalk, endangering the health of future crops (Kocks 1998). Infected seed is widely considered to be the primary source of infection from which long distance black rot spread and subsequent epidemics occur (Cook, Larson, and Walker 1952; Schaad 1980; Roberts et al. 1999; Dániel-Gómez, Reeves, and Meadows 2022). Once established in a field, the bacteria exits the hydathodes of infected plants, spreading several meters primarily through splashing rain and irrigation water, but also being transmitted by insects, equipment, and

clothing (Pape 2021). It can survive on and spread from soil-bound brassica debris for up to two years (Schaad and White 1974; Dzhalilov and Tiwari 1995). Black rot is also known to infect several weeds that can serve as reservoirs for the disease (Koike 2017). The disease develops best in warm, humid conditions, historically causing the most destruction in tropical and subtropical climates (Williams 1980). For this reason, the disease can cause significant damage in greenhouses, where these favorable conditions are often present (Roberts et al. 1999). As an effect of climate change, these favorable conditions will also become increasingly common in more northern latitudes, favoring black rot progression and subsequent crop losses (Joana G. Vicente and Holub 2013). Several management strategies, such as seed treatment and testing, cultural management techniques, and foliar treatments, have been developed and commonly adopted to prevent and slow disease development.

3.1 Management of Brassica Black Rot

3.2 Cultural Management

There are several strategies that vegetable growers can use to reduce XCC inoculum, decreasing favorable conditions for disease development, and slowing the spread of disease. This process begins with the selection of certified disease-free seeds, as well as transplants inspected for signs of black rot and grown under optimal conditions for disease exclusion. Cabbage seed can also be home-treated by soaking for 25 minutes at 122ºF with hot water to reduce black rot inoculum (Colquhoun et al. 2022). Transplants can also be certified disease-free, and should not be planted if they show signs of black rot. There are several available

varieties of fresh market, storage, and processing cabbage that have moderate-to-high disease tolerance to black rot, which can be selected for use to effectively reduce infestations (Seaman 2016).

When selecting a site to plant cabbage, growers can consider the planting history of a field to mitigate disease risk. Rotating away from susceptible brassica crops for three or more years can prevent outbreaks caused by infected plant debris in the soil. Planting late-season varieties upwind from early-season varieties can prevent spread, while selecting sites with proper drainage and airflow can reduce favorable conditions for disease development (Seaman 2016).

Opting for drip irrigation, or overhead irrigating in the morning, can also prevent long periods of leaf wetness. Providing proper plant nutrition, as well as engaging in cropping strategies that enhance the biodiversity of soil and foliar microorganisms, can also support disease prevention and management (Koike 2017). Growers can limit the spread of disease throughout the farm by avoiding scouting and working with plants when foliage is wet. Infected plants can be removed from the farm or burned, and crop debris can be destroyed, deep plowed, or disked to reduce on-farm inoculum. Host weeds can also be removed to reduce inoculum.

3.3 Organic Chemical & Biological Management

Many of the currently available foliar and seed treatments for black rot are comprehensively outlined in Liu et al. (2022), which provides the informational basis for several product categories outlined below.

3.3.1 Seed Treatments

Hot water treatment is the primary and most accessible method of treating seeds for black rot. The process of hot water seed treatment was first formally documented in 1888 by Jensen, and was first formally found to have a lethal effect on XCC in 1923 (Jensen 1888; Walker 1923). Numerous trials have shown the efficacy of hot water treatment in preventing disease development on cabbage and other brassicas (Lockhart, Gourley, and Chipman 1976; Sharma 1981; Nega et al. 2003; Mandiriza, Kritzinger, and T.A.S. Aveling 2018). There have been some reports of a reduction in germination, which can be mitigated by proper timing and heat control, with current cabbage guidelines recommending treating at 112ºF for 25 minutes (Bradford et al. 2023). Current management guidelines advocate for the hot water treatment of cabbage seed to reduce XCC inoculum (Delahaut 2003; Bradford et al. 2023).

Seed soaks including a calcium hypochlorite slurry and 3% hydrogen peroxide have also been shown to prevent XCC infection (Schultz, Gabrielson, and Olson 1986; Sanna et al. 2022). Various synthetic seed treatments, such as streptocycline, chloramphenicol, mancozeb, Validamycin-A, and acibenzolar-S-methyl have been used to manage black rot, though these products are not approved for organic use.

3.3.2 Foliar Treatments

Coppers:

The 2023 Wisconsin Commercial Vegetable Production Guide (Bradford et al. 2023) lists several strategies to manage brassica black rot, with 'fixed coppers' listed as the only recommendation for foliar products. The vegetable disease section of this guide is not a comprehensive listing of inputs to manage disease, rather it is offered by vegetable extension pathologist Amanda Gevens of UW-Madison Plant Pathology as a listing of treatments with evidence of effectiveness and appropriate fit in the agricultural ecosystem. Copper products are recommended to prevent the spread of black rot; active ingredients such as basic copper sulfate, copper hydroxide, copper oxychloride, copper sulfate pentahydrate, and cuprous oxide are commonly used, and have been shown to reduce XCC populations and prevent spread in both transplants and adult cabbage populations (Lange 2010, Vincent et al. 2018). Proper timing of copper applications is imperative; coppers do not provide proper management of XCC in persistently wet conditions, and cannot prevent disease development in plants that are already infected (Seaman 2016). Copper application can at times lead to phytotoxicity, resulting in plant injury that could impact marketability (Kemble et al. 1999; Bradford et al. 2023).

Copper resistance has become a growing concern in the management of numerous vegetable diseases, including brassica black rot (Lugo et al. 2013; Toporek and Keinath 2022). The extensive use of copper-based bactericides has facilitated copper resistance in numerous pathosystems, with the evolution of diverse resistance mechanisms in response to

varied environmental and host conditions (Fan, Saleem, and Zou 2022). In cabbage production systems, this could lead to the reduced reliability and efficacy of copper products.

Microbial Biologicals:

Two primary genera of bacteria are used to manage brassica black rot: *Bacillus* and *Pseudomonas*. *Bacillus* have been shown to possess inhibitory effects against XCC *in vitro* (Wulff et al. 2006; Ghazalibiglar et al. 2016; Li'aini et al. 2017). *In vivo*, *Bacillus* strains and their supernatant have the potential to reduce black rot severity and incidence, though factors like crop species, application style, soil type, and other growing conditions can affect their efficacy (Wulff et al. 2002; Massomo et al. 2004; Sain, Gour, and Sharma 2007; K. Liu et al. 2016; da Silva et al. 2018). Studies investigating *Pseudomonas* tell a similar story; *in vitro* studies show inhibition, and *in vivo* studies demonstrate the potential of both *Pseudomonas* strains and their cell-free medium (Mishra and Arora 2012; K. Liu et al. 2016; Umesha and Roohie 2017; Jelušić et al. 2021).

Bacteriophages have also been investigated for their potential to manage XCC (Marroni and Germani 2014; Nagai et al. 2017; Holtappels et al. 2022). Several bacteriophages have been approved for use in fruit and vegetable disease management, although no bacteriophage products for brassica black rot are currently commercially available (Jagannathan, Dakoske, and Vijayakumar 2022).

Biopesticides:

Several products containing hydrogen peroxide and peroxyacetic acid (PAA) are on the market for organic use in managing brassica black rot. Hydrogen peroxide and PAA disrupt

cellular structure and function, and are labeled for use to both prevent and manage bacterial and fungal diseases of vegetables (Juven and Pierson 1996; OMRI 2000).

Extracts & Oils:

Giant knotweed (*Reynoutria sachalinensis*) extract is one of the main extracts used in black rot management in brassicas. It is known to induce plant defenses when applied, supporting resistance against plant pathogens when applied preventatively or during early stages of infection (EPA 2010; Margaritopoulou et al. 2020). Other plant oils, including clove oil (eugenol), thyme oil (thymol), and geraniol, have multiple modes of action, and are known to interfere with cellular function and biosynthesis.

Sulfurs:

Sulfurs have been used for thousands of years to manage pests and diseases in agriculture (Williams and Cooper, 2004). Sulfur inhibits pathogen development by disrupting electron transport and producing a byproduct that is toxic to bacteria and fungi (Wang et al. 2022).

4.1 Research Justification

Brassica black rot, along with many other prevalent vegetable diseases, presents a significant challenge to vegetable growers in Wisconsin and across the United States. Changing climatic conditions can create favorable conditions for plant stress and pathogen development, exacerbating disease issues and creating an unreliable environment for grower management planning (Hunjan and Lore 2020). Pesticide and fungicide resistance have also become a growing concern, reducing the reliability of products that have historically provided ample protection against and prevention of diseases (Hahn 2014; Ma et al. 2021). As such, effective pest and disease management is a high priority, and often a critical issue for successful cabbage production.

Organic vegetable growers can face additional management challenges, including increased fluctuation in pest and disease pressure, the inability to rely on often more consistently effective and well-studied synthetic treatments, and greater complexity in managing diversified production systems (Koike 2017). As a result, successful organic management of vegetable pests and diseases is predicated upon comprehensive research and understanding of these pathosystems and production strategies, as well as the following development of practical, accessible, and informed resources for growers. Extension materials are often available online and in print to vegetable growers, often with varying degrees of recency and ease of access. Available recommendations are often based on the results of a number of university-managed field trials, with data that may not be accessible to the general public, or applicable to different production systems and regions of the country.

Within this context, organic vegetable growers in Wisconsin have expressed the need for centralized, online pest and disease management resources, and research-based management recommendations for the pests and diseases of highest concern in the state. An advisory board of these organic vegetable growers directed several objectives for this project to research and develop these desired resources. In particular, this group suggested the exploration of meta-analytical methods as a tool for identifying and highlighting the most appropriate and functional tools for disease control. In addition, this group identified brassica black rot as a disease of interest for local vegetable production systems. The following meta-analysis approach aims to investigate this approach, using brassica black rot as a model pathogen and several meta-analyses in plant pathology as foundational models for this pursuit.

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Chapter 2: Multiple Meta-Analyses Assessing the Efficacy of Organic Foliar Treatments for Black Rot on Cabbage

Introduction

1.1 Black Rot Overview

Brassica black rot is caused by the gram-negative bacterium *Xanthomonas campestris pv. campestris* (Pammel) Dowson (XCC), and is regarded as one of the most important diseases of brassicas in the world (Williams 1980). The progression of black rot in a field can cause marketable yield loss through early defoliation and a decline in head quality, as well as inhibit seedling development (Gupta, Vikram, and Bharat 2013; Vega-Álvarez, Francisco, and Soengas 2021).

Black rot is both present and remains as a significant concern in Wisconsin, posing serious production challenges for the cabbage industry in the state, which has an annual production value worth $29.6 million (Delahaut 2003; O'Rourke, Delahaut, and Hutchinson 2003; Wisconsin Department of Agriculture, Trade and Consumer Protection 2019). These challenges are further compounded by changing climatic conditions and the associated prevalence of ideal conditions for pathogen growth and plant stress, as well as an increase in pesticide and fungicide resistance across numerous pathosystems (Hahn 2014; Hunjan and Lore 2020; Ma et al. 2021). Organic vegetable growers can face additional disease-related challenges in successful production, including a smaller pool of available foliar products and often more complex and comprehensive management requirements in well-functioning

diversified production systems (Koike 2017). Taken together, these obstacles to a resilient vegetable production system in Wisconsin and beyond necessitate a responsible and thorough approach to the management of black rot and other vegetable diseases. This in turn requires the research and development of practical and functional management best-practice recommendations for growers.

1.2 Foliar Treatment Overview

Cabbage growers can employ a number of techniques to reduce XCC inoculum, mitigate favorable conditions for disease development, and limit the spread of disease. Strategies include seed treatment and the purchase of certified disease-free seed and transplants, tolerant variety selection, moisture and airflow management, proper planting and rotation practices, and the thorough disposal of diseased material (Mew and Natural 1993; Seaman 2016).

Table 1: Organic foliar treatments assessed by Plant Disease Management Reports in management of Brassica black rot (XCC)

MOA[1]	**Description**	**FRAC** [2]	**Description**	**Active Ingredients**
BM	Biologicals with multiple modes of action	BM01	Plant extracts	Plant oils: Clove oil (eugenol), thyme oil (thymol), geraniol
		BM02	Microbial	*Bacillus amyloliquefaciens, Bacillus subtilis*
NC	Not classified	NC	Biopesticides	Hydrogen Peroxide, Peroxyacetic Acid
P	Host plant defense induction	P05	Anthraquinone elicitors	Giant knotweed (*Reynoutria sachalinensis*) extract
		P06	Microbial elicitors	*Bacillus mycoides* isolate J
M	Chemicals with multi-site contact activity	M01	Coppers	Basic copper sulfate, copper hydroxide, copper oxychloride, copper sulfate pentahydrate, and cuprous oxide
		M02	Sulfurs	Sulfur

[1] Mode of Action
[2] Fungicide Resistance Action Committee Code

Organic vegetable growers also can select from numerous available foliar treatment options with the intent to prevent and limit the spread of black rot. This includes biologicals, biopesticides, coppers, extracts, oils, and sulfurs (Table 1). These products show varying

degrees of reported efficacy in university-led field trials, when reported, and up-to-date recommendations for use tend to vary by extension source (Seaman 2016; Bradford et al. 2023). A comprehensive synthesis of available organic treatment efficacy data and associated treatment options for black rot on cabbage has not yet been conducted.

Foliar treatment products can be categorized by biochemical mode of action (MOA) and Fungicide Resistance Action Committee (FRAC) code. Multiple unique FRAC codes can be grouped by the same MOA; for example, both giant knotweed (*Reynoutria sachalinensis*) extract (P05) and *Bacillus mycoides* isolate J (P06) are both grouped as host plant defense inducers (P) for MOA.

1.3 Meta-analyses in Agricultural Science

A meta-analysis is a research tool used to synthesize research findings across multiple independent sources. It does so by estimating effect sizes, or magnitudes of effect between two treatments, then weighing each effect size with a calculated variance associated with its respective study or report (Harrer et al. 2021). These effects can then be summarized, compared, or analyzed based on present moderating factors across studies.

Meta-analyses have been used in plant pathology for over twenty years, as documented in Ngugi et al. (2011). These meta-analyses are typically used to make three kinds of inquiries: i) assessing comparative treatment efficacy (most common), ii) quantifying relationships between disease variables or with agronomic outcomes like yield, and iii) investigating factors impacting the relationship between a pathogen and an associated treatment. A number of meta-analyses involving treatment efficacy analyze the data collected

from internal university trials conducted over several years (Paul et al. 2008; Edwards Molina et al. 2019; Dangal 2022). Other studies such as Ngugi et al. (2010) and Toporek and Keinath (2022) assess report data made available through the Plant Disease Management Reports (PDMR) database, which was previously known as the F&N and B&C Tests reports until 2007. These reports provide relatively uniform trial data, and are published regardless of product efficacy, making them an ideal candidate for meta-analytical research. In more traditional meta-analysis across ecological fields, including entomological analyses such as Lowe et al. (2021), relevant studies are collected from one or more database searches using refined strings of search terms. These more complex analyses pull from a wider range of data formats and study subjects, and often rely on a more robust pool of accessible research in their respective fields. This method of search and screening is not often, if ever, used in plant pathological meta-analyses, which rely on university-led trials or standardized online reports instead.

Two primary characteristics of meta-analytical models include fixed effects and random effects, which rely on different assumptions in the inclusion of study effects (Harrer et al. 2021; Toporek and Keinath 2022). A traditional fixed effects model makes the assumption that all of the studies included in a meta-analysis belong to a homogenous population with one true overall effect size, and the source of variation in effect sizes is due to individual sampling error in each study. In contrast, a traditional random effects model assumes that included studies belong to a heterogenous population with a distribution of true effect sizes, from which the mean effect of the distribution is calculated. In a random effects

model, the source of variation can belong to sampling error and an additional error term that accounts for this distribution of effect sizes.

The three-level meta-analytical model selected for use in this study has been widely employed in meta-analyses of fungicide efficacy data (Toporek and Keinath 2022; Machado et al. 2017; Edwards Molina et al. 2019; Paul et al. 2010). It functions particularly well when working with multi-arm studies, which include multiple treatments that are compared to one untreated control within each study. This is because a three-level meta-analysis adds an additional, third level to the model that accounts for this within-study 'clustering' of treatment effects (Harrer et al. 2021). As a result, this model accounts for two sources of heterogeneity: within-study heterogeneity and between-study heterogeneity, resulting in a more accurate depiction of variation and dependence among studies and treatment comparisons.

This model can also be used to perform subgroup analyses of included effects, using both categorical and continuous variables that are present across studies to assess sources of heterogeneity and potential trends. This is done by creating a mixed effects model, which involves the addition of a predictor variable (β) to the model equation (Harrer et al. 2021).

1.4 Objectives

In this study, we aimed to assess the accessibility of fungicide efficacy trial data for organic management of Brassica black rot, as well as explore the feasibility of meta-analytical approaches to analyze organic treatment efficacy and moderating effects in trials. We

followed multiple meta-analytical methodologies to evaluate (i) the overall effect of organic foliar treatments, (ii) the comparative efficacy of individual treatments grouped by category, FRAC, and MOA, and (iii) the potential effects of moderating trial variables on overall and specific treatment efficacy. The results can be used to inform management recommendations for organic vegetable growers, as well as provide a more comprehensive framework for future endeavors in this form of research.

Methods

2.1 Scoping Review: Web-based Databases

2.1.1 Database Search Methods

We compiled references using the Web of Science Core Collection Database, CABI Abstracts, and Agricola using the following search string:

Table 2: Search terms used in scoping review grouped by search topic

Management	**AND**	**Disease**	**OR**	**Disease (Common Name) + Crop**
"control" OR "manag*" OR "suppress*" OR "reduc*"*	AND	*"Xanthomonas campestris pv. campestris" OR "X. campestris pv. campestris" OR ("XCC" NOT "citrus canker")*	OR	*"black rot" AND ("brassica oleracea*" OR "cabbage" OR "broccoli" OR "cauliflower" OR "kale" OR "brussels" OR "collard greens" OR "collards" OR "kohlrabi")*

2.2.2 Article Screening

The first author conducted a primary screening of articles by reading titles and abstracts. This screening excluded any articles that did not evaluate the effects of one or more foliar or seed treatments on in-vivo black rot development on cabbage, as well as those that were not available in English.

The remaining articles were read in full to determine if they were suitable for inclusion in a meta-analysis. Secondary criteria for inclusion required that articles were peer-reviewed, involved a greenhouse or field component, included at least one commercially available organic treatment, compared treatments to an untreated control, and included a minimum sample size of 3 replicates in both the treatment and control groups. We also

required that each study include a response variable related to disease control, including disease severity (%), incidence, or total yield, as well as a reported mean, and a measure of variance (standard deviation, standard error, standard error of the mean, confidence interval, or interquartile range), in the text, tables, or figures.

2.2 PDMR Meta-Analysis

2.2.1 Plant Disease Management Reports Search & Screening

We obtained trial data published in Plant Disease Management Reports (PDMR) from 2000 to 2021, using the keywords ““black rot” AND “brassica””. We then hand-searched these results for trials involving *Xanthomonas campestris* pv. *campestris* management on cabbage. Secondary screening criteria excluded reports that did not contain at least one organic treatment, did not contain an explicit or estimable measure of variance, or did not contain at least one of the following response variables: disease severity, incidence, or total yield.

2.2.3 Dataset Creation

Data were extracted from the remaining studies to create two datasets for disease severity corresponding to FRAC Code and MOA. We coded each treatment with its corresponding FRAC code and MOA, using “NC” (not classified) for any undesignated treatments. If multiple products within the same treatment were classified with the same FRAC code or MOA, the label was only listed once. If multiple treatments within the same study had the same designated FRAC code or MOA, these treatment means were averaged in order to allow for indirect comparisons of groups between studies. Disease severity data were extracted from the latest rating date for each study. For trials that included both non-inoculated and inoculated components for the same treatments, the inoculated treatment data were selected and extracted. We coded each treatment with associated categorical moderator variables, including region, variety, and number of treatment applications, as well as continuous variables including trial year, precipitation in inches, and number of applications.

Additionally, we coded each treatment with average temperature (ºF), which was estimated using the NOAA Statewide Time Series Tool. For each report, the month(s), year, and state in which the trial took place were used to estimate an average temperature during the trial.

Effect Size Calculations

For each PDMR report, each treatment group was associated with both an experimental mean disease severity averaged across replicates ($\underline{X_E}$), as well as a control mean ($\underline{X_C}$). When fitting a three-level model with this data, there are two primary options for effect size selection that require different assumptions and model-fitting. We explored both options by creating a model for each. One possibility is to fit the model to a response ratio as an effect size, in this case "L" and the variance of L (V_L), as is done in Toporek et al. (2022). This method allows for the estimation of overall treatment efficacy, comparative treatment efficacy, and subgroup analysis of continuous and categorical moderator variables in relation to efficacy. L was calculated for each treatment within each study using the reported disease severity values for both treatment and control:

$$\underline{L} = \ln (R) = \ln (\bar{X}_E / \bar{X}_C) \quad \text{(Equation 1)}$$

where $\bar{X}_E$ designates the mean disease severity of a treatment type, and $\bar{X}_C$ designates the mean severity for the non-treated control in that study. L was then averaged within treatment types FRAC or MOA as described previously.

Another possibility is to fit the model to ln ($\underline{X_E}$) (denoted as LOG(XE) in R) and the variance of LOG(XE), then set "control" (LOG(XC)) as a reference in our model software.

This method allows users to assess the comparative efficacy of FRAC and MOA groups without fitting a variance-covariance matrix for each study, instead using the variance of each mean.

Variance Calculations: Estimating LSD

In order to conduct a meta-analysis, each included study or group must be associated with some estimate of pooled sample variance (V). Of the 21 studies considered for analysis, none reported V. Pooled sample variance can also be directly calculated by several other reportable statistics, such as least significant difference (LSD). Only one study reported a statistic (LSD) from which we could calculate V.

Instead, most reports indicated mean separations based on multiple comparison tests such as Fisher's LSD, Tukey's HSD, or the Waller-Duncan test. In order to calculate pooled sample variance from these reports, we adopted and modified a method of estimating LSD developed by Ngugi et al. (2010). Of all employed multiple comparison tests, Fisher's protected LSD is the least conservative, and can be obtained from the same values presented by more conservative tests such as HSD or Waller-Duncan. In theory, the true LSD of a study lies between the smallest significant difference and largest nonsignificant difference. For each study, we calculated both the smallest observed significant difference and largest observed nonsignificant difference. We selected the larger of these two values to provide a more conservative estimate of LSD (ELSD). This method requires a study to report at least one significant mean separation in order to estimate LSD. For this reason, we had to exclude 3 of 15 studies from the disease severity dataset, 4 of 7 studies from the incidence dataset,

and all 5 studies from the total yield dataset. This rendered the incidence and yield datasets unsuitable for use. From these ELSD values, we calculated the pooled sample variance (V) for each study using the following formula also provided in Ngugi et al. (2010):

$$V = \frac{n \times \left(\frac{ELSD}{t_{0.975,df}}\right)^2}{2} \quad \text{(Equation 2)}$$

where n is number of replicates and $t_{0.975,df}$ is the calculated critical value for each study, using the number of treatments minus the number of replicates for df.

Variance of LOG(XE)

The variance of the log means (LOG(XE)) for each study was calculated using the methods described in Paul et al. (2008), where n is equal to number of replicates:

$$V_{LOG(XE)} = \frac{V}{n * X_E^2} \quad \text{(Equation 3)}$$

Variance in the LOG(XE)-based model was fit to this value.

Variance of L

Using this pooled sample variance value, we then calculated the estimated (sampling) variance of L for each treatment (V_L) using the following equation as described by Madden and Paul (2011) where n is again equal to number of replicates:

$$V_{\underline{L}} = \frac{V}{n} \times \left(\frac{1}{X_C^2} + \frac{1}{X_E^2}\right) \quad \text{(Equation 4)}$$

Because multi-treatment studies use the same control value to calculate $\underline{L}$ for each treatment, accounting for variance-covariance matrices for each study should be used to

address within-study effect size correlation and variance dependency, and avoid underestimating within-study variability. We then manually constructed a variance matrix including the covariance between controls for each study using a method similar to that used in the “VCALC” function in R, and fit the variance of our model to this object.

2.2.2 Model Selection

We selected and fitted two models as described in Toporek and Keinath (2022) and Harrer et al. (2021). Many treatment-efficacy reports such as those found in the PDMR include multiple unique treatments, and thus can contribute multiple effect sizes to a meta-analysis. These effect sizes are 'clustered' within each study. This introduces unit-of-analysis error, violating the assumption that each effect size in the meta-analysis is independent. A three-level multivariate meta-analysis accounts for clustered effect sizes by adding an additional level to a traditional random effects model and pooling the effect sizes within each study into "clusters" (Level 2), which are then pooled across studies (Level 3) (Harrer et al. 2021):

$$\hat{\theta}_{ij} = \mu + \zeta_{(2)ij} + \zeta_{(3)j} + \epsilon_{ij} \qquad \text{(Equation 5)}$$

In this model, $\hat{\theta}ij$ estimates the true effect size of i, which is nested inside the cluster j. The average overall population effect is represented by μ. $\zeta_{(2)ij}$ represents level 2 heterogeneity within a cluster, while $\zeta_{(3)j}$ represents level 3 heterogeneity between clusters. The sampling error of each study is denoted by ϵ_{ij}.

An additional three-level model was created to conduct subgroup analyses on the categorical variables including region, variety, and number of treatment applications, as well as continuous variables including trial year, precipitation in inches, average temperature in Fahrenheit, and number of applications:

$$\hat{\theta}_{ij} = \theta + \beta\chi_i + \zeta_{(2)ij} + \zeta_{(3)j} + \epsilon_{ij} \qquad \text{(Equation 6)}$$

In this model, θ indicates the model intercept, and β is the regression weight of χ_i, which is a predictor variable (Harrer et al. 2021; Toporek and Keinath 2022).

In exploring potential model options, we built and compared fixed and random effects models using “rma.mv” in R, as well as fixed and random effects models using “netmeta” in R. Although varying in function and assumptions, these models delivered very similar results in modeling FRAC efficacy and overall effect. As the “netmeta” function could not support subgroup analyses, we selected the “rma.mv” function of the R package “metafor” to fit both three-level models. In order to more accurately model and assess population heterogeneity within our dataset, we chose to set Level 2 (FRAC or MOA) and Level 3 (PDMR Study) as random effects, and level 2 was nested within level 3 using “random = ~ 1 | PDMR/FRAC” and “random = ~ 1 | PDMR/MOA”. We set the method for model parameter estimation to “REML”, or restricted maximum likelihood.

To evaluate the comparative efficacy of foliar treatments grouped by FRAC or MOA, we created two models using LOG_{XE} as our effect size, $V(LOG_{XE})$ as our variance, and control treatments (CON) were set as a reference. In order to isolate and compare treatments by FRAC and MOA, moderators in each model were set to “~ PDMR + FRAC - 1” and “~ PDMR + MOA - 1”, respectively, then FRAC and MOA were specified for a test of moderators and effect estimation in each model. The “-1” in each moderator string serves to remove the intercept automatically set by R, allowing for more straightforward interpretation of model results.

In order to assess the overall effect of organic treatment application, as well as subgroup analyses of moderating effects on treatment efficacy, we created a second model with $\underline{L}$ as our effect size and V_L as our variance. For analysis of overall effect, model results and variance estimates were recorded. For subgroup analyses, additional moderating models

were fit for each moderator variable by setting moderators to "~ FRAC + (Moderator) - 1" . Excluding 'number of applications', the moderator variables are each study-specific, and thus the effects would be confounded with the effects of study. For this reason, and unlike in the treatment efficacy analysis models, "PDMR" was removed from the moderating effects here. In order to further assess the differences between categorical moderator subgroups, we used the "emmeans" function in R to average results over the level of FRAC treatment groups to compare group estimates, setting df to the number of moderator groups minus one.

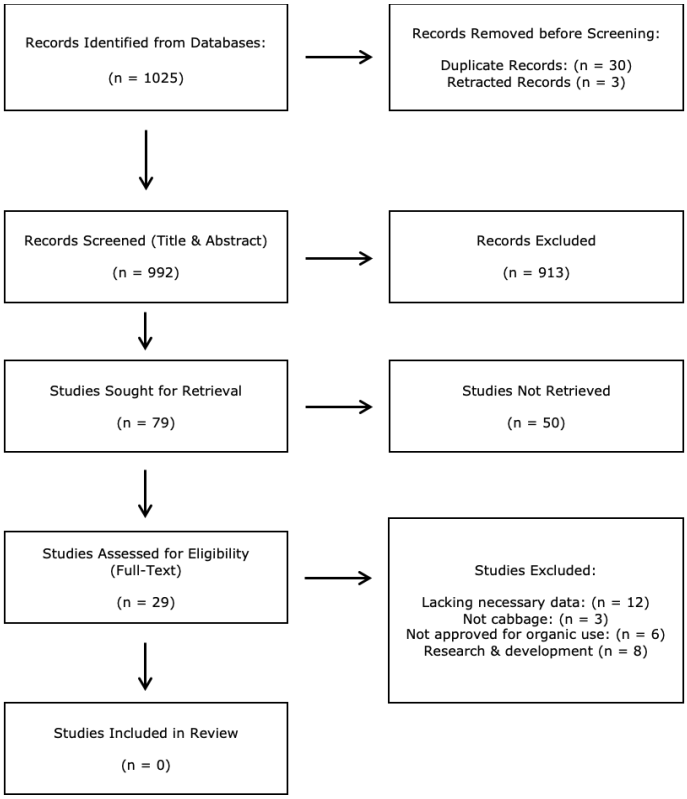
Finally, we explored the possibility of conducting subgroup analyses within a single treatment group to observe potential trends in moderating effects and subgroups. Because coppers (M01) were by far the largest FRAC group (n=10) included in our dataset, we selected that FRAC group for use in this analysis. A smaller data subset was generated from our larger dataset as described above, with one copper treatment group per study. This model was fit to L, but did not require a variance-covariance matrix, as there was only one treatment instance per study. As such, variance was fitted to V_L as previously described, with moderators set to "Year".

Results

3.1 Scoping Review Summary

The database search produced a total of 992 unique citations after deduplication (n = 30) and removing retracted studies (n = 3) (Fig. 2). The first screening of titles and abstracts excluded 92% of available records (n = 992). This removed studies that included the incorrect pathogen or crop, as well as those that focused on the *in vitro* effects of treatments, varietal resistance, XCC epidemiology or genetics, or reported on new outbreaks of the disease. This first screening yielded 79 potential articles to be read in full for secondary screening criteria, 50 of which were inaccessible for further screening. Several of these studies included English abstracts, but the reports themselves were not available in English.

Figure 2: PRISMA flow diagram for the web database scoping review process


Records Identified from Databases:
(n = 1025)
Records Removed before Screening:
Duplicate Records: (n = 30)
Retracted Records (n = 3)
Records Screened (Title & Abstract)
(n = 992)
Records Excluded
(n = 913)
Studies Sought for Retrieval
(n = 79)
Studies Not Retrieved
(n = 50)
Studies Assessed for Eligibility
(Full-Text)
(n = 29)
Studies Excluded:
Lacking necessary data: (n = 12)
Not cabbage: (n = 3)
Not approved for organic use: (n = 6)
Research & development (n = 8)
Studies Included in Review
(n = 0)

After screening and study retrieval, 29 studies remained for full-text evaluation of meta-analysis eligibility (Fig. 2). Of these studies, none were deemed fit for inclusion in a meta-analysis.

Twelve studies lacked the necessary data to conduct a meta-analysis. Several of these studies did not include an appropriate, comparable response variable such as disease severity, incidence, or total yield. Instead, this group comprised *in vitro* trials, germination assays, or used variable methods to calculate an external black rot index (EBRI), which could not be accurately compared in a meta-analysis. The remainder of these studies failed to report necessary data to conduct a meta-analysis, including number of replicates and variance.

Three studies did not include cabbage (*Brassica oleracea* L. *var. capitata*) in their trials. Instead, these studies used either Chinese cabbage (*Brassica rapa pekinensis*) or Kohlrabi (*Brassica oleracea* Gongylodes Group), which is also known as “turnip cabbage”.

Just under 25% of the eligible studies in review did not include an organic treatment (n = 6). Instead, these studies assessed the efficacy of synthetic antibiotics (agrimycin, streptocycline, carbendazim, benomyl, terramycin), nyolate seed treatments, validamycin A, and mancozeb.

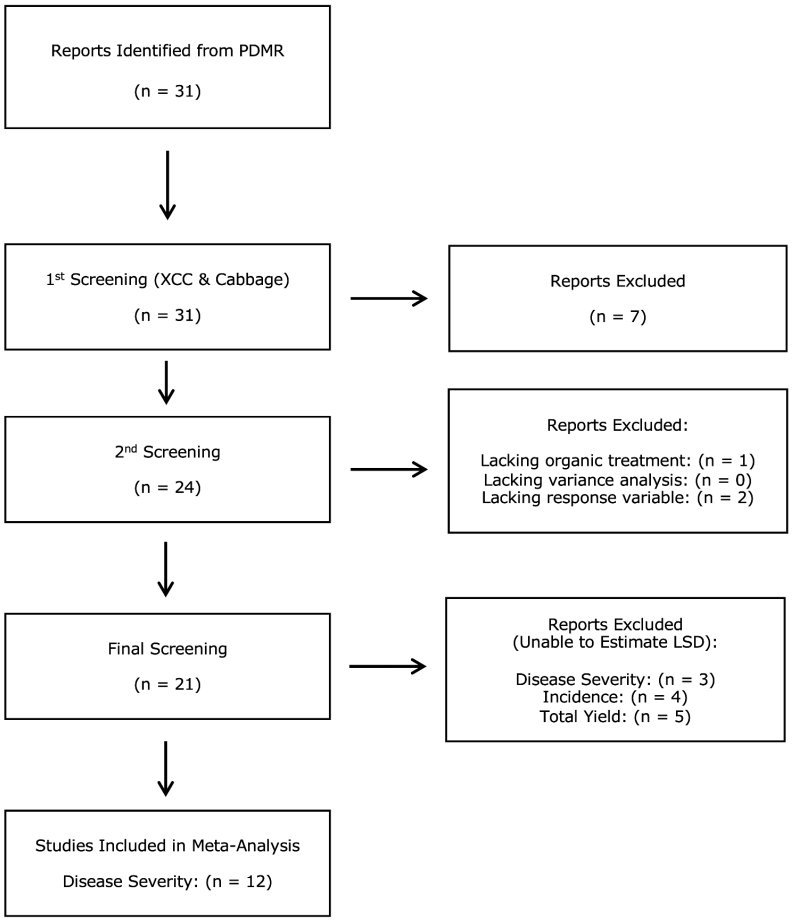
The remaining eight studies assessed materials that are not readily available for commercial use by organic growers, or were not deemed suitable for categorization alongside commercially available products. These studies assessed yeast isolates, UV-C, bacteriophages, electrically charged disinfectants, and multiple unique bacterial strains. Both Liu et al. studies assessed multiple strains and mixtures of plant growth-promoting rhizobacteria, which are available for commercial use. These studies both used a whole-plant

spraying or transplant drenching technique to apply the strains, which differs from the more broad spraying technique often used when trialing commercially available biologicals. For this reason, a suitable comparison between trials could not be conducted with these studies, and they were excluded.

3.2 PDMR Summary Data

After searching the Plant Disease Management Reports database, 31 treatment efficacy reports were identified as potential candidates for inclusion in our meta-analysis. Initial hand-screening yielded 24 reports evaluating the management of *Xanthomonas campestris pv. campestris* management on cabbage, removing 7 reports (Fig. 3).

Figure 3: PRISMA flow diagram for the PDMR search & screening process



Secondary screening yielded 21 reports, excluding those that did not contain at least one organic treatment (n=1), did not contain an analysis of variance (n=0), or did not contain at least one of the following response variables: disease severity, incidence, or total yield (n=2). This secondary screening yielded 21 reports. Tertiary exclusion criteria required a study to report at least one significant mean separation in order to estimate LSD. This removed 3 of 15 available studies from the disease severity dataset, 4 of 7 studies from the incidence dataset, and all 5 studies from the total yield dataset. This resulted in 12 studies for

inclusion in a meta-analysis of disease severity (Table S2), and too few studies to conduct an analysis of incidence and total yield.

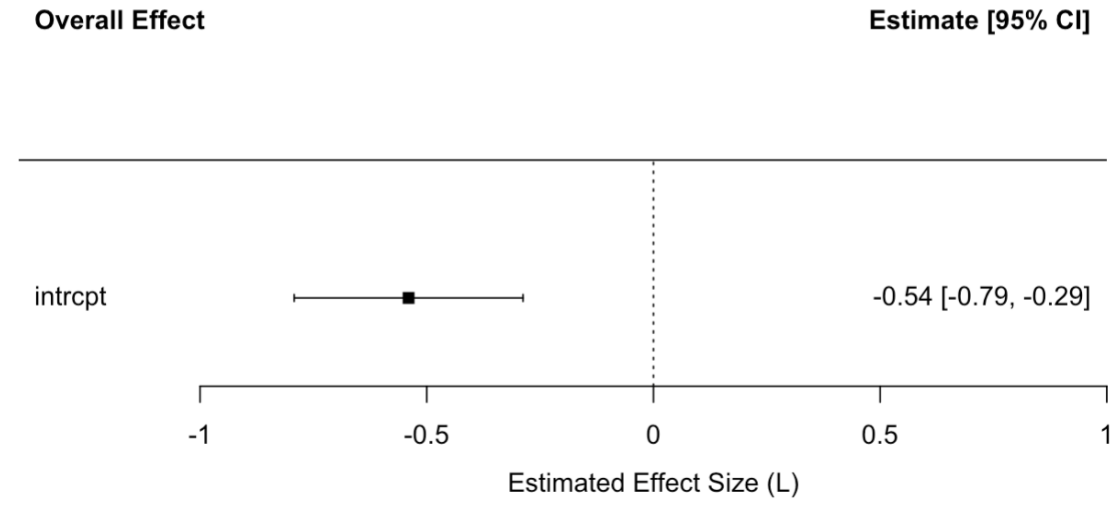
The twelve PDMR trials included for disease severity meta-analysis were conducted from 2007 to 2020, and spanned across the central, northeastern, and southeastern United States. The disease severity in non-treated controls ranged from 13.8% - 70.0%, and total precipitation ranged from 3.72 - 22.6 inches.

3.3 Overall Effect (L Model)

Among the 33 foliar treatments, $\underline{L}$ ranged from 0.20 to -1.71, with a corresponding percent disease control range of -22.4% to 81.9%. The mean overall estimated $\underline{L}$ of organic foliar treatment application was -0.54 with a standard error of 0.1287 (Fig. 4), and a corresponding mean of disease control of 41.7%. There was a significant overall effect (t = -4.20, p = 0.0015), meaning that the application of organic fungicides reduced disease severity.

The estimated variance components of our three-level multivariate model were $\sigma^2_{Level\ 2}$= 0.0380 and $\sigma^2_{Level\ 3}$= 0.1321. The corresponding percentage of total heterogeneity between effect sizes within-studies ($I^2_{Level\ 2}$) was 19.8% (n = 33), while between-study heterogeneity ($I^2_{Level\ 3}$) was 68.9% (n=12). The total variance value in this model (I^2) was 88.7%.

Figure 4: Forest plot showing the overall model effect of organic fungicide application when compared to non-treated control.

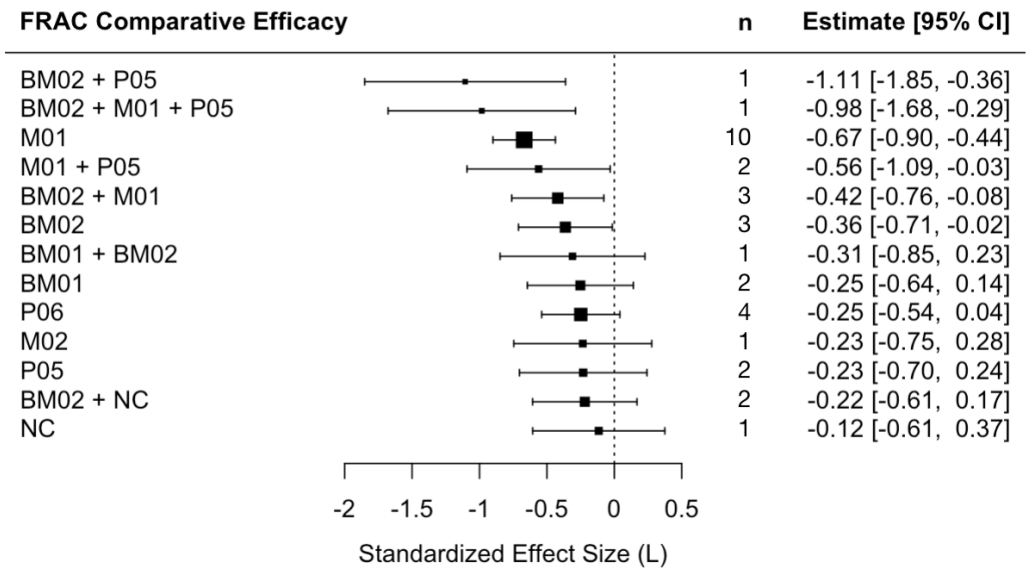


3.4 Comparative Treatment Efficacy (LOG_{XE} Model)

3.4.1 FRAC

Estimates of $\underline{L}$ among 13 different FRAC Code combinations ranged from -0.12 to -1.11, which corresponded to a mean percent disease control range of 10.9% to 66.9%. The following FRAC code combinations differed significantly from zero, suggesting they suppressed disease when compared with the non-treated control: M01, BM02 + P05, BM02 + M01 + P05, M01 + P05, BM02 + M01, and BM02 (Fig. 5).

Figure 5: Forest plot showing the comparative effect of FRAC groups on treatment efficacy



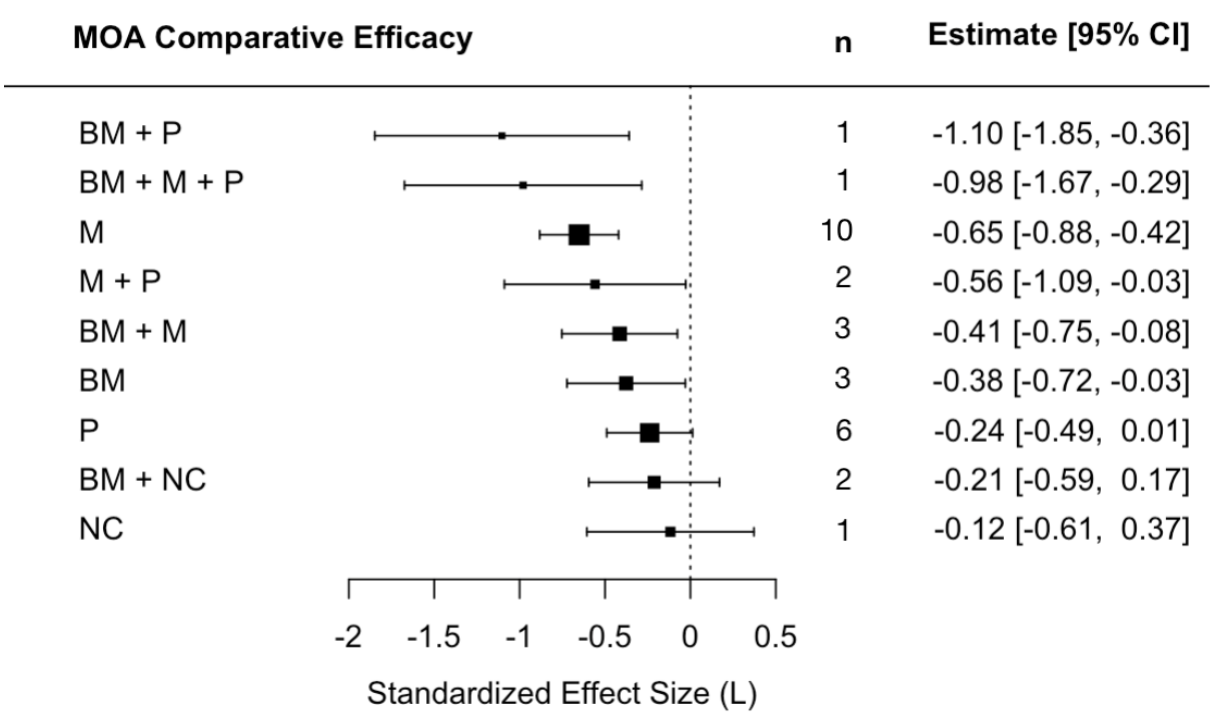
Combined multi-modal microbes and giant knotweed extract (BM02 + P05) (n=1), combined multi-modal microbes, coppers, and giant knotweed extract (BM02 + M01 + P05) (n=1), and coppers (M01) (n=10) were the most effective active ingredients. The least effective FRAC combinations were uncategorized treatments (NC) (n=1), combined multi-modal biological and uncategorized treatments (BM02 + NC) (n=2), and giant knotweed

extract by itself (P05). These results are understood in the context of linear contrasts conducted using the “emmeans” function in the L-based model, in which no treatments significantly differed from one another.

3.4.2 MOA

Among the 9 different MOA combinations, BM + P, M, BM + M + P, BM, M + P, BM + M, and P differed significantly from zero (Fig. 6). The most effective MOA groups were a combination of multi-modal biologicals and host plant defense inducers (BM + P) (n=1) and multi-modal chemicals (M) (n=10), while uncategorized (NC) (n=1) and combined multi-modal biological and uncategorized treatment (BM + NC) (n=2) groups were the least effective.

Figure 6: Forest plot showing the comparative effect of MOA groups on treatment efficacy


MOA Comparative Efficacy
n
Estimate [95% CI]
BM + P
1
-1.10 [-1.85, -0.36]
BM + M + P
1
-0.98 [-1.67, -0.29]
M
10
-0.65 [-0.88, -0.42]
M + P
2
-0.56 [-1.09, -0.03]
BM + M
3
-0.41 [-0.75, -0.08]
BM
3
-0.38 [-0.72, -0.03]
P
6
-0.24 [-0.49, 0.01]
BM + NC
2
-0.21 [-0.59, 0.17]
NC
1
-0.12 [-0.61, 0.37]
-2
-1.5
-1
-0.5
0
0.5
Standardized Effect Size (L)

3.5 Subgroup Analyses

Within the three categorical moderators (region, variety, number of applications), no subgroups were significantly different from each other (Tables S15 & S6). None of the four continuous moderators (year, precipitation, average temperature, and number of applications) showed a significant effect on treatment efficacy (Tables S15 & S6). Notably, closer observation of treatment efficacy trends across years by study shows a potential outlier report (V045) with lower clustered L-values in 2019, with the remainder of studies showing a positive trend in L (decreasing product efficacy) over time.

In subgroup analyses involving only copper treatments, year was highly significant ($p = 0.0014$) with a positive coefficient (0.0652), suggesting a decreasing trend in product efficacy and percent disease control from 2007 to 2020 (Table S7). The remainder of continuous and categorical moderator variables did not show any evident trends.

Discussion

4.1 Scoping Review Findings

Our scoping review did not yield reports fit for inclusion in a meta-analysis of organic foliar treatment efficacy in black rot of cabbage, but provided valuable information about the availability of related studies in web-based databases, as well as the kinds of studies available for review in future work. Ninety-two percent of located records were excluded in primary screening due to their subject matter, including the incorrect pathogen, incorrect crop, incorrect study stype (*in vitro*), or incorrect research endeavor (varietal trials, pathogen genetics, outbreak reports, etc.). These excluded studies could be useful in related systematic reviews or meta-analyses aimed at synthesizing information about other methods of black rot management. For example, at least 72 records assessed the biochemical mechanisms or in-field results of varietal resistance to black rot in brassicas. Many studies assessing pathogen mechanisms and the biochemical pathways of pathogen-treatment interactions could be suitable for a review of XCC epidemiology and future direction in treatment development, as has been done in entomological reviews and meta-analyses (Bhavanam and Stout 2022; Leybourne and Aradottir 2022). It is also important to note that a more broad approach capturing *in vitro* studies of foliar treatment efficacy on *Brassica oleracea*, instead of cabbage alone, could have greater success in locating suitable studies in future endeavors. Several studies instead included broccoli, cauliflower, and brussels sprouts, and though not explored, these records could hold promise for future iterations of this review.

From our full-text evaluated studies, studies categorized as “Research and Development” also provide useful information for scoping the efficacy of products being developed for commercial use. While there is not currently a bacteriophage-based product on the market for managing XCC, the Holtappels et al. (2022) study shows promising results, and bacteriophages have successfully managed bacterial disease in numerous trials, including black rot of brassicas (Vu and Oh 2020). The routine identification and summarization of potential products can be a useful exercise for both extension and research, allowing for up-to-date management recommendation forecasting and the selection of potential products for in-field research.

4.2 PDMR Findings

Our search in the Plant Disease Management Reports database for reports involving black rot on cabbage yielded 31 treatment efficacy reports for potential inclusion. In comparison with the number of initial reports identified in the PDMR-based meta-analyses of Toporek and Keinath (2022) (n = 74) and Ngugi et al. (2010) (n = 69), this number of initial reports was relatively low. Our secondary screening was not limited by our exclusion of studies that did not include an organic treatment (n = 1), which removed a study that assessed conventional soil fumigants. Black rot is one of the few bacterial diseases of cabbage, with several notable fungal counterparts in cabbage production. While chemical management recommendations for these fungal diseases often include several conventional products, general recommendations for black rot often only include coppers, if any chemical products (Bradford et al. 2023).

Reports available for our meta-analyses were significantly limited by the lack of reporting on pooled sample variance or the results of multiple comparison test results (LSD) for response variable analyses. Of our 21 available records, 9 reports (43%) were removed for non-significant results, from which we could not estimate an LSD value for use in calculating variance. This eliminated the possibility of analyzing useful response variables such as incidence and total yield in our analysis. One of the strengths of the PDMR database, as well as meta-analytical research, is the inclusion of non-significant results, thus avoiding selective outcome reporting bias. This bias is reintroduced by the methods necessary to calculate variance from these reports, and could likely lead to the overestimation of treatment effects in this meta-analysis and those using similar methods.

4.3 Overall + FRAC & MOA Comparisons

Our meta-analysis found that the use of organic foliar treatments reduces disease severity in treatment plots when compared to non-treated control, controlling disease by an estimated 41.7%. This is consistent with findings on the efficacy of various treatment groups included in our analysis, as well as overall syntheses of the efficacy of organic products in managing plant disease as explored below.

Biologicals with multiple modes of action (BM)

Multimodal biologicals (plant extracts (BM01) and *B. amyloliquefaciens/B. subtilis* (BM02) had a wide spread of efficacy, ranking throughout the list of treatments in both FRAC and MOA comparisons. As a MOA group, multimodal biologicals reduced disease severity both alone and when combined with host plant defense inducers (n=1), multi-modal chemicals

(n=3), and a combination of those three groups (n=1). When combined with biopesticides (NC)(n=2), this group did not differ from a null effect. Among FRAC treatments, the two groups with the highest percent disease control were a combination of multimodal microbes and giant knotweed extract (BM02 + P05) (n=1), and combined multimodal microbes, coppers, and giant knotweed extract (BM02 + M01 + P05) (n=1), respectively.

When interpreting these results, it's important to note that several of these treatment combinations only had one instance across our studies. (BM02 + P05/BM + P) and (BM02 + M01 + P05/BM + M + P) had a single instance, and were taken from the same study (V045). This study had relatively low disease severity in the untreated control (14.5%), and was among studies that appeared to have more amplified overall effects in terms of treatment efficacy. The combination of plant extracts (BM01) and multimodal microbes (BM02) also had a single instance in FRAC analysis. Notably, when combined with other instances of individual biological treatment efficacy in our MOA analysis (n=3), this group differed significantly from zero, but did not do so when isolated and analyzed by FRAC. This demonstrates the sensitivity of our analyses, as well as the level of specificity that can be lost both by calculating group averages within studies and by grouping products by MOA, particularly when two products within the same MOA are combined during coding.

There are several possible explanations for the variation among multimodal biologicals, particularly among groups including *B. amyloliquefaciens/B. subtilis* (BM02), as well as *B. mycoides* isolate J (P06). Multiple studies have demonstrated the efficacy of biologicals, particularly plant growth-promoting rhizobacteria in managing plant disease, including black rot of brassicas (Saharan and Nehra 2011; Mishra and Arora 2012; Wulff et

al. 2002). Simultaneously, it's recognized that there numerous abiotic and biotic factors, such as application conditions and plant-pathogen interactions, can modulate the efficacy of *Bacillus* spp., but many of which are yet to be investigated (Cawoy et al. 2011; Miljaković, Marinković, and Balešević-Tubić 2020). Mixtures of plant growth-promoting rhizobacteria (PGPR) strains may provide additional biocontrol when compared to single strains, perhaps by enhancing multiple diverse plant defense mechanisms and supporting rhizospheric microbial community health (Jetiyanon, Fowler, and Kloepper 2003; Domenech et al. 2006; Zhang et al. 2010; Liu et al. 2016). Given more available data, further investigations could take a closer look at the composition of biological products to assess the comparative efficacy of single and multiple-strain products, as well as the moderating effects of abiotic and biotic factors on biological treatment groups in particular.

Chemicals with multi-site contact activity (M)

As the most-studied treatment group across studies, multi-site chemicals (M) as a group and specifically coppers (M01) ranked high among treatment efficacy estimates. This MOA group consisted primarily of coppers (M01), with a single instance of sulfur that ranked low in our FRAC analysis. Coppers (M01) had the next-highest percent disease control (48.8%) after the grouped biological estimates, and were represented in 10 out of 12 studies. Notably, treatments that included both copper and giant knotweed extract (P05) (n=2) or multimodal microbes (n=3) ranked slightly lower than those with copper alone (n=10).

Many studies have shown the efficacy of copper-based fungicides in inhibiting brassica black rot (Lange 2010; Krauthausen, Laun, and Wohanka 2011). Its function as a

disrupter of cellular membranes and several cellular processes has been well-documented, making it a popular candidate for fungicidal and bactericidal in fruit and vegetable production (Flemming and Trevors 1989; Rawat, Bisht, and Naithani 2021). There are multiple formulations of copper, which could potentially have differential efficacy in disease management. Copper is also an essential component of cellular respiration and electron transport, and is used by plants and their pathogens alike in cellular function (Sommer 1931). In excess, copper is known to cause phytotoxicity, which could in turn reduce the marketability of cabbage and other brassicas on which it is applied (Bradford et al. 2023). There are also known concerns about environmental toxicity and persistence of residues in routine copper use, which can be taken into account in the formulation of management recommendations (Flemming and Trevors 1989).

Due to the greater number of reports testing copper that were included in our dataset, we were able to conduct a separate subgroup analysis of copper products analyzing the same continuous and categorical variables affecting copper efficacy. Notably, and alarmingly, we observed a trend of decreasing copper efficacy over time in our subgroup analysis by "Year" between 2007 and 2020. While taken together with the fact that there are ten available data points for this analysis, there are several potential explanations for this trend. One potential avenue is copper resistance in XCC, which has been documented in *Xanthomonas* pathosystems as the routine use of copper continues to provide ample conditions for the evolution of resistance traits (Lamichhane et al. 2011; Behlau et al. 2017). With this in mind, many current management recommendations involve the rotation of copper with other products. Another possible explanation is the potential differential efficacy of different

copper formulations, with the possibility of certain, less-effective formulations being used more frequently in later years. This is not an aspect of our dataset that we explored, and could certainly be included in later meta-analyses with more available data.

Host plant defense inducers (P)

As a group, host plant defense inducers (P), which include giant knotweed extract (P05) and *B. mycoides* isolate J (P06), had varied efficacy outcomes in our MOA and FRAC analyses. When taken alone, both P05 and P06 ranked in the lower half of treatments and did not significantly differ from control in disease severity reduction. In combination with coppers and multimodal microbes, however, treatments including P05 show improved performance.

Giant knotweed (*Reynoutria sachalinensis*) extract is known as a preventative treatment, inducing plant defenses by eliciting phytoalexins and thus supporting resistance (EPA 2010; Margaritopoulou et al. 2020). As a preventative treatment, general commercial guidelines for use recommend applying this product ideally prior to first disease symptoms, or even as early as during the transplanting process. In a similar way, commercial recommendations for *B. mycoides* isolate J suggest application prior to infection or symptoms in order to reduce disease severity, and recommend combination with curative products if disease is already present. Perhaps decisions about application timing and sequence with other products during PDMR trials, especially in inoculated trials, can impact the efficacy of host plant defense inducers. This could be taken into consideration in future efficacy studies, as well as be a topic for exploration in future meta-analyses.

Not classified (NC): Biopesticides

Taken as an MOA and FRAC group with one instance, biopesticides (NC) performed the worst out of the analyzed groups when used alone, and slightly better when combined with multimodal microbes (BM02)(n=2). Hydrogen peroxide and peroxyacetic acid (PAA) are known disruptors of cellular function and components, and are labeled for use to both prevent and manage bacterial and fungal diseases of vegetables (Juven and Pierson 1996; OMRI 2000). Despite this, not much information seems to be available on the bactericidal effects of hydrogen peroxide and PAA on different plant pathogenic bacteria, and efficacy reports do not seem to be well established. Further investigation of the effects of these biopesticides in PDMR trials and *in vitro* studies could provide more information for management best-practice recommendations.

Notes on Product Efficacy and Comparative Analysis

When it comes to understanding potential explanations for changes in product efficacy when combined with other ingredients, it's important to note that trials differ in their methods of combining treatment groups. Some treatments are applied at the same time across routine sprays, while others are alternated at varying frequencies. These variations in application methodology could account for some discrepancy in treatment outcomes, perhaps with the potential to compound or diminish the effects of associated treatments being used. For example, an *in vitro* study conducted by Patikarnmonthon et al. (2010) found that copper ions can enhance the bactericidal effects of hydrogen peroxide. While the combination of hydrogen peroxide (NC) and copper (M01) was not available for assessment in this study,

similar modulating effects, either positive or negative, could be observed among treatment combinations with copper and other products.

Another important factor in interpreting these results is taking into account the averaging of treatment types within each study in order to analyze treatment-by-study effects. This method assumes homogeneity within these groups, which may not be the case. Often, trials will include two instances of the same product at different application rates. This could very reasonably impact the efficacy of treatment programs, and could be explored in a product-specific meta-analysis pulling from a larger dataset.

4.4 Subgroup Analyses

With the exception of year in the copper treatment subgroup moderator analysis, no continuous moderators demonstrated an evident effect on treatment efficacy, and categorical variables did not show notable consistency or differences among groups. Black rot develops best in warm and wet conditions, and has been known to cause the most extensive damage in more tropical regions (Williams 1980). As such, we could reasonably expect to see higher disease pressure in trials located in the south, as well as those with higher precipitation and average temperature.

A thorough understanding of the outcomes of subgroup and moderator analyses should be weighted against the knowledge that typically, these analyses draw from a relatively small group of data points, and that even steep regression lines can be ruled non-significant given such a small "sample size" (Hak et al. 2016). These tests can be very sensitive to study removal; if V045 were removed from our study pool as an outlier in the "Year" subgroup analysis among all FRAC groups, the resulting regression line and assigned significance could change greatly. There are no indications in the report for V045 that indicate any potential reasons for depressed L values.

It is also important to note that our conservative selection of degrees of freedom (df) in testing differences between categorical variables could reasonably have impacted the outcomes. In multivariate meta-analysis designs, it is often unclear what df should be set to, due to potential biases in variance calculations included in these models. There are several methods to account for this through machine-based approximations in R, as well as a default setting provided in "emmeans" if residuals are not determined by the experimenter. We

concluded that the most practical decision was to include a conservative estimate as recommended by our R package. These comparison estimates were non-significant, in all categorical analyses. This is in contrast with the results obtained when using the default setting in "emmeans" (df = Inf), which, for example, evidenced a significant difference between the Midwest and the South in analyzing LOG(X_E), and another between the Mid-Atlantic and the South in analyzing efficacy estimates between these groups. Because of the sensitive and relatively low statistical power of these tests, they are not necessarily best used to test the presence or lack of an effect, but instead to explore potential trends and areas for further investigation (Hak et al. 2016).

4.5 Comparing Models

The two models used in this meta-analysis aimed to answer similar questions about the overall and comparative efficacy of organic foliar products, as well as potential effects of moderating variables on efficacy. The outcome, functionality, and use potential, however, could be quite different in certain areas. The model using LOG(XE) as an effect size aimed to assess all three potential outcomes without needing to create variance-covariance matrices for studies. By modeling LOG(XE) and setting a pooled estimate of non-treated controls as a baseline, this model was able to rank treatment efficacy in a similar manner to L. Indeed, the results of the two models were similar, though not identical, in their provided FRAC and MOA estimates and confidence intervals. The ranking of products was, importantly, the same between both models. While the LOG(XE) model did have this functionality, we were not able to find an intuitive solution to provide estimates of overall and moderated efficacy using this method. This led us to investigate and create a model fit to L, as has been used in previous meta-analyses of treatment efficacy. The method for modeling variance-covariance matrices in R was difficult to locate in the plant-pathological literature, and we explored a few methods of generation including the "vcalc" function in R, as well as a manual approach. We compared the coefficients and standard error produced by these methods, as well as a model fit to V_L without a variance-covariance matrix, and found them all to be quite similar. The total variance not attributable to sampling error (I^2) was very similar between the manually-fitted and unfitted models (78.14% and 77.25%, respectively), while the level of identified within-study heterogeneity was much higher in the matrix-fitted model (54.81%) than in the unfitted model (33.14%). As shown, both models can serve important functions in

exploring treatment efficacy relationships and trends. Something not explored, but potentially useful, in the LOG(XE)-based model, could be an analysis of trends in non-treated controls. This could provide more information about the differences in disease severity among studies and across different regions, years, and climatic conditions, and could support the body of knowledge for a particular pathosystem.

4.6 Research Needs & Future Directions

Due in part to the limited availability of treatment data from available reports, the effects of many treatment groups could be ranked by efficacy estimates, but could not be significantly differentiated from one another in this analysis. While this exercise does aim to function as a synthesis of available data and associated trends, as well as a proof-of-concept for future research, it also holds the potential to be a powerful standard tool for grower management recommendations when given the proper resources. This investigation demonstrates a substantial need for additional treatment efficacy trials for black rot of cabbage. Within these trials, the inclusion of a variety of organic treatment options, both alone and in combination with other products, could provide valuable information about the efficacy of products with less substantial analysis to-date. Perhaps most importantly, the inclusion of a measure of pooled variance, most notably an LSD value for each response variable analysis, could drastically increase the amount of information available for meta-analytical research. This outcome could be considered by publishers to enhance the utility of the work in practice.

Future Work

We observed that certain organic foliar treatments, such as coppers, have more demonstrated and more consistent efficacy against black rot than other groups. However, in order to more confidently build management recommendations from these results, additional research is required to investigate comparative product efficacy and potential factors of differential performance as more information becomes available. One possible avenue could be to complete a similar meta-analysis using trial data for *Brassica oleracea* as a whole, including trials on cauliflower, kale, and Brussels sprouts, then running subgroup analyses on crop type. Given increased access to reports, future meta-analyses could also more closely examine treatment-specific trends over time and across moderating variables. For example, a meta-analysis could assess the efficacy of different *Bacillus* spp. in relation to climatic conditions, investigate potential variation in efficacy across different copper formulations, or evaluate the potential effects of staggered versus simultaneous application of different product mixtures. Because the information required for these analyses is most often accessible in current PDMR reports, the limiting factor on such analyses is the report accessibility for a given pathosystem.

Given the observed trend of decreasing copper efficacy between 2007 and 2020, informed management recommendations would benefit from the continued investigation of potential sources of decline, especially copper resistance.

4.7 Conclusion & Management Implications

Overall, the use of organic foliar treatments in PDMR trials effectively managed brassica black rot, and treatment efficacy varied among FRAC and MOA groups. Coppers by themselves were by far the most studied treatment group across reports, and thus were the most well-supported FRAC group with efficacy against black rot. Multimodal microbial biologicals demonstrated efficacy in managing XCC both alone and when combined with coppers or giant knotweed extract, but performed widely with some of the highest and lowest efficacy estimates when combined with different products. Host defense inducers (giant knotweed extract and *Bacillus mycoides* isolate J) also varied in their efficacy estimates; both did not significantly reduce disease on their own, but giant knotweed extract efficacy improved when combined with other products. Plant extracts, biopesticides, and sulfurs did not have significant disease management efficacy alone or when combined, and were some of the least studied FRAC groups across studies. Subgroup analyses across treatment FRACs and MOAs did not evidence any significant trends, but did provide areas to explore in future analyses of black rot or other pathosystems. A decreasing trend was observed for copper efficacy across years.

Taken together, our results suggest that the efficacy of organic foliar treatments can vary among FRAC groups, as well as treatment combinations. The need for additional treatment efficacy trials evaluating multiple organic treatments alone and in combination to more clearly understand product performance and more confidently make management recommendations cannot be overstated. Meta-analyses continue to hold great potential for

extension recommendations in plant pathology and beyond as the amount of accessible data continues to increase. Data-driven decision support systems can inform the development of well-functioning foliar treatment management plans, reducing the need for unnecessary sprays and targeting treatments that function best in specific environments, as well as in sequence with other products.

This is to be understood alongside the knowledge that successful and sustained organic management of black rot should involve a responsive and integrated approach, including cultural management techniques, tolerant variety selection, use of disease-free seed and transplant selection, and responsible and diversified foliar treatment application when necessary. This meta-analysis investigates the efficacy of previously studied active ingredients and explores areas for growth in research and development of organic treatment options, providing a comprehensive view of available data that can be used to inform management recommendations, with the understanding that more work must be done to validate product efficacy and associated trends.

Appendix

Table S1: Scoping Review - Studies identified for secondary screening by our scoping review

S[a]	Author(s)	Year	Treatment	Type	Reason for Exclusion
1	Assis et al.	1999	Yeast isolates	Foliar	Research & development [b]
2	Brown et al.	2001	UV-C	Seed	Research & development
3	Cunningham	1939	Hot water	Seed	Lacking necessary data [c]
4	Dong et al.	2020	Glycine-copper(II) hydroxide nanoparticles	Foliar	Not cabbage
5	Fallahzadeh-Mamaghani et al.	2021	Paenibacillus polymixa N179	Foliar	Not cabbage
6	Ghazalibiglar et al.	2015	Paenibacillus isolate P16	Seed	Research & development
7	Gupta	1991	Agrimycin, Streptocycline, Carbendazim, Benomyl	Foliar	Not approved for organic use
8	Harman et al.	1987	Nyolate seed treatment	Seed	Not approved for organic use
9	Holtappels et al.	2022	Bacteriophages	Foliar	Research & development
10	Humaydan et al.	1980	Antibiotics and sodium hypochlorite	Seed	Lacking necessary data
11	Ishikawa et al.	2004	Validamycin A (VMA)	Foliar	Not approved for organic use
12	Karuku & Maobe	2018	Stabilized orthosilicic acid	Foliar	Lacking necessary data

13	Kliseewicz & Pound	1961	Antibiotics (Terramycin, Agrimycm, Streptomycin, etc.)	Seed	Not approved for organic use
14	Kliseewicz	1960	Antibiotics (Terramycin, Agrimycm, Streptomycin, etc.)	Seed	Not approved for organic use
15	Krauthausen et al.	2011	Copper hydroxide, benzoic acid, chlorine dioxide	Foliar	Not cabbage
16	Liu et al.	2016	Plant growth-promoting rhizobacteria (PGPR)	Foliar	Research & development
17	Liu et al.	2016	Plant growth-promoting rhizobacteria (PGPR)	Foliar	Research & development
18	Marin & Bautista	2020	Weed extracts	Foliar	Lacking necessary data
19	Massomo et al.	2004	Bacillus strains	Seed, Foliar, Root	Lacking necessary data
20	Mishra & Arora	2012	Rhizospheric Pseudomonas species	Foliar	Lacking necessary data
21	Nega et al.	2003	Hot water	Seed	Lacking necessary data
22	Raghavendra et al.	2017	Beta-Amino butyric acid	Foliar	Lacking necessary data
23	Sakudo et al.	2020	Electrically Charged Disinfectant	Seed	Research & development
24	Sanna et al.	2022	Hot water, Biopesticides, Electrolyzed water	Seed	Lacking necessary data
25	Schultz et al.	1986	Calcium hypochlorite	Seed	Lacking necessary data
26	Sharma et al.	2006	Mancozeb	Foliar	Not approved for organic use
27	Wulff et al.	2002	Bacillus subtilis	Foliar	Lacking necessary data
28	Wulff et al.	2006	Bacillus strains	Foliar	Lacking necessary data

29	Ye et al.	2020	Quorum-Quenching Bacteria, *Burkholderia anthina* HN-8	Foliar	Research & development

[a] Study Number

[b] Study did not assess specific treatment methods that are readily available to growers at present, including physical, chemical, and biological treatments that cannot be categorized with available commercial products

[c] Study either did not assess a comparable metric of foliar disease management, including disease severity, incidence, or total yield, or did not include necessary data to conduct a meta-analysis, including reported mean, sample size, and an appropriate measure of variance

Table S2: PDMR Summary - Summary data for the twelve PDMR trials included for disease severity meta-analysis

S[a]	PDMR[b]	TY[c]	Author(s)	Region	Variety	DS_{CON} (%)[d]	PRE (in)[e]
1	V012	2018	Miller et al.	Midwest	Cheers	21.5	7.6
2	V045	2019	Miller et al.	Midwest	Cheers	14.5	10.8
3	V052	2017	Dutta et al.	South	Bravo	55.3	-
4	V060	2012	Lange and Smart	Mid-Atlantic	Surprise	13.8	3.69
5	V061	2017	Miller et al.	Midwest	Padoc	19.3	6.1
6	V084	2010	Lange and Smart	Mid-Atlantic	Surprise	52.5	8.35
7	V087	2017	Lange and Smart	Mid-Atlantic	Storage Hybrid 4	56.3	22.6
8	V106	2011	Lange and Smart	Mid-Atlantic	Surprise	22.5	3.72
9	V121	2007	Lange and Smart	Mid-Atlantic	Moreton	31.3	6.97
10	V132	2020	Vallad and Hughes	South	Bravo	30.7	6.9
11	V154	2019	Vallad et al.	South	Bravo	70.0	10.1
12	V261	2013	Lange and Smart	Mid-Atlantic	Surprise	39.0	8

[a] Study

[b] PDMR Report Number

[c] Trial Year

[d] Disease Severity in non-treated control

[e] Precipitation in inches

Table S3: Summary statistics from LOG_{XE} meta-analysis grouped by FRAC combinations

FRAC	n	$\underline{L}$	se($\underline{L}$)	Z	CI_{LB}	CI_{UB}	p		$\underline{C}$ (%)	CI_{LB} (%)	CI_{UB} (%)
BM01	2	-0.25	0.20	-1.26	-0.65	0.14	0.209		22.27	-15.15	47.53
BM02	3	-0.36	0.18	-2.05	-0.71	-0.02	0.0408	*	30.45	1.51	50.88
BM02 + M01	3	-0.42	0.17	-2.41	-0.76	-0.08	0.016	*	34.26	7.51	53.28
BM02 + NC	2	-0.22	0.20	-1.11	-0.61	0.17	0.268		19.65	-18.34	45.44
NC	1	-0.12	0.25	-0.46	-0.61	0.37	0.6444		10.90	-45.44	45.41
P06	4	-0.25	0.15	-1.68	-0.54	0.04	0.0927	.	22.03	-4.21	41.66
BM02 + M01 + P05	1	-0.98	0.35	-2.77	-1.68	-0.29	0.0056	**	62.58	25.03	81.32
BM02 + P05	1	-1.11	0.38	-2.91	-1.85	-0.36	0.0036	**	66.93	30.36	84.30
M01	10	-0.67	0.12	-5.66	-0.90	-0.44	< 0.0001	***	48.76	35.41	59.35
M01 + P05	2	-0.56	0.27	-2.07	-1.09	-0.03	0.0382	*	42.96	3.01	66.46
P05	2	-0.23	0.24	-0.96	-0.70	0.24	0.3382		20.63	-27.35	50.53
BM01 + BM02	1	-0.31	0.27	-1.13	-0.85	0.23	0.2577		26.66	-25.48	57.14
M02	1	-0.23	0.26	-0.90	-0.75	0.28	0.3697		20.87	-31.97	52.56

Table S4: Summary statistics from LOG_{XE} meta-analysis grouped by MOA combinations

MOA	n	$\underline{L}$	se($\underline{L}$)	Z	CI_{LB}	CI_{UB}	p		$\underline{C}$ (%)	CI_{LB} (%)	CI_{UB} (%)
BM	3	-0.38	0.18	-2.13	-0.72	-0.03	0.0333	**	31.61	2.96	51.32
BM + M	3	-0.41	0.17	-2.40	-0.75	-0.08	0.0164	*	33.63	7.69	52.76
BM + NC	2	-0.21	0.20	-1.09	-0.59	0.17	0.2769		18.94	-18.53	44.57
NC	1	-0.12	0.25	-0.47	-0.61	0.37	0.6390		11.31	-44.77	45.66

P	6	-0.24	0.13	-1.86	-0.49	0.01	0.0631	*	21.34	-1.01	38.74
BM + M + P	1	-0.98	0.35	-2.76	-1.67	-0.29	0.0057	**	62.47	25.17	81.18
BM + P	1	-1.10	0.38	-2.90	-1.85	-0.36	0.0037	***	66.71	30.23	84.28
M	10	-0.65	0.12	-5.53	-0.88	-0.42	<.0001	***	47.80	34.30	58.52
M + P	2	-0.56	0.27	-2.06	-1.09	-0.03	0.0392	*	42.88	2.96	66.38

Table S5: Continuous moderator statistics

Moderator	**Estimate**	**se**	**t**	**p**	**CI_{LB}**	**CI_{UB}**
Year	0.0699	0.5762	2.49	0.2432	-0.2870	0.4267
Precipitation (in)	-0.0054	0.0245	-0.22	0.8612	-0.3168	0.3060
Average Temperature (ºF)	0.0170	0.0295	0.58	0.6672	-0.3577	0.3916
Number of Applications	0.0394	0.0392	1.01	0.3269	-0.0426	0.1215

Table S6: - Categorical moderator statistics by efficacy

Moderator	**Subgroup**	**n_{Group}**	**p**
Region	Overall	3	0.3669
Variety	Overall	6	0.5851
Number of Apps	Overall	9	0.9008

Moderator	**Subgroup**	**n**	**L**	**se**	**CI_{LB}**	**CI_{UB}**
Region	Mid-Atlantic	10	-0.736	0.199	-1.59	0.118
	Midwest	18	-0.424	0.143	-1.04	0.191
	South	5	-0.156	0.204	-1.03	0.721
Variety	Bravo	8	-0.191	0.231	-0.785	0.4032
	Cheers	14	-0.469	0.216	-1.023	0.0852
	Moreton	2	-1.182	0.490	-2.441	0.0772
	Padoc	7	-0.327	0.310	-1.123	0.4687
	Storage Hybrid 4	3	-0.539	0.366	-1.479	0.4013
	Surprise	11	-0.797	0.263	-1.473	-0.1201
Number Apps	3	3	-0.540	0.657	-2.06	0.975
	4	1	-1.109	0.636	-2.58	0.358
	5	4	-0.604	0.421	-1.57	0.367
	6	2	-0.888	0.526	-2.10	0.325

7	4	-0.391	0.416	-1.35	0.568
9	2	-0.562	0.589	-1.92	0.797
10	5	-0.887	0.607	-2.29	0.512
12	6	-0.321	0.559	-1.61	0.969
14	6	-0.165	0.551	-1.44	1.107

Table S7: Copper continuous moderator statistics

Moderator	**Estimate**	**se**	**z**	**p**	**CI_{LB}**	**CI_{UB}**	
Year	0.0652	0.0204	3.20	0.0014	0.0253	0.1051	***
Precipitation (in)	0.0023	0.0263	0.09	0.9312	-0.0493	0.0539	
Average Temperature (ºF)	0.0047	0.0300	0.16	0.8750	-0.0541	0.0636	
Number of Applications	0.0130	0.0613	0.21	0.8325	-0.1071	0.1330	

Table S8: - Copper categorical moderator statistics by efficacy

Moderator	**Subgroup**	**n_{Group}**	**p**
Region	Overall	3	0.3669
Variety	Overall	6	0.5851
Number of Apps	Overall	9	0.9008

Moderator	**Subgroup**	**n**	**L**	**se**	**CI_{LB}**	**CI_{UB}**
Region	Mid-Atlantic	10	-0.736	0.199	-1.59	0.118
	Midwest	18	-0.424	0.143	-1.04	0.191
	South	5	-0.156	0.204	-1.03	0.721
Variety	Bravo	8	-0.191	0.231	-0.785	0.4032
	Cheers	14	-0.469	0.216	-1.023	0.0852
	Moreton	2	-1.182	0.490	-2.441	0.0772
	Padoc	7	-0.327	0.310	-1.123	0.4687
	Storage Hybrid 4	3	-0.539	0.366	-1.479	0.4013
	Surprise	11	-0.797	0.263	-1.473	-0.1201
Number Apps	3	3	-0.540	0.657	-2.06	0.975
	4	1	-1.109	0.636	-2.58	0.358
	5	4	-0.604	0.421	-1.57	0.367
	6	2	-0.888	0.526	-2.10	0.325

7	4	-0.391	0.416	-1.35	0.568
9	2	-0.562	0.589	-1.92	0.797
10	5	-0.887	0.607	-2.29	0.512
12	6	-0.321	0.559	-1.61	0.969
14	6	-0.165	0.551	-1.44	1.107

R Code: LOG(XE) Model

 # Libraries & Importing Data

```
library(netmeta)
library(metafor)
library(here)
library(msm)
library(tidyverse)

load("data_raw.RData")
data_edit <- data_raw
```

 # Summarizing and Cleaning Data: Grouping by FRAC

```
data_clean_frac <- data_edit |>

# Grouping Product by FRAC Within Each Report
group_by(PDMR, FRAC) |>
summarize(
      XE = mean(XE), V_XE = mean(V), Number_Apps = mean(Number_Apps),
      C_Avg = mean(C),.groups = "drop_last") |>

# Relevel so Control is Treated as Reference
mutate(FRAC = relevel(factor(FRAC), ref = "CON")) |>

# Adding Moderator Variables & Identifying Information
left_join(
      data_edit %>% select(PDMR,Year,Region,Variety,Precipitation,Temp)
      %>% distinct(), by = "PDMR") %>%
rowwise() |>

# Calculating Effect Size & Variance
mutate(LOG_XE = log(XE),V_LOG_XE = (V_XE / XE^2)/4,.after = V_XE) |>

# Reorder Variables
select(c("PDMR", "FRAC", "LOG_XE", "V_LOG_XE"), everything())
```

```
# Creating the LOG(XE) FRAC Model
model_frac <- rma.mv(
      yi = LOG_XE,
      V = V_LOG_XE,
      data = data_clean_frac,
      slab = PDMR,
      method = "REML",
      random = ~ 1 | PDMR/FRAC,
      mods = ~ PDMR + FRAC - 1,
      btt = "FRAC")

# Model Results
summary(model_frac)

# Model Variance Results
i2 <- var.comp(model_frac)
i2


# Data Visualization: Forest Plots
# Creating Coefficients & Variance
coef_FRAC <- tail(coef(model_frac), 13)
var_FRAC <- tail(diag(vcov(model_frac)), 13)

# Creating a Forest Plot
forest(
      trt_coef_re, trt_var_re,
      slab = names(trt_coef_re),
      order = "yi",
      xlab = "Standardized Effect Size (L)",
      header = "FRAC Comparative Efficacy")


## Note: This same process can be done for MOA by substituting “MOA” for
“FRAC”
```

Copper Model

```
# Summarizing and Cleaning Data
disease_copper_avg <- data_edit |>
      filter(FRAC == "M01") %>%
      group_by(PDMR, FRAC) |>
      summarize(XE = mean(XE), V_XE = mean(V),
      Number_Apps = mean(Number_Apps), C_Avg = mean(C), L_Avg = mean(L),
      n_copper = n(), VL_Avg = sum(VL) / n_copper^2,
      .groups = "drop_last") %>%
      left_join(disease_save %>%

select(PDMR,Year,Region,Variety,Precipitation,Temp) %>%
distinct(), by = "PDMR") %>%
ungroup() %>%
mutate(Year_c = as.numeric(Year))

# Creating the Copper Model
model_cop <- rma.mv(
      yi = L_Avg,
      data = disease_copper_avg,
      method = "REML",
      V = VL_Avg,
      slab = PDMR,
      mods = ~ Region - 1,
      random = ~ 1 | PDMR/ FRAC)

# Model Results
summary(model_cop)

# Model Variance Results
i2_L <- var.comp(model_cop)
i2_L
```

R Code: L Model

```
# Libraries & Importing Data

library(netmeta)
library(metafor)
library(here)
library(dmetar)
library(emmeans)
library(msm)
library(netmeta)
library(tidyverse)

# Summarizing and Cleaning Data: Grouping by FRAC
ldata_clean_frac <- data_edit |>

# Grouping Product by FRAC Within Each Report
group_by(PDMR, FRAC) |>
summarize(
      L_Avg = mean(L),n_L = n(),VL_Avg = sum(VL) / n_L^2,
      Number_Apps = mean(Number_Apps),.groups = "drop_last") |>

# Relevel so Control is Treated as Reference
mutate(FRAC = relevel(factor(FRAC), ref = "CON")) |>

# Adding Moderator Variables & Identifying Information
left_join(data_edit %>%
select(PDMR,Year,Region,Variety,Precipitation,Temp) %>% distinct(), by =
"PDMR") %>%
rowwise() |>

# Reorder Variables
select(c("PDMR", "FRAC", "LOG_XE", "V_LOG_XE"), everything())

# Create United Column & Grouping Product by FRAC Within Each Report
unite(col = pdmr_frac, PDMR, FRAC, remove = FALSE) |>
group_by(PDMR) |>

# Calculating Effect Size
mutate(L = LOG_XE - LOG_XE[FRAC == "CON"], .before = LOG_XE) |>
      filter(FRAC != "CON") |>

# Remove Redundant Predictor Warning
mutate(FRAC = factor(FRAC)

# Calculating Variance & Matrix Creation
con_var <- ldata_clean_frac |>
      filter(FRAC == "CON") |>
      select(PDMR, VL_Avg) |> pull(VL_Avg, PDMR)
V_manual <- expand.grid(
      dat1$PDMR, dat1$PDMR) |>
      rownames_to_column() |>
      mutate(off_diag = ifelse(Var1 == Var2, con_var[Var1], 0)) |>
      pull(off_diag) |>
```

```
      matrix(nrow = nrow(dat1), ncol = nrow(dat1))

diag(V_manual) <- data_edit$VL_Avg
# Creating the L 'Overall' Model
model_frac_L <- rma.mv(
      yi = L_Avg,
      V = V_manual,
      data = ldata_clean_frac,
      random = ~ 1 | PDMR/FRAC,
      dfs = "contain") # leads to more conservative tests

# Model Results
summary(model_frac_L)

# Model Variance Results
i2_L <- var.comp(model_frac_L)
i2_L


# Creating the L Continuous Moderator Variable
model_year_L <- rma.mv(
      yi = L_Avg,
      V = V_manual,
      data = ldata_clean_frac,
      random = ~ 1 | PDMR/FRAC,
      dfs = "contain",
      mods = ~ FRAC + Year - 1,
      btt = "Year")

# Model Results
summary(model_year_L)

# Visualization
ldata_clean_frac |> ggplot() +
  geom_point(aes(x = Year, y = L, color = PDMR), alpha = .4)


# Creating the L Categorical Moderator Variable
model_reg_L <- rma.mv(
      yi = L_Avg,
      V = V_manual,
      data = ldata_clean_frac,
      random = ~ 1 | PDMR/FRAC,
      dfs = "contain",
      mods = ~ FRAC + Region - 1,
      btt = "Region")

# Model Results
summary(model_reg_L)

# Analysis & Comparisons
region_lqd <- qdrg(object = model_reg_L, data = ldata_clean_frac, df = 2)
# Note: be careful with the df, default is somewhat liberal

region_emm <- emmeans(region_lqd, specs = c("Region"))
```

```
region_emm
pairs(region_emm)
plot(region_emm)
```

 # Data Visualization: Forest Plots

```
# Creating Coefficients & Variance
coef_L <- tail(coef(model_frac_L), 2)
var_L <- tail(diag(vcov(model_frac_L)), 2)


# Creating a Forest Plot
forest(coef_L, var_L,
      slab = names(trt_coef_L),
      xlim = c(-1.0,1.0),
      xlab = "Estimated Effect Size (L)",
      header = "Overall Effect")

## Note: This same process can be done for MOA by substituting “MOA” for
“FRAC”
```

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Chapter 3: Extension Documents

Following discussions with an advisory board of organic vegetable growers in Wisconsin, several research and resource development objectives were determined for this project. In addition to meta-analytical pursuits, growers identified the usefulness of centralized, accessible online insect pest and disease management resources. In particular, the availability of up-to-date, informative summaries of locally-common vegetable diseases and their management could facilitate improved production outcomes and more well-informed on-farm strategies to mitigate risk in the future. With this in mind, we created fourteen online "disease profiles" that included symptom summaries, clearly demonstrative photos, epidemiological information, management recommendations, and forecast modeling descriptions and instructions when applicable. In addition, we created and presented a tutorial of our online Vegetable Disease and Insect Forecasting Network tool, an accessible online model that allows users to assess the current risk of a given insect pest or disease by inputting relevant crop information. Taken together, these resources aim to supplement the efforts of extension specialists in supporting the integrated management of insect pests and diseases by providing growers with the tools necessary to more confidently identify, understand, and manage these challenges on the farm. These materials are included below, and may also be found on the UW Vegetable Pathology website.

Brassica Black Rot

Authors: A.A. Abbrescia, A.J. Gevens, R.L. Groves, B. Bradford

Last Updated: March 2023

Description & Symptoms:

Brassica black rot is a common bacterial disease of brassica crops (such as cabbage, Brussels sprouts, kale) caused by *Xanthomonas campestris pv. campestris.* It causes V-shaped yellow lesions that move from the outer edges of the leaves inwards, with nearby veins turning black and thickening. Foliar symptoms can appear similar to those of plant stressors including drought, overwatering, or over-fertilization. Once established in the leaves, this disease can cause black discoloration inside the stem, which will become visible when cut. As the disease progresses, the roots may also turn black.

Infection:

Most often, primary infection occurs when infected seed or transplants enter a field. Some brassica weeds, like mustards and radishes, can also carry and spread the disease. Once established in a field, the disease spreads via splashing water, wind, equipment, workers, and some insects. The bacteria can survive in and on infested soil-bound plant debris that can survive for up to two years. Favorable conditions include high moisture**,** hot temperatures**,** and poor airflow.

Disease Cycle:

The black rot disease cycle begins with primary infection, which can occur as early as the seedling stage. The bacteria can survive in or on brassica seeds, infecting seedlings as they grow. These infections may not present with distinct symptoms, or may mimic other forms of stress. If seedlings are grown in a greenhouse, infected flats or soil can be a source of inoculum. Transplants that have been clipped via mowing can carry disease as well. Once a plant is infected, the bacteria can be spread from one plant to another by splashing water, wind, or contact with equipment and some insects. During favorable conditions, the bacteria is able to enter a plant through the hydathodes (water pores on the outer edge of the leaf) or

wounds, which can be caused by insects or machinery. Heavy black rot infection can often be followed by secondary soft-rot infections. At the end of a season, the bacteria can survive on seeds, or in soil-bound plant debris.

Cultural Control:

Cultural management includes scouting regularly to identify the presence of the disease early and mitigate, before it spreads and causes significant damage. The following practices can help reduce the risk of this disease:

- Plant resistant varieties when possible
- Plant certified disease-free seed (may include process of hot-water seed treatment
- Rotate away from susceptible brassica crops for ≥ 3 years
- Maintain proper spacing between plants
- Plant in areas with good airflow
- Avoid overhead irrigation
- Avoid working in fields when plants are wet
- Manage host weeds
- Remove and destroy infected plants
- Destroy infested plant debris
- Disinfest tools and equipment

Chemical Control:

Properly-timed copper or biopesticide elicitors such as acibenzolar-S-methyl can also be used to manage disease. For Wisconsin-specific fungicide information, refer to the Commercial Vegetable Production in Wisconsin (A3422), a guide available through the UW Extension Learning Store website. Or, for home garden fungicide recommendations, see Home Vegetable Garden Fungicides (D0062), a fact sheet available through the UW Plant Disease Diagnostic Clinic website. Always follow label directions carefully.

Photos

Photo Credit: Gerald Holmes, Strawberry Center, Cal Poly San Luis Obispo, Bugwood.org

Photo Credit: Robert Wick, University of Massachusetts, Bugwood.org

Photo Credit: Gerald Holmes, Strawberry Center, Cal Poly San Luis Obispo, Bugwood.org

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Cucurbit Alternaria Leaf Blight

Authors: A.A. Abbrescia, A.J. Gevens, R.L. Groves, B. Bradford

Last Updated: April 2023

Cucurbit *Alternaria* leaf blight is a common fungal disease of cucurbits caused by *Alternaria cucumerina*. Cucurbit crops include watermelon, cantaloupe, cucumber, zucchini, pumpkin, and winter squashes. This pathogen causes brown lesions on the leaves that can develop concentric, target-like rings and a yellow surrounding halo. Lesions can also develop on the fruit, appearing first as sunken, brown spots that can become dark and fuzzy as the lesion produces spores (sporulation). Fruit can also experience sunscald from leaf loss, which results in heightened susceptibility to other diseases as well as reduced yield. *Alternaria cucumerina* survives on infected soil-bound plant debris, the spores of the pathogen spread on wind, splashing water, workers, equipment, or insects.

Infection & Disease Cycle:

The primary source of inoculum for *A. cucumerina* is infected soil-bound plant debris. The fungus can survive for up to two years in this debris as dormant fungal threads called “mycelia”. Once temperatures warm and leaf wetness increases, these soil-bound mycelia produce spores called “conidia” that can infect living plant tissue. These conidia can spread via wind, splashing water, equipment, or insects, causing lesions where they contact and infect the plant. These lesions can produce new conidia that infect new plant tissue, spreading through the same process. The pathogen may also survive on infected seed. Favorable conditions for spread and infection include warm temperatures (70-90ºF), high & prolonged leaf wetness, early & late-season plants, and poor plant nutrition, especially low nitrogen.

Cultural Control:

Cultural management includes scouting regularly to identify the presence of the disease early, before it has had a chance to spread and cause significant damage. The following practices can also help prevent disease development:

- Plant resistant varieties when possible
- Plant certified disease-free seed
- Rotate away from susceptible cucurbit crops (>2 years)
- Destroy or deep-plow infested plant debris
- Maximize distance between susceptible cucurbit fields
- Maximize spacing between plants (both in row and between rows)
- Avoid overhead irrigation
- Avoid working in fields when plants are wet
- Maintain proper nutrition, especially nitrogen

Chemical Control:

Properly-timed fungicides can also be used to manage this disease. For Wisconsin-specific fungicide information, refer to the Commercial Vegetable Production in Wisconsin (A3422), a guide available through the UW Extension Learning Store website. Or, for home garden fungicide recommendations, see Home Vegetable Garden Fungicides (D0062), a fact sheet available through the UW Plant Disease Diagnostic Clinic website. Always follow label directions carefully.

Photos

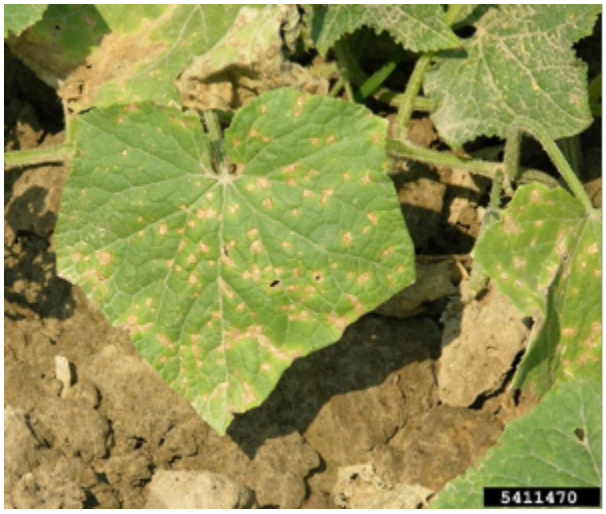

Photo Credit: Don Ferrin, Louisiana State University Agricultural Center, Bugwood.org

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Onion Botrytis Leaf Spot/Leaf Blight

Authors: A.A. Abbrescia, A.J. Gevens, R.L. Groves, B. Bradford

Last Updated:

Description & Symptoms:

Onion Botrytis leaf blight/leaf spot is a common fungal disease of alliums caused by *Botrytis squamosa*. Symptoms first appear as small whitish spots on the leaf. These spots are oval-shaped, and sometimes surrounded by a light green or silver halo that often appears water-soaked. Leaf tips will begin to dry and wither as the disease progresses, sometimes until the whole leaf dies back. Progressed infection can stunt bulb growth and reduce yield. Heavily infected fields often appear yellowish and blighted. Severe infection can stunt bulb growth and reduce yield.

Infection:

Primary infection occurs from *B. squamosa* spores that overwinter in infected in-field plant debris, cull piles, stored bulbs, volunteer bulbs in-field, and in infected soil. Secondary infection can occur when conidia, or "spores" spread from moist, infected leaves. Favorable conditions for disease development include high relative humidity and rainfall, prolonged leaf wetness, and warm temperatures.

Disease Cycle:

Botrytis squamosa overwinters as sclerotia in infected in-field plant debris, cull piles, stored bulbs, volunteer bulbs in the field, and infested soil. These sclerotia (or durable, overwintering fungal structures) produce airborne spores and ascospores (sexual spores) that travel to and infect onion leaves during periods of high moisture and low air movement. These same favorable conditions allow for secondary cycles of infection, where infected leaves produce more spores, which spread to further infect the same leaf or new leaves. Sclerotia are once again formed at the end of the onion production season, and the disease cycle will continue the following season.

Disease Modeling:

To view the predicted onion Botrytis risk on any given day, visit the Vegetable Disease and Insect Forecasting Network (VDIFN) website. From the Disease tab, select the "Botrytis leaf blight" model. This BOTCAST model uses a cumulative disease severity index (CDSI) computed from gridded NOAA weather data to calculate the risk of onion botrytis development, which is displayed as a colored map overlay.

Threshold 1: (21 ≤ CDSI < 31) Warning threshold of "no spray applied unless rain predicted or overhead irrigation applied"

Threshold 2: high risk of rapid disease development, apply initial spray as soon as possible

CDSI > 40: extremely elevated risk

The start point should be set to the date of crop emergence. Click any grid point in VDIFN to get more detailed weather and disease progression information for that location.

Cultural Control

Cultural control strategies include scouting regularly to identify the presence of the disease early before it has had a chance to spread and cause significant damage. Disease spread can be limited by avoiding working in fields when plants are wet and disinfesting tools and machinery. The following practices can help mitigate the risk of this disease:

- Maintain proper spacing between plants
- Destroy cull piles
- Rogue volunteer plants
- Distance seed and commercial onion fields
- Destroy infested plant debris
- Rotate away from susceptible crops (Alliums) to reduce sclerotia in soil (3 years)
- Chemical control

Use disease forecasting tools to properly time the most effective disease prevention sprays. For Wisconsin-specific fungicide information, refer to the Commercial Vegetable Production in Wisconsin (A3422), a guide available through the UW Extension Learning Store website. Or, for home garden fungicide recommendations, see Home Vegetable Garden Fungicides

(D0062), a fact sheet available through the UW Plant Disease Diagnostic Clinic website. Always follow label directions carefully.

Adapted from UW Extension publication A3803, written by Karen Delahaut and Walt Stevenson in 2004.

Photos:

Photo Credit: Lindsey du Toit, Washington State University, via Bugwood.org

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Potato Early Blight

Authors: A.A. Abbrescia, A.J. Gevens, R.L. Groves, B. Bradford

Last Updated: May 2023

Description & Symptoms:

Early blight is a common fungal disease of solanaceous crops (tomatoes, potatoes, peppers, eggplants) caused by *Alternaria solani*. Symptoms first appear as circular dark-brown spots on leaves and stems that can later develop concentric, target-like rings, often surrounded by yellow margins. Lesions are sometimes limited by veins, giving an 'angular' appearance. Early foliar symptoms often appear near the base of the plant, spreading up to higher leaves as the disease progresses. On tubers, lesions appear as dark, sunken, cork-like spots with raised margins, although tuber symptoms are less frequently seen in the Midwestern U.S.

Infection & Favorable Conditions:

When conditions are right, overwintering spores (conidia) can travel within and between fields and infect healthy plant tissue. Spores can spread via wind, splashing rain, irrigation water, equipment, and workers. Spores can then spread locally from infected tissue in a similar manner. Favorable conditions for early blight development and spread include canopy closure, high humidity, prolonged leaf wetness, poor airflow, nitrogen deficiency. Older or senescing leaves are most susceptible to early blight infection. Once the growing season is over, the pathogen can overwinter on infected soil-bound plant debris for several years.

Disease Cycle:

At the end of the growing season, *A. solani* spores (conidia) and fungal threads (mycelium) are able to overwinter on diseased plant debris in the soil. Once temperature and wetness increase in the spring, conidia are primarily spread via wind or splashing water. These

conidia then infect healthy plant tissue through the foliar plant parts including the leaf and stem surfaces, stomata, or wounds, causing lesions to form. These lesions will develop conidiophores, which produce airborne and waterborne spores. These spores will then spread to cause secondary infections on the leaves. *Alternaria solani* conidia present on soil-bound plant debris can also infect tubers wounded during harvest, although this is not commonly seen in the Midwest. At the end of the cropping season, the pathogen will be present in the field as spores (conidia) or mycelium in the soil, continuing the disease cycle.

Disease Modeling:

Early blight can be modeled using what are called Potato Physiological Days (P-days), which were originally developed to model the progress of potato plants through the growing season. P-days were later implemented to quantify the amount of heat energy to promote early blight disease development throughout a season. Conceptually, they are similar to Growing Degree Days, which are used to track how plants and insects develop over a season in response to daily air temperature highs and lows. To view the predicted early blight risk on any given day, visit the Vegetable Disease and Insect Forecasting Network (VDIFN) website. From the Disease tab, select the "Early Blight" model. This model uses P-days computed from gridded NOAA weather data to calculate the risk of early blight development, which is displayed as a colored map overlay. The start point should be set to the date of approximately 50% crop emergence for potato. For tomato, pepper, or eggplant transplants, the start point should be the date of transplanting to the field. At the accumulation of 300 P-days, after crop emergence in a season at a given location, temperature conditions have been met to support early blight infection on susceptible host crops. This provides a time at which crops should be intensively scouted for first infection and/or protected with preventative fungicide treatments to reduce first infection. This initial threshold is critical because first infection creates lesions and news spores which establish the overall in-field inoculum load for the rest of the production season. In concentrated vegetable production regions, *A. solani* inoculum is typically highly abundant. Beyond the risk threshold of P-day 300, daily risk scores are calculated from the average daily P-day accumulation over the past week. High

accumulations indicate enhanced early blight disease risk. Click any grid point in VDIFN to get more detailed weather and disease progression information for that location."

Cultural Control:

Scouting regularly allows early identification of disease before significant spread and damage. The following practices can also help prevent disease development:

- Plant resistant (possibly late season) varieties when possible
- Rotate away from susceptible solanaceous crops (3-4 years)
- Maximize distance between susceptible fields
- Maintain proper plant nutrition with appropriate nitrogen fertilization
- Avoid over-irrigating (reduce leaf wetness)
- Maintain proper spacing between plants (promote airflow)
- Destroy or deep-plow infested plant debris
- Monitor potato physiological days (P-Days) with the VDIFN disease modeling tool described above

Chemical Control:

Fungicides can provide good control of early blight in vegetables when applied early on in infection. Multiple applications of fungicide are often necessary to sustain disease management to time of harvest due to the typically high abundance of inoculum and susceptibility of most common cultivars. For Wisconsin-specific fungicide information, refer to the Commercial Vegetable Production in Wisconsin (A3422), a guide available through the UW Extension Learning Store website which is annually updated. Or, for home garden fungicide recommendations, see Home Vegetable Garden Fungicides (D0062), a fact sheet available through the UW Plant Disease Diagnostic Clinic website. Always follow label directions carefully.

Photos

Photo Credit: Howard F. Schwartz, Colorado State University, Bugwood.org

Photo Credit: Gerald Holmes, Strawberry Center, Cal Poly San Luis Obispo, Bugwood.org

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Tomato Septoria Leaf Spot

Authors: A.A. Abbrescia, A.J. Gevens, R.L. Groves, B. Bradford

Last Updated: May 2023

Description & Symptoms:

Tomato septoria leaf spot is a common fungal disease of solanaceous crops caused by *Septoria lycopersici*. Symptoms appear on the leaves as circular, tan-to-gray spots with darker brown margins and dotted with dark, raised pycnidia inside the lesion. These lesions are often surrounded by a yellow halo. The disease typically develops on lower leaves first, moving up to higher leaves as infection progresses. Lesions can converge and lead to defoliation of lower leaves, and in severe cases the death of an entire plant. Stem lesions appear similar to leaf lesions, but are often darker. Fruit lesions are uncommon, but appear similar to leaf lesions under very high disease pressure.

Primary Source: Primarily diseased solanaceous crop or weed debris in soil, also infected seeds and equipment
Spread: Rainfall, irrigation, workers, equipment, and several insects
Favorable Conditions: High humidity, moderate temperatures (68-77ºF), high dew point/wet conditions, poor airflow

Infection & Disease Cycle:

The main source of inoculum for primary infections is *S. lycopersici* spores that overwinter on diseased solanaceous crop or weed debris in the soil. The fungus can also survive on equipment, as well as infected seed, which will produce diseased seedlings. Spores (conidia) are produced and spread during wet and warm periods, especially when airflow is poor due to canopy closure and densely-spaced plants, These spores are spread from primarily debris to leaves via rainfall, irrigation, workers, equipment, and several insects, often reaching and infecting the lower and older leaves first. These spores penetrate the leaf tissue via the stomata, leading to lesion development within ~5 days. Pycnidia (asexual fruiting bodies)

will develop ~14 days after inoculation, releasing more spores that will be spread and create new, secondary infections of healthy plant tissue including leaves, stems, and fruit.

Cultural Control:

Scouting regularly allows early identification of disease before significant spread and damage. The following practices can also help prevent disease development:

- Plant resistant varieties
- Rotate away from susceptible solanaceous crops (1-2 years)
- Stake or trellis plants to improve airflow
- Remove 'suckers' or lowest lateral tomato plant growth (https://hort.extension.wisc.edu/articles/tomato-pruning/)
- Maintain proper spacing between plants
- Control host weeds
- Destroy infested plant debris
- Avoid over-irrigating (reduce leaf wetness)

Disease spread can be limited by proper mulching, which can reduce plant-soil contact, as well as disinfecting tools and equipment like stakes and cages.

Chemical Control:

Preventative applications of fungicides containing copper or chlorothalonil can be useful in areas with chronic *Septoria lycopersici* infections. For Wisconsin-specific fungicide information, refer to the annually updated Commercial Vegetable Production in Wisconsin (A3422), a guide available through the UW Extension Learning Store website. Or, for home garden fungicide recommendations, see Home Vegetable Garden Fungicides (D0062), a fact sheet available through the UW Plant Disease Diagnostic Clinic website. Always follow label directions carefully.

Photos

Photo Credit: Bruce Watt, University of Maine, Bugwood.org

Photo Credit: Paul Bachi, University of Kentucky Research and Education Center, Bugwood.org

Additional References:

Douglas, Sharon M. “Septoria Leaf Spot of Tomato.” The Connecticut Agricultural Experiment Station.https://portal.ct.gov/CAES/Fact-Sheets/Plant-Pathology/Septoria-Leaf-Spot-of-Tomato.

Hudelson, Brian. “Septoria Leaf Spot.” UW Plant Disease Diagnostics Clinic, May 22, 2021. https://pddc.wisc.edu/wp-content/blogs.dir/39/files/Fact_Sheets/FC_PDF/Septoria_Leaf_Spot.pdf.

Adapted from UW Extension publication A2606, written by Karen Delahaut and Walt Stevenson in 2004.

Potato Brown Spot

Authors: A.A. Abbrescia, A.J. Gevens, R.L. Groves, B. Bradford

Last Updated: May 2023

Description & Symptoms:

Brown spot and Black pit are fungal diseases of potato caused by the fungus *Alternaria alternata*. On leaves, it causes relatively small dark brown spots of necrotic tissue with a dark brown margin. Starting as small lesions, the spots can coalesce to cover a large percentage of leaf or petiole surface. On tubers, the disease causes black, deep sunken pits with definite margins that often develop in storage. The pathogen causing these diseases survives on infected soil-bound plant debris and susceptible weeds. *Alternaria alternata* is easily confused with *A. solani*, causal agent of the more common and destructive disease early blight. Brown spot tends to be favored by warmer temperatures than early blight.

Primary Source: Soil-bound plant debris, susceptible weeds
Spread: Spreads to leaves via wind, and wounded tubers through infected soil
Favorable Conditions: Long dew periods, standing water on foliage, temperatures over 64ºF, reduced airflow, plant maturity, and low nitrogen status

Infection & Disease Cycle:

In Wisconsin, *A. alternata* overwinters on host weeds and in plant debris as spores (conidia) and fungal threads (hyphae). Spores will spread from these sources after heavy rainfalls or changes in relative humidity, with the resulting windborne conidia then coming into contact with potato leaves. Resulting infections are worsened by increased leaf wetness (rainfall, dew, irrigation, etc.) and warmer temperatures. During moist conditions, mature lesions will produce new spores that are able to travel to new plant material. Stressed plants, or plants infected with other pathogens, can be more susceptible to brown spot. *Alternaria alternata* is

a relatively weaker pathogen than *A. solani* (causing early blight) and can be saprophytic in its activity. Tubers that were both bruised and introduced to soil-bound inoculum during harvest can also become infected.

Cultural Control:

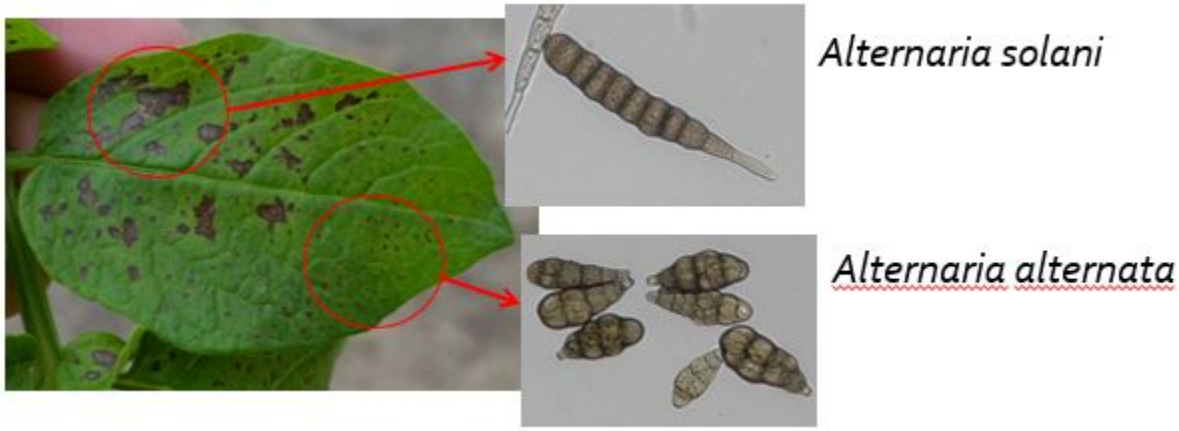
Scouting regularly allows early identification of disease before significant spread and damage. The following practices can also help prevent disease development:

- Plant certified disease-free seed
- Manage host weeds
- Maintain proper plant nutrition to avoid plant stress
- Rotate away from solanaceous crops for 3 or more years
- Avoid excessive and overhead irrigation
- Destroy or deep-plow infested plant debris
- Avoid bruising tubers during harvest
- Manage other diseases to reduce susceptibility to brown spot

Chemical Control:

Well-timed foliar protectant, broad spectrum foliar fungicide applications can prevent the development and spread of *A. alternata* at the first sign of disease or after flowering. The pathogen has shown significant resistance to strobulurins, which should be avoided. For Wisconsin-specific fungicide information, refer to the Commercial Vegetable Production in Wisconsin (A3422), a guide available through the UW Extension Learning Store website. Or, for home garden fungicide recommendations, see Home Vegetable Garden Fungicides (D0062), a fact sheet available through the UW Plant Disease Diagnostic Clinic website. Always follow label directions carefully.

Photos



Amanda Gevens, UW-Madison Plant Pathology, & Shunping Ding, Cal Poly San Luis Obispo.

Additional References:

"Alternaria Alternata - an Overview | ScienceDirect Topics." n.d. Accessed August 5, 2021. https://www.sciencedirect.com/topics/immunology-and-microbiology/alternaria-alternata.

"Brown Leaf Spot (E3182)." n.d. MSU Extension. Accessed May 21, 2023. https://www.canr.msu.edu/resources/brown_leaf_spot_e3182.

"Potato (Solanum Tuberosum)-Brown Spot and Black Pit." 2019. Text. Pacific Northwest Pest Management Handbooks. April 11, 2019. https://pnwhandbooks.org/plantdisease/host-disease/potato-solanum-tuberosum-brown-spot-black-pit.

Potato Pink Rot

Authors: A.A. Abbrescia, A.J. Gevens, R.L. Groves, B. Bradford
Last Updated: May 2023

Description & Symptoms:

Pink rot is a water mold or oomycete disease of potato tubers caused primarily by *Phytophthora erythroseptica*. The soilborne pathogen causes darkened, water-soaked lesions with defined margins near the stem-end of the tuber, and is often identified by the characteristic pink/salmon color and ammonia-like odor of a potato cut and exposed to air after 20-30 minutes. Potato vines can also appear stunted or wilted later in the season, with noticeable leaf yellowing and drying as the wilt moves up the stem.

Source: Infested soil (up to 7 years), infected tubers in storage
Spread: In Field: Direct contact with infested soil, swimming zoospores during wet conditions
Field-to-Field: Transfer of infested soil to a new field on machinery or equipment
During and Post-Harvest: Direct contact with infected tubers through bruises and wounds.
Favorable Conditions: High temperatures (75 to 82ºF), very wet, poorly draining soils, moist storage conditions

Disease Cycle:

Phytophthora erythroseptica spores (typically oospores) can overwinter in field soil, and in unharvested potato tubers (volunteers), as well as be transferred from other infested fields on machinery. Once present in a field, the pathogen can infect all underground parts of the plant through the epidermis. During very wet conditions, swimming spores (zoospores) can also move freely between plants, infecting through the epidermis, eyes, or lenticels. During and after harvest, infected tubers will rot and spread spores to healthy tubers through wounds and bruises, with high moisture in storage aiding infection. Spores left in a field can survive for up to seven years, and repeat the disease cycle in a following growing season whenever a susceptible crop is planted.

Cultural Control:

Scouting regularly, especially in waterlogged parts of a field, allows for early identification of disease before significant spread and damage occurs. The following practices can also help prevent disease development:

- Destroy infested plant debris
- Rogue volunteer plants
- Maintain proper soil moisture
- Rotate away from susceptible crops (4 years)
- Avoid bruising and wounding during harvest
- Avoid harvesting in hot conditions
- Store tubers in cold, well-ventilated storage spaces

Chemical Control:

Up-to-date Wisconsin-specific conventional in-furrow and postharvest fungicide information and recommendations can be found in the Commercial Vegetable Production in Wisconsin (A3422), a guide available through the UW Extension Learning Store website. It is important to be aware of the risk of pathogen resistance to the phenylamide fungicides (such as metalaxyl and mefenoxam). With use over time, these fungicides have selected for resistant pathogen populations in many locations. This means that the use of phenylamide fungicides will not control pink rot. Or, for home garden fungicide recommendations, see Home Vegetable Garden Fungicides (D0062), a fact sheet available through the UW Plant Disease Diagnostic Clinic website. Always follow label directions carefully.

Photos

Photo Credit: Gerald Holmes, Strawberry Center, Cal Poly San Luis Obispo, Bugwood.org

Photo Credit: Gerald Holmes, Strawberry Center, Cal Poly San Luis Obispo, Bugwood.org

Additional References

"Pink Rot / Potato / Agriculture: Pest Management Guidelines / UC Statewide IPM Program (UC IPM)." 2019. 2019. https://ipm.ucanr.edu/agriculture/potato/pink-rot/.

"Potato Diseases: Pink Rot (E2993)." 2015. MSU Extension. 2015. https://www.canr.msu.edu/resources/potato_diseases_pink_rot_e2993.

"Potato (Solanum Tuberosum)-Pink Rot." 2015. Text. Pacific Northwest Pest Management Handbooks. September 11, 2015. https://pnwhandbooks.org/plantdisease/host-disease/potato-solanum-tuberosum-pink-rot.

Potato Silver Scurf

Authors: A.A. Abbrescia, A.J. Gevens, R.L. Groves, B. Bradford

Last Updated: May 2023

Description & Symptoms:

Silver scurf is a fungal blemish disease of potato tubers caused by *Helminthosporium solani.* The pathogen causes tan-to-gray circular lesions typically initiating on the stem-end of the tuber surface, often appearing shiny and silver when wet. Infection reduces both the visual appeal and quality of potato tubers, as the pathogen causes damage to the periderm or skin which enables the onset of other pathogens or enhanced desiccation. This disease is primarily a concern for stored, commercial fresh market potatoes.

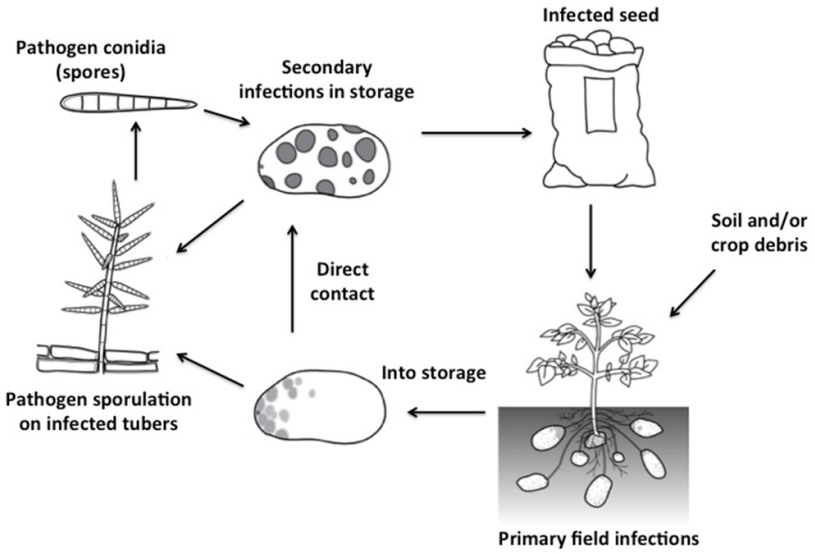
Primary Source: Infested soil, debris-borne, infected seed potatoes, infected tubers in storage

Spread: Rain or irrigation washes spores through infested soil during initial spread. Once in storage, warm temperatures and high humidity allow sporulation to occur. Airborne spores can then infect new stored tubers.

Favorable Conditions: High humidity (> 90%), high temperatures

Disease Cycle:

The silver scurf disease cycle begins with primary infection, which can occur when overwintered spores (conidia) are washed through infested soil and plant debris and onto tubers. Other sources of primary inoculum are infected seed tubers, which can spread the pathogen to daughter tubers. The pathogen infects and causes lesions on the tuber, which can produce more conidia that are released into the soil. At the end of the growing season, *H. solani* conidia are able to overwinter in soil, and fungal parts can subsist in soilborne crop debris. Once harvested and in storage, the lesions on infected tubers can enlarge and again produce spores (sporulate) in moderate temperatures and high humidity. These spores can then spread and cause secondary infection in stored tubers.



Disease Cycle of Potato Silver Scurf. Amanda Gevens, UW-Plant Pathology.

Cultural Control:

The following practices can help reduce inoculum and spread for this disease:

- Plant certified disease-free seed
- Rotate away from susceptible crops (2-3 years)
- Rogue volunteer plants
- Assess seed prior to planting, and daughter tubers prior to storage
- Disinfest storage spaces between uses
- Store at low temperature and humidity
- Avoid leaving potato tubers in the field for >2 weeks post vine kill
- Store potatoes in environments with good airflow and temperature control

Chemical Control:

Fungicides can be applied during the production season as well as post-harvest to limit silver scurf on potato. Up-to-date Wisconsin-specific conventional seed, in-furrow, and postharvest fungicide information and recommendations can be found in the Commercial Vegetable Production in Wisconsin (A3422), a guide available through the UW Extension Learning Store website. Or, for home garden fungicide recommendations, see Home Vegetable Garden Fungicides (D0062), a fact sheet available through the UW Plant Disease Diagnostic Clinic website. Always follow label directions carefully.

Photos

Photo Credit: Amanda J. Gevens, UW Extension

Additional References

"Silver Scurf / Potato / Agriculture: Pest Management Guidelines / UC Statewide IPM Program (UC IPM)." n.d. Accessed May 16, 2023. https://ipm.ucanr.edu/agriculture/potato/silver-scurf/.

"Silver Scurf of Potato | Cornell Vegetables." n.d. Accessed May 21, 2023. https://www.vegetables.cornell.edu/pest-management/disease-factsheets/silver-scurf-of-potato/.

Cucurbit Downy Mildew

Authors: A.A. Abbrescia, A.J. Gevens, R.L. Groves, B. Bradford

Last Updated: May 2023

Description & Symptoms:

Cucurbit downy mildew is a water mold or oomycete disease of cucurbit crops caused by *Pseudoperonospora cubensis.* Symptoms first appear on the upper leaf surface as angular, vein-bounded, yellow to pale-green spots, turning brown and coalescing to turn entire leaves brown with disease progression. In very humid conditions, the underside of leaves may appear fuzzy as the pathogen produces numerous spores which enable the pathogen to spread. This foliar disease can very rapidly destroy above ground plant parts reducing potential for yield and quality, and making fruit more susceptible to sunscald and secondary pathogen infection.

Primary Source: Living cucurbit plant tissue
Spread: Windborne spores, rain and irrigation splash, human spread on equipment and hands
Favorable Conditions: Very wet, humid conditions, moderate temperatures (59-68° F)

Infection & Disease Cycle:

Pseudoperonospora cubensis does not overwinter on plant debris in Wisconsin, and can only survive on living plant tissue. No soilborne, long-term survival structures of the pathogen have been identified in our growing region. For this reason, the pathogen generally overwinters in warmer climates and in protected greenhouses. Spores spread northward on airborne spore-like structures called “sporangia”. The pathogen infects cucurbit leaves, producing lesions that create more spores when leaf wetness and humidity are high. These spores spread to nearby plants via water splash and human spread, and can travel longer

distances via wind currents. The pathogen does not directly infect cucurbit fruits. Currently, two types of the cucurbit downy mildew pathogen are known. One type will infect cucumber and melon ("Clade 2") and seems to be much more aggressive on these select cucurbit types. Clade 2 also has resistance to some currently used fungicides. The second type of downy mildew pathogen will infect pumpkin, watermelon, winter squash, bittermelon, and balsam apple ("Clade 1"). Clade 1 seems to arise a bit later in the production season than Clade 2.

https://hort.extension.wisc.edu/articles/cucurbit-downy-mildew-identification-and-management/

Cultural Control:

Scouting regularly allows early identification of disease before significant spread and damage. The following practices can also help prevent disease development:

- Plant resistant varieties when possible
- Avoid overhead irrigation
- Maintain proper spacing between plants
- Plant in areas with good airflow

Chemical Control:

Keep track of locations of known cucurbit downy mildew infection, and the cucurbit types infected, to best understand your risk and prescriptively manage this disease. For many years this disease was tracked and field reports were used to generate a disease forecast: https://cdm.ipmpipe.org/forecasting/. While this service is currently suspended, the website offer useful resources for management. For Wisconsin-specific fungicide information, refer to the Commercial Vegetable Production in Wisconsin (A3422), a guide available through the UW Extension Learning Store website. Or, for home garden fungicide recommendations,

see Home Vegetable Garden Fungicides (D0062), a fact sheet available through the UW Plant Disease Diagnostic Clinic website. Always follow label directions carefully.

Photos

Photo Credit: Gerald Holmes, Strawberry Center, Cal Poly San Luis Obispo, Bugwood.org

Photo Credit: Rebecca A. Melanson, Mississippi State University Extension, Bugwood.org

Additional References:

"Downy Mildew of Cucumber, Melon and Squash." n.d. Accessed May 23, 2023. https://extension.umn.edu/disease-management/downy-mildew-cucurbits.

Gevens, Amanda, and Michelle Marks. n.d. "Cucurbit Downy Mildew: Identification & Management (A3978)."

Phytophthora Blight or Phytophthora Crown & Fruit Rot

Authors: A.A. Abbrescia, A.J. Gevens, R.L. Groves, B. Bradford

Last Updated: May 2023

Description & Symptoms:

Phytophthora blight / crown rot is a water mold or oomycete disease of several fruiting vegetable crops including cucurbits (cucumber, melon, squash), solanceous plants (tomato, eggplant, pepper), and to a lesser extent, legumes (snap beans, lima beans) caused by *Phytophthora capsici*. It causes large, irregular brown spots on leaves, which expand and coalesce in warm and wet conditions. On vines, water-soaked, dark lesions can girdle the stem and cause whole-plant wilt and collapse. *Phytophthora capsici* also causes damping-off in cucurbits, rotting the crown and root tissues and most often resulting in plant death. Fruit rot often occurs on the side of the fruit touching the soil, beginning as a water-soaked lesion that expands and is covered with white sporulating pathogen growth.

Primary Source: Infested soil and infected plant debris

Spread: Sporangia spread via very local wind currents and workers/equipment, while swimming zoospores spread via saturated soil and splashing water; the spores (sporangia) cannot travel long distances

Favorable Conditions: Warm temperatures and high humidity, high leaf wetness, high precipitation and irrigation, poorly draining soil

Infection & Disease Cycle:

Phytophthora capsici can overwinter in the soil as oospores, surviving for several years (>20 years). Warmer temperatures and splashing precipitation/irrigation allow spores in the soil to come into contact with nearby plants. These spores can also travel longer distances when infested soil is transported by workers and equipment. After initial infection, lesions on the

plant can bear another aerial spore type known as a sporangium. In saturated soil and warm temperatures, *P. capsici* can also release swimming zoospores. These zoospores infect the roots and crown of the plant, as well as lower leaves and fruit by splashing water. The pathogen can infect crops several times through a growing season, and remain in the soil after harvest. The disease can also continue to be active post harvest causing breakdown of cucurbit or solanaceous crop fruits. Moisture and airflow management is critical to maintain healthy produce.

Cultural Control:

Scouting regularly allows early identification of disease before significant spread and damage. The following practices can also help prevent disease development:

- Rotate away from susceptible crops (>3 years)
- Plant resistant varieties when possible
- Plant in areas with well-draining soil
- Disinfest tools and equipment
- Maintain proper soil moisture
- Mulch with straw or dropped cover crops to reduce splash
- Destroy infected plant debris
- Do not irrigate from retention ponds that may receive run-off from infested fields (swimming spores can be present in the water and inoculate fields)

Chemical Control:

Phytophthora capsici populations are known for developing resistance to fungicides when used over time. In particular, many populations have resistance to phenylamides such as metalaxyl or mefenoxam. For Wisconsin-specific fungicide information, refer to the Commercial Vegetable Production in Wisconsin (A3422), a guide available through the UW Extension Learning Store website. Or, for home garden fungicide recommendations, see Home Vegetable Garden Fungicides (D0062), a fact sheet available through the UW Plant Disease Diagnostic Clinic website. Always follow label directions carefully.

Photos

Photo Credit: Gerald Holmes, Strawberry Center, Cal Poly San Luis Obispo, Bugwood.org

Additional Resources:

Scheufele, S., and G. Higgins. 2015. "Phytophthora Blight." Text. Center for Agriculture, Food, and the Environment. January 6, 2015. https://ag.umass.edu/vegetable/fact-sheets/phytophthora-blight.

Schuh, Marissa, and Michelle Grabowski. 2022. "Phytophthora in Vegetable Crops." 2022. https://extension.umn.edu/disease-management/phytophthora.

Onion Stemphylium Leaf Blight

Authors: A.A. Abbrescia, A.J. Gevens, R.L. Groves, B. Bradford

Last Updated: May 2023

Description & Symptoms:

Onion Stemphylium leaf blight is a fungal disease of alliums caused by *Stemphylium vesicarium.*

It causes oval-shaped, tan or brown lesions on the leaves, which may appear water-soaked and darker when sporulating. These lesions can enlarge and overtake entire leaves, as well as girdle seed stems. Blighted leaves can compromise the bulb, reducing yield and leading to secondary infections.

Primary Source: Infected plant debris

Spread: Airborne spores, often appears as a secondary infection of downy mildew lesions, herbicide or physical plant injury, and heat-stressed/drought-stressed leaves

Favorable Conditions: High humidity, moderate temperatures, excess moisture from precipitation or irrigation, high dew point

Infection & Disease Cycle:

Stemphylium vesicarium overwinters in plant debris. Once temperatures warm in the spring, airborne spores called “ascospores” are released from this plant debris, infecting nearby leaves that have been wounded by other diseases (including downy mildew), insects, heat-stress, or damaging elements including weather, or chemical/mechanical injury. Subsequent lesions will produce airborne and waterborne spores called “conidia” that will travel, causing

secondary infections. At the end of the cropping season, the pathogen will again overwinter in plant debris, continuing the disease cycle.

Cultural Control:

Scouting regularly allows early identification of disease before significant spread and damage. The following practices can also help prevent disease development:

- Rotate away from susceptible crops (3-4 years)
- Maintain proper nutrition & avoid excessive nitrogen application
- Maintain proper moisture levels in the crop
- Take care with use of herbicides to avoid phytoxicity or other injury
- Destroy infested plant debris & culls
- Manage onion downy mildew

Chemical Control:

For Wisconsin-specific fungicide information, refer to the Commercial Vegetable Production in Wisconsin (A3422), a guide available through the UW Extension Learning Store website. Or, for home garden fungicide recommendations, see Home Vegetable Garden Fungicides (D0062), a fact sheet available through the UW Plant Disease Diagnostic Clinic website. Always follow label directions carefully.

Photos

Photo Credit: Gerald Holmes, Strawberry Center, Cal Poly San Luis Obispo, Bugwood.org

Additional References:

Nischwitz, Claudia. 2020. “Purple Blotch and Stemphylium Leaf Blight.” 2020. https://extension.usu.edu/vegetableguide/onion/purple-blotch-stemphylium-leaf-blight.

Swett, C.L., B.J. Aegerter, T.A. Turini, and A.I. Putman. 2019. “Purple Blotch and Stemphylium Leaf Blight / Onion and Garlic / Agriculture: Pest Management Guidelines / UC Statewide IPM Program (UC IPM).” 2019. https://ipm.ucanr.edu/agriculture/onion-and-garlic/purple-blotch-and-stemphylium-leaf-blight/.

Onion Downy Mildew

Authors: A.A. Abbrescia, A.J. Gevens, R.L. Groves, B. Bradford

Last Updated: May 2023

Description & Symptoms:

Onion Downy mildew is a water mold or oomycete disease of alliums caused by *Peronospora destructor*. It causes irregular foliar lesions that begin as pale-green, then progress to yellow or brown necrotic tissue. Eventually, lesions coalesce and lead to the collapse of the leaf. During periods of high moisture, fuzzy, gray-to-violet sporangia appear on leaf surfaces. These symptoms can also be seen on seed stalks and flowers. Bulbs can be stunted and sponge-like during systemic plant infection and, when the disease infects the bulb itself, can become watery.

Primary Source: Infested soil, infected plant debris, and perennial alternate host plants
Spread: Airborne spores, wind currents, splashing water
Favorable Conditions: High humidity, moderate temperatures with an optimal temperature of 55ºF, high moisture

Infection & Disease Cycle:

Peronospora destructor mainly overwinters in volunteer infected onions and those in cull piles as mycelium. It is also known to overwinter in perennial onion varieties, as well as soil-bound spores and plant debris. On nights with moderate temperatures and high humidity, overwintered mycelia produce spores (sporangia) that spread throughout the day via wind currents. These spores require free water, whether from rain, irrigation, or heavy dew to germinate and infect the plant, often beginning infection at the tops of leaves. Resulting lesions produce new sporangia and zoospores (swimming water spore borne out of the

sporangia), which travel both down the leaves of individual plants and to new nearby plants via wind currents or splashing water.

Cultural Control:

Scouting regularly allows early identification of disease before significant spread and damage. The following practices can also help prevent disease development:

- Plant resistant varieties when possible
- Rotate away from susceptible crops (3+ years)
- Plant in areas with good airflow
- Maintain proper spacing between plants
- Avoid overhead irrigation
- Maintain proper soil moisture
- Destroy plant debris, cull piles, volunteers

Chemical Control:

For Wisconsin-specific fungicide information, refer to the Commercial Vegetable Production in Wisconsin (A3422), a guide available through the UW Extension Learning Store website. Or, for home garden fungicide recommendations, see Home Vegetable Garden Fungicides (D0062), a fact sheet available through the UW Plant Disease Diagnostic Clinic website. Always follow label directions carefully.

Photos

Photo Credit: Howard F. Schwartz, Colorado State University, Bugwood.org

Additional References:

Lorbeer, James, and John Andaloro. 1984. “Onions-Downy Mildew Fact Sheet.” 1984. http://vegetablemdonline.ppath.cornell.edu/factsheets/Onions_Downy.htm.

Olis, Jim, and Brian Hudelson. 2021. “Downy Mildew | Plant Disease Diagnostics Clinic.” 2021. https://pddc.wisc.edu/2015/07/21/downy-mildew/.

Brassica Alternaria Leaf Spot

Authors: A.A. Abbrescia, A.J. Gevens, R.L. Groves, B. Bradford

Last Updated: May 2023

Description & Symptoms:

Brassica Alternaria leaf spot is a fungal disease of brassica crops caused by *Alternaria brassicicola*. Symptoms begin as small, black lesions on leaves that enlarge to form target-like concentric rings of necrotic tissue surrounded by a yellow halo. When humidity is high, these lesions produce black spores on the leaf surface.

Primary Source: Infected seed, infected overwintering plant debris, infected brassica weeds
Spread: Windborne spores, rain and irrigation splash, insects like flea beetles
Favorable Conditions: Spores are produced in high humidity (>87%) and moderate-to-high temperatures (68-88ºF). Optimal temperatures for infection are 55-75ºF.

Infection & Disease Cycle:

Alternaria brassicola can overwinter on plant debris in the soil. Once temperature and humidity rise, spores (conidia) can spread from plant debris via wind, rain, and irrigation. These spores will inoculate healthy plant tissue, usually on lower leaves, causing lesions that will produce spores (sporulate) in high humidity. Lesions may also occur on plants coming from infected seeds, as well as brassicaceous weeds. Spores will disseminate to new healthy plant material, continuing the disease cycle.

Cultural Control:

Scouting regularly allows early identification of disease before significant spread and damage. The following practices can also help prevent disease development:

- Plant disease-free seed
- Manage host weeds
- Manage insect vectors (ex. flea beetles)
- Rotate away from crucifers (3 years)
- Maintain proper spacing between plants
- Avoid overhead irrigation
- Avoid working in fields when plants are wet
- Steam or fumigate seedbed soil
- Destroy infested plant debris

Chemical Control:

For Wisconsin-specific fungicide information, refer to the Commercial Vegetable Production in Wisconsin (A3422), a guide available through the UW Extension Learning Store website. Or, for home garden fungicide recommendations, see Home Vegetable Garden Fungicides (D0062), a fact sheet available through the UW Plant Disease Diagnostic Clinic website. Always follow label directions carefully.

Photos

Photo Credit: Elizabeth Bush, Virginia Polytechnic Institute and State University, Bugwood.org

Photo Credit: Gerald Holmes, Strawberry Center, Cal Poly San Luis Obispo, Bugwood.org

Additional References:

Hoidal, Natalie. 2022. "Alternaria Leaf Spot and Head Rot of Brassica Crops." 2022. https://extension.umn.edu/disease-management/alternaria-leaf-blight.

Sharma, Pratibha, Julie Kikkert, and Sarah Pethybridge. 2021. "Alternaria Leaf Spot of Brassicas | Cornell Vegetables." 2021. https://www.vegetables.cornell.edu/pest-management/disease-factsheets/alternaria-leaf-spot-of-brassicas/.

Marbleseed 2022 Slides:

https://vegento.russell.wisc.edu/

https://vegpath.plantpath.wisc.edu/

https://vegento.russell.wisc.edu/

https://vegento.russell.wisc.edu/

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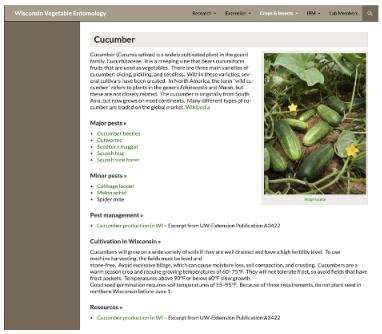

- General information
- Major Pests
- Minor Pests
- Management
- WI Cultivation Tips
- Resource Links

https://vegento.russell.wisc.edu/

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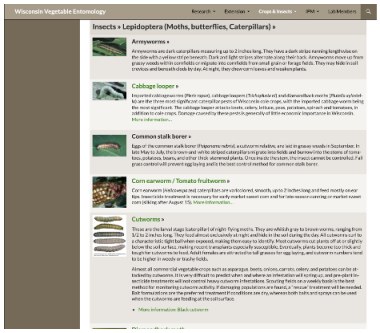


https://vegento.russell.wisc.edu/

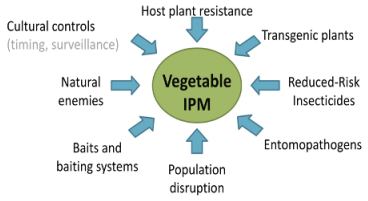
https://vegento.russell.wisc.edu/

- General information
- Appearance
- Symptoms/effects
- Life cycle
- Management
- Resource Links
  - UW-Extension fact sheets
  - UW-Extension publications
  - Additional useful websites

https://vegento.russell.wisc.edu/

https://vegento.russell.wisc.edu/

Insect pest management tactics for vegetables



Using many or all available tools to manage pests

Vegetable IPM Resources

Cornell University
Organic Guide for Vegetables

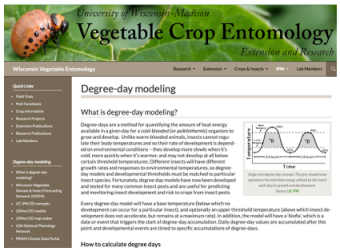
http://nysipm.cornell.edu/organic_guide/veg_org_guide.asp

Organic Materials Review Institute
Web-page

http://www.omri.org/omri-lists/download

ATTRA
Sustainable Agriculture Topics

https://attra.ncat.org/publication.html



https://vegento.russell.wisc.edu/

Warm and cold-blooded animals

- **Homeotherm:** an organism whose internal temperature remains constant

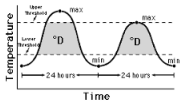
- **Poikilotherm**: an organism whose internal temperature varies considerably

  - Temperature controls the developmental rate of insects

Degree Day Models: The Basics

Models aim to quantify daily heat energy available for insects to develop

- **Biofix:** date or event after which degree days will begin to accumulate (Jan 1, eggs)
- **Lower Threshold**: temperature beneath which no development will occur
- **Upper Threshold**: temperature above which development plateaus at maximum rate



http://fyi.uwex.edu/hort/files/2014/11/Degree-Daysfor-Common-Fruit-and-Vegetable-Insect-Pests.pdf

Degree Day Models: The Basics

Different insect species have different developmental min, max, and biofix

List of degree-day models for insect pests of vegetable crops in Wisconsin

Search:

COMMON NAME	BINOMIAL NAME	TMIN F	TMAX F	BIOFIX
Alfalfa weevil	Hypera postica	48	none	Jan 1
Asparagus beetle (common)	Crioceris asparagi	50	86	Jan 1
Black cutworm	Agrotis ipsilon	50	86	May 15*
Brown marmorated stink bug	Halyomorpha halys	54	92	Jan 1
Cabbage looper	Trichoplusia ni	50	90	May 15*
Cabbage maggot	Delia radicum	42.8	86	Jan 1
Colorado potato beetle	Leptinotarsa decemlineata	52	none	May 1*

* Note: Models with biofix dates other than Jan 1 are probably less reliable and the biofix may need to be adjusted to match an observed event such as the appearance of egg masses.

Why use degree-day modeling?

- Unpredictable spring temperatures can make traditional calendar dates less reliable

- Using observed temperatures in a specific year can often give more accurate results

Squash vine borer, *Melittia cucurbitae*

- Flying clearwing moth
- Rusty brown abdomens
- Seen during daylight and dusk
- Adults emerge around 900 DD_{50F}

- Quickly mate & lay eggs after emergence
- Females can lay 150-200 total eggs

- Larvae ¾ - 1 inch in length
- Hatch & burrow in 10-15 days
- Apparent entry hole & frass at plant base

- Advanced damage may look like bacterial wilt

Squash vine borer - Management

Cultural Control

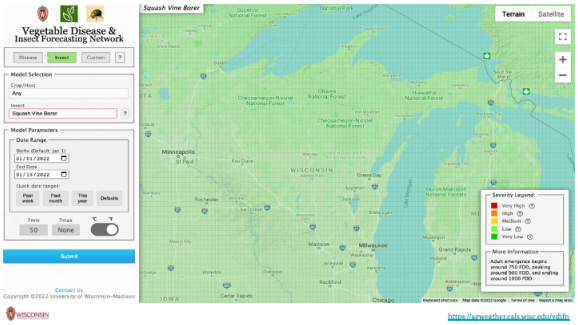
- Scouting
  - Look for entrance holes & frass at plant base
  - Yellow water-filled bowls in late June
  - Adults can also sometimes be seen flying
- Planting crops early in season
- Floating row covers
  - Most effective during peak adult activity
- Planting trap crop (eg. summer squash)
  - Plant early, destroy residue before larvae pupate

Chemical Control

- Difficult to chemically control
  - Larvae are protected within stem
- Want to target before/during egg-laying period

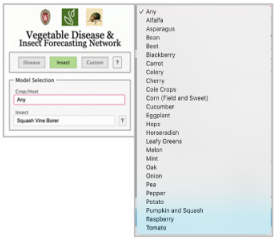
A Brief Window of Opportunity

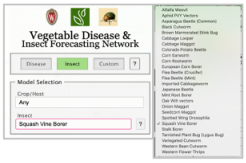
- Adults emerge around 900 DD_{50} & eggs hatch/burrow within two weeks
- Management is most effective when we know the timing of pest development
- Window varies yearly
- **How do we catch this window?**



https://agweather.cals.wisc.edu/vdifn

1.Select your crop and insect



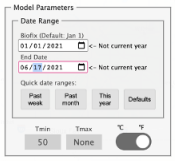


https://agweather.cals.wisc.edu/vdifn

Note: Find insect information

https://agweather.cals.wisc.edu/vdifn

2.Select your biofix date and end date



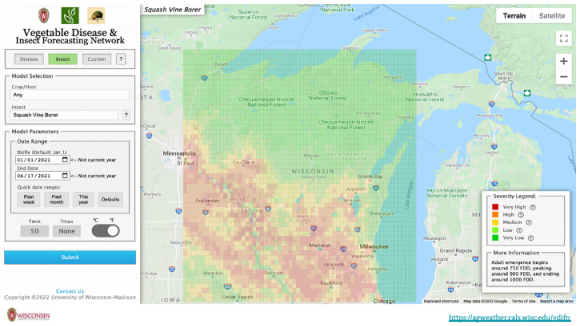
Squash Vine Borer, (1 generation per year)

Base temperature = 50°F

Biofix - January 1

Peak 1st gen adult emergence @ 900 DD_{50}

Temperatures auto-populate for every insect model



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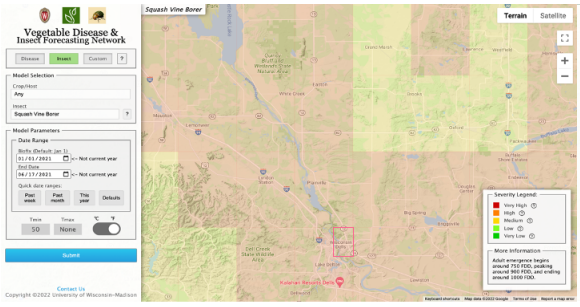

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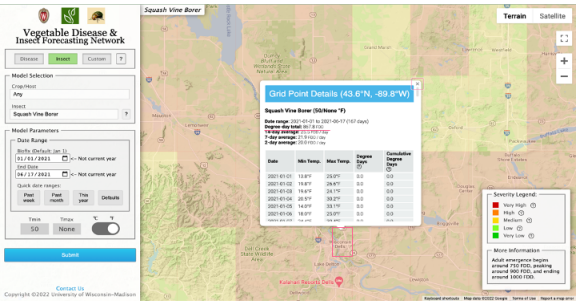


https://agweather.cals.wisc.edu/vdifn

Up Next: Disease!

Insect Pests

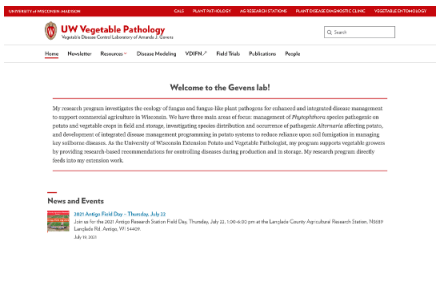
- Vegetable Entomology Website Resources
  - Research, Extension, Identification, IPM
- Pest-control case study: Squash Vine Borer
- VDIFN Website: What is it and How to Use It

https://vegento.russell.wisc.edu/

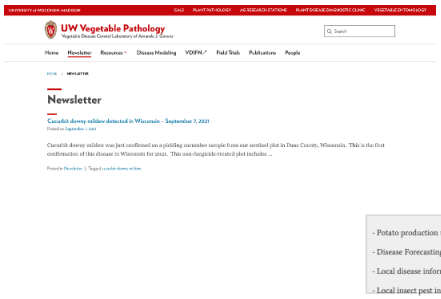
Diseases

- Vegetable Pathology Website Resources
  - Newsletters, Research, Identification, IPM
- Disease-control case study: Tomato Late Blight
- VDIFN Website: Part 2

https://vegento.russell.wisc.edu/

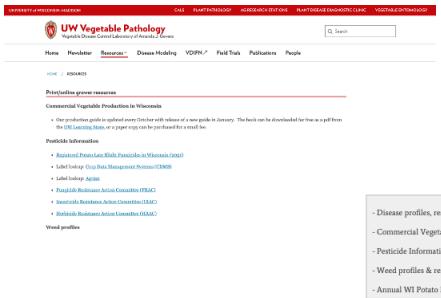


https://vegpath.plantpath.wisc.edu/



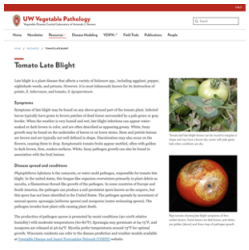
- Potato production updates
- Disease Forecasting Tools & updates
- Local disease information & updates
- Local insect pest information & updates

https://vegpath.plantpath.wisc.edu/



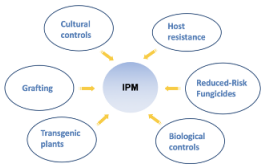
- Disease profiles, resources, + projects
- Commercial Vegetable Production Guide
- Pesticide Information
- Weed profiles & resources
- Annual WI Potato Meeting links

https://vegpath.plantpath.wisc.edu/



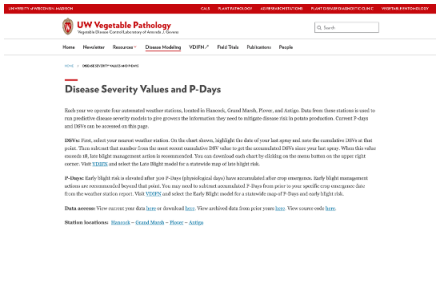
- Symptoms (with pictures)
- Disease spread & conditions
- Life cycle
- Disease modeling (VDIFN)
- Management

Disease management tactics for vegetables



Using many or all available tools to manage disease

https://vegpath.plantpath.wisc.edu/



Vegetable Disease Model Variables

- **Temperature** (much like insects)
- **Moisture**: Relative humidity, leaf wetness
- **Plant physiology**: time since emergence, etc.

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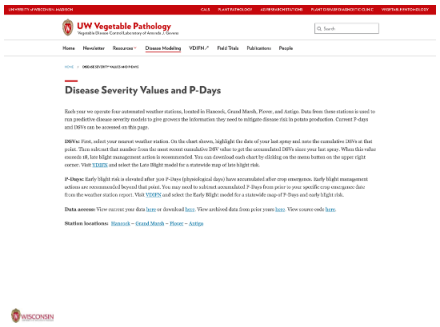


https://vegpath.plantpath.wisc.edu/

Tomato Late Blight, *Phytophthora infestans*

- Foliar lesions: round/irregular shape, brown center with pale green halo when conditions are dry
- When moist, lesions appear greasy and white, fuzzy sporulation underneath leaf

- Lesions on stem and flower discoloration
- Firm, sunken lesions on fruit

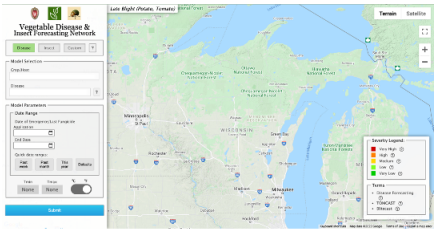
Tomato Late Blight - Management

Cultural Control

- Planting resistant cultivars
- Eliminating volunteers plants
- Properly spacing plants
  - Increases airflow and reduces humidity

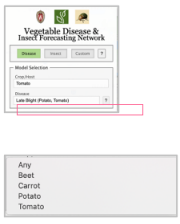
Chemical Control

- Apply fungicides before infection for best control
- Action recommended when DSV > 18



https://legweather.cals.wisc.edu/vdifn

1.Select your crop/host and disease



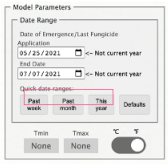
https://legweather.cals.wisc.edu/vdifn

Note: Find disease information

?

https://legweather.cals.wisc.edu/vdifn

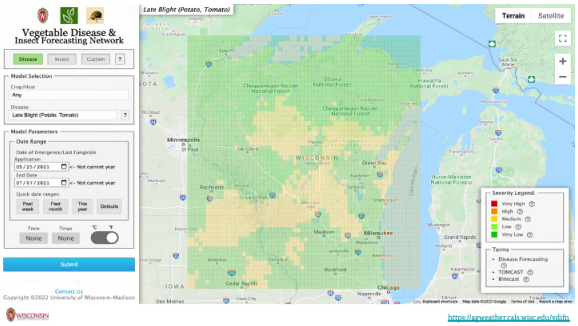
2.Select emergence/application date and end date



Tomato Late Blight

Date of Emergence: set out tomato transplants

Action recommended at DSV 18



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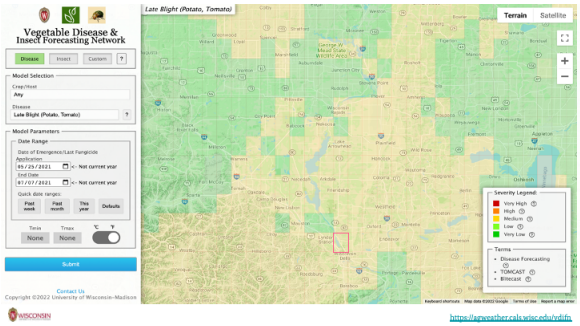

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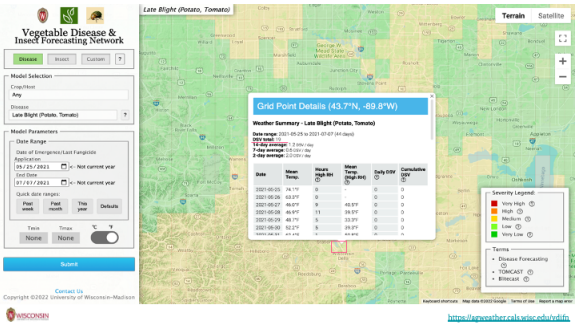
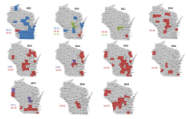


https://agweather.cals.wisc.edu/vdifn

Important Note: Risk vs. Pathogen Presence

- Model assumes equal disease distribution/presence across state
- In reality, late blight can be present in some counties and not others
- Nearby disease presence should affect management decisions



Tomato Late Blight in WI (2009-2019)

https://vegpath.plantpath.wisc.edu/

Tracking Late Blight in WI: Newsletter Updates

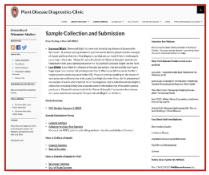
- Dr. Gevens puts out newsletter updates when notable diseases are confirmed in WI

- Updates often include confirmed location, action plan, relevant disease information, and management recommendations

https://vegpath.plantpath.wisc.edu/

Plant Disease Diagnostics Clinic

- Difficult to distinguish between some diseases
- Submit samples for testing
  - Late blight diagnostics for free!
- Educational programs & resources
- Disease identification information



https://pddc.wisc.edu/

Questions?