Alternative Control Methods for *Verticillium wilt*: A Literature Review

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ABSTRACT

Verticillium wilt (*V.albo-atrum* and *V.dahiae*) is a soil-borne fungus that is causing economic losses and lower yields for farmers across the country. The disease has a wide host range and can live in the soil without a host for a decade or more. Finding effective and reasonable control methods has been difficult for some industries. Some methods such as sanitation, chemical application and crop rotation have not been completely effective at suppressing or eliminating the disease. Alternative control methods have been researched and tested, with some completely eliminating the disease, but these methods have to be continuously implemented and monitored in order for them to be effective. This literature review investigated the availability of scientific research on effective alternative control methods for *Verticillium wilt*. Potential effective alternative control methods were identified, including anaerobic soil disinfection, soil solarization, broccoli incorporation, mustard incorporation, compost and green manure. Further research is needed to fill knowledge gaps related to successful implementation of these controls in suppressing or eliminating *Verticillium wilt.*

Contents

Introduction

Background and Setting

Verticillium wilt is a disease that affects multiple different hosts ranging from trees and shrubs to vines, field crops and vegetables. The disease is caused by the soil-borne fungi *Verticillium albo-atrum* and *Verticillium dahiae*. Once the Verticillium fungus is introduced into a field or garden, it can survive for several years in the soil (University of Illinois Extension, 1997). The fungi spreads through flowing water (i.e. irrigation furrows), strong winds (i.e. seeds, tools or farm machinery), and in the soil and roots of transplants.

The symptoms may vary somewhat among hosts but all hosts share characteristics of premature foliar chlorosis and necrosis and vascular discoloration in stems and roots (Berlanger and Powelson, 2000). Discoloration of the vascular tissue, especially in roots and lower stems, is commonly used as a diagnostic tool but is not always present. Plants often have symptoms on one branch or one side of the plant. The entire plant may die suddenly in a few weeks or slowly over a period of years (Olsen, 1998).

The disease cycle of both species is similar in most aspects except that *Verticillium dahliae* produces microsclerotia and *Verticillium albo-atrum* produces melanized mycelia (Berlanger and Powelson, 2000). Optimum growth of *Verticillium albo-atrum* occurs at 68° to 77°F, while *Verticillium dahliae* prefers slightly higher temperatures 77° to 81°F and is somewhat more common in warmer regions. Different strains within each species differ considerably in virulence and other characteristics. Although some Verticillium strains show host specialization, most of them attack a wide range of host plants. Agricultural soils may contain up to 100 or more microsclerotia per gram. Six to 50 microsclerotia per gram are sufficient to generate 100 percent infection in such susceptible crops as eggplant, pepper, potato, and tomato (University of Illinois Extension, 1997).

After the host dies or the growing season ends, *Verticillium wilt* can survive by overwintering in dead plant parts that have fallen to the ground; the fungi can also live in the soil whether or not a host is available. Thus the disease is capable of long-term survival (up to 15 years) without contact with a host plant (University of Illinois Extension, 1997). Also, *Verticillium wilt* is known to naturally colonize soils where susceptible hosts have never been grown but once contact is made with a new host, the fungi again infects the root system, progresses upward, and the disease cycle is repeated.

Since *Verticillium wilt* can survive for long periods of time with or without a host it makes it a difficult disease to suppress and reasonably eliminate. It is known to strive in temperate zones which encompasses majority of the United States. If the disease is not properly controlled then it can lower yields and have a huge economic impact.

Statement of the Problem

Verticillium wilt affects a large number of crops, vegetables, fruits and trees. Some of the main ones of significance include lettuce in the Salinas Valley in California, cotton in the High Plains of Texas and strawberries in California.

The value of California’s lettuce crop, which represents the majority of the United States’ lettuce production, was $2.0 billion in 2016 (National Agricultural Statistics Service 2017). In the Salinas Valley of California the *Verticillium dahliae* fungus has spread rapidly through the prime lettuce production region resulting in devastating economic losses. *Verticillium wilt* first killed a lettuce crop in California’s Salinas Valley in 1995. Prior to 1995, lettuce was believed to be immune. By 2010, more than 175 fields were known to be infected with *Verticillium wilt*

(Subbarao, 2011). Researchers have narrowed the introduction and spread of the fungus to three ways – spread locally, infested lettuce seeds or infected spinach seeds. The only control that farmers used to have is to fumigate with methyl bromide. But since it was discovered that methyl bromide is an ozone-depleting substance the Montreal Protocol has eliminated its use for fumigation of vegetable crops such as lettuce (Caroll et al., 2017).

The Great Plains of Texas are currently struggling with finding control methods for soil-borne diseases in the cotton fields. *Verticillium dahliae* is one of the most economically important diseases in the region (Woodward, 2014). In cotton the disease can make defoliation occur prematurely which negatively impacts yields and fiber quality. One of the main control options for farmers in that area is to change their variety selection. In 2013 the Texas AgriLife Extension conducted research trials evaluating the most common varieties sold and which one perform better against *Verticillium dahiae* under certain conditions (Woodward, 2014).

Verticillium wilt continues to be one of the most potentially damaging diseases caused by soil-borne pathogens in strawberries grown in California (Bolda and Koike, 2013). In contrast to *Verticillium wilt* of other crops such as lettuce, vascular discoloration in strawberry crowns may be subtle or absent. There have been several suggestions and research done in regards to managing the disease; these include plant breeding for resistance, soil treatments, sanitation and crop rotation. None of these have been completely effective against the spread and distribution of the disease.

Invasive plant pathogens, including fungi like *Verticillium wilt*, cause an estimated $21 billion in crop losses each year in the United States (Rossman, 2009). States that are major agricultural producers and global traders sustain significant economic damage form soil-borne diseases. Fungi damage a wide variety of crops, resulting in yield- and quality-related losses, reduced exportability, and increased fungicide expenditures (Palm, 2001). In addition to economic losses, there are no effective treatment exists once plants are infected by *Verticillium wilt* (Fradin and Thommas 2006; Xiao and Subbarao 1998).

Significance of Problem

In most areas there are no effective and reasonable control methods in place to reduce or eliminate *Verticillium wilt*. The fungus attacks a very wide range of hosts and can survive for extended periods of time without a host. It could also be present in fields before any planting occurs. Without tests farmers and growers have no idea how much microsclerotia per gram are present and how bad the infection could be to their crops or vegetables.

Infection from *Verticillium wilt*, if not properly controlled, can lower yields and have a huge economic impact. In the Northeast alone 1,687,080 tons of fresh market and processing vegetables on 264,490 acres, worth $701,377,000 suffer 10-15% losses from soil borne diseases (NASS Crop Profiles, 2007). While other soil-borne diseases such as *Fusarium wilt* and Corky Root Rot are equally as damaging, *Verticillium wilt* is particularly concerning because of its wide host range and susceptibility to survive under different conditions. It is one of the most damaging diseases in cotton, lettuce and strawberries.

Alternative control methods are needed to ensure that farmers don't lose some or all of their crops or vegetables to the fungus.

Purpose of the Project

The purpose of this project is to investigate alternative control methods to effectively and efficiently control *Verticillium wilt*, as identified through a review of scientific research studies. This includes the investigation of control methods researched in different states, environments and applied to different crops and vegetables.

Project Objectives

The objectives of this project are to summarize available research on alternative control methods of *Verticillium wilt* including related applications, identify gaps in knowledge, and provide recommendations for future research needs in this area.

Review of Literature

Anaerobic Soil Disinfection

Aerobic soil disinfection was developed independently in Japan and the Netherlands in the 1990s and 2000s, and more recently has been researched as a potential fumigation alternative in the United States. ASD has also been referred to as biological soil disinfestation, soil reductive sterilization, reductive soil disinfestation, and anaerobically-mediated biological soil disinfestation (Shrestha, Wszelaki, and Butler, 2014). Anaerobic soil disinfection is a non-chemical, pre-plant soil treatment developed for control of soil borne diseases. Soil treatment by ASD includes incorporating a labile carbon source, tarping with plastic, and irrigation of the topsoil to saturation to facilitate the development of anaerobic soil conditions driven by soil microbes (McCarthy, 2012). This method of soil-borne disease management is effective against a wide range of soil-borne pathogens, including bacteria, fungi and nematodes (Testen and Miller, 2017). The processes occurring during the anaerobic decomposition of the added carbon source have been reported to reduce or completely eliminate soil-borne disease populations.

A study conducted by Blok, Lamers, Termorshuizen and Bollen in 2000 tested ASD on broccoli and grass to determine if it effectively suppressed *Verticillium dahliae*. There were two field experiments that occurred over two years. Plots were amended with fresh broccoli or grass (3.4 to 4.0 kg fresh weight m–2) or left nonamended, and covered with an airtight plastic cover (0.135 mm thick) or left noncovered. In plots amended with broccoli or grass and covered with plastic sheeting, anaerobic and strongly reducing soil conditions developed quickly. After 15 weeks, survival of *Verticillium dahliae* in inoculum samples buried 15 cm deep was strongly reduced in amended, covered plots in both experiments. The pathogens were not or hardly inactivated in amended, noncovered soil or nonamended, covered soil. The latter indicates that thermal inactivation due to increased soil temperatures under the plastic cover was not involved in pathogen inactivation. The results show the potential for this approach to control soil-borne pathogens.

Anaerobic soil disinfection has shown to be a practical technique that permits the management of soil-borne fungi for different high value crops.

Soil Solarization

Soil solarization is a process that utilizes the sun to heat soils under transparent plastic tarps to temperatures lethal to soil-borne organisms (Pullman, DeVay, Garber and Weinhold, 1981). The use of solarization technology has also been researched for weed management. Preplant soil fumigation with methyl bromide is phased out so farmers had to switch to nonchemical and cultural methods as alternatives.

In 2001 Lopez-Escudero and Blanco-Lopez studied the effect of soil solarization to control *Verticillium wilt* in established olive orchards in Spain. Four soil solarization experiments were completed in three commercial olive orchards infested with *Verticillium dahliae* in southern Spain. Solarization treatments were applied to lines of trees for either one (single) or two consecutive (double) years. Solarization significantly reduced pathogen populations in the top 20 cm of soil for at least 3 years in relation to control plots. Disease severity was reduced only in orchards with medium or high initial inoculum densities. In orchards with low inoculum densities, soil solarization did not result in significant differences in disease incidence and severity, but improved recovery of trees from the disease. Also, soil-solarized plots remained free of weeds.

Another study conducted by Pullman, DeVay, Garber and Weinhold the summers of 1977-1979 tested solarization of the soil by covering it with transparent polyethylene tarps to determine its effectiveness in controlling soil-borne pathogens. Propagules of *Verticillium dahliae* were greatly reduced or completely eliminated 0-46 cm in soil tarped for 14-66 days. Higher soil temperatures and a more rapid decline in pathogen populations occurred in soils irrigated after placement of tarps than in those pre-irrigated and then tarped.

Soil solarization has been an effective nonchemical method to effectively controlling *Verticillium wilt* and weeds. It can improve soil structure and increase the availability of nitrogen (N) and other essential plant nutrients. A potential drawback to this control method is that it most effective in warm, sunny locations so some areas might not be able to use this control method.

Broccoli Incorporation

A method of reducing *Verticillium wilt* disease in crops, specifically cauliflower, is by adding and incorporating broccoli residue into the soil. This method has been successfully studied and researched with every study concluding that broccoli is resistant to the *Verticillium dahliae* infection and does not express wilt symptoms. In 2001 Bhat and Subbarao conducted a study on several different broccoli cultivars and the effects of *Verticillium dahliae* on their root growth and coloring. Broccoli cultivars Baccus, Greenbelt, Parasol, Patriot, and Symphony showed resistance to *Verticillium wilt* infection thus making broccoli an attractive rotation crop for the management of *Verticillium wilt* in many cropping systems (Bhat and Subbarao, 2001).

One study conducted from 1993 to 1995 determined that the cauliflower disease incidence and severity were consistently and significantly reduced in the broccoli residue plots when compared with no broccoli (Koike and Subbarao. 2000). Another study tested the effects of broccoli residue on the colonization of roots by *Verticillium dahliae* in both broccoli and cauliflower in soils with different levels of *Verticillium dahliae* inoculum and with or without fresh broccoli residue amendments. The three soils included a low-Verticillium soil, a high-Verticillium soil, and a broccoli-rotation soil (soil from a field after two broccoli crops) with an average of 13, 38, and below- detectable levels of microsclerotia per gram of soil, respectively. Cauliflower plants in broccoli-amended high-Verticillium soil had significantly ($P \leq 0.05$) lower wilt incidence and severity than did plants in unamended soil. In high-Verticillium soil, the broccoli residue amendment caused a marked reduction in colonization rate of *Verticillium dahliae* per unit of inoculum on both cauliflower and broccoli roots. In addition to its detrimental effects on the viability of microsclerotia in soil, broccoli residue may also have an inhibitory effect on the root-colonizing potential of surviving microsclerotia (Shetty, Subbarao, Huisman and Hubbard, 2000).

Another way of incorporating broccoli to control *Verticillium wilt* is to plant it near, around or before planting a crop that is susceptible to the disease. Some growers have experimented with this solution, but relatively low returns from broccoli in some regions prevent this option from becoming a widespread solution. Planting all infected acreage to broccoli may also flood the market, further driving down broccoli prices. With a season length of 2 to 3 months, between 4 and 6 crops of broccoli could be planted within a year, and multiple crops of broccoli would be necessary to reduce *Verticillium wilt*. Using the very conservative estimate of 4,000 acres infected by *Verticillium wilt*, this could result in harvested acres of broccoli ranging from 16,000 to 24,000 acres per year (or 32,000 to 48,000 acres if infected acres are equal to 8,000) (Carroll et al. 2017).

Several studies emphasized how damaging *Verticillium wilt* is to cauliflower and supported that the disease was successfully managed by incorporating broccoli residues into infested soil or planting broccoli nearby. Broccoli is not susceptible to *Verticillium wilt* and it reduces the levels of microsclerotia in the soil.

Mustard Incorporation

Cover crops are seeded primarily to provide soil health and other benefits. One cover crop, high glucosinolate mustard (HGM), has unique properties that influence soil biology. HGM cover crops have become popular for their biofumigant properties, meaning that they have compounds that when managed can reduce pest pressure in the soil (Darby and Gupta, 2017).

High glucosinolate mustard cover crops have been bred to contain elevated levels of glucosinolates, throughout the whole plant. These plants also contain an enzyme called myrosinase. When the plant is growing, the glucosinolates are separated physically from the myrosinase enzyme. When the HGM cover crops are damaged through mowing or tillage, the glucosinolate comes in contact with the myrosinase and is broken down to secondary compounds, including isothiocyanates. The isothiocyanates are the active ingredients that make the plant work as a biofumigant. Mustards vary with the types and concentrations of glucosinolates they contain. Some glucosinolates are biologically active against insects, nematodes, and fungal pathogens, while others are better for preventing weeds from growing. The mustard can be grown in fruit and vegetable gardens, grains, vineyards, orchards, hoop houses, and fallow soil in need of rehabilitation (Darby and Gupta, 2017).

A Penn State Extension agent, Tianna Dupont, worked with Meadow Gate Vista farm from 2010 to 2013 to study the effects of cover crops on *Verticillium wilt.* They planted strips of cover crops in fields that had a history of *Verticillium wilt* on tomato. They used mustard cv.

Caliente 119 which is known to have "biofumigant" properties and compared it to buckwheat as a control. In 2011 tomatoes after a rotation of mustard yielded twice as much as tomatoes grown after the buckwheat cover crop control.

Glucosinolates in cover crops have been shown to be effective for preventing *Verticillium wilt* and other soil-borne diseases (Brown and Morra, 2005; Larkin, 2013; Larkin et al., 2011). While HGM has the ability to reduce disease, weed, and insect pest pressure, biofumigation should not be considered a single solution to these management issues. HGM and biofumigation from cover cropping should be used as part of an integrative approach to maintaining healthy crops, especially considering that biofumigation efficacy will decrease as the season continues.

Compost

Growers have started using compost amendments to improve the physical and chemical properties of soil. Compost can also enhance the activity of microorganisms that are inhibitory to plant pathogenic fungi (Mazzola, 2004). Numerous container-based studies in greenhouses or growth rooms have consistently demonstrated a suppressive effect of composts on soil-borne diseases like *Verticillium dahliae*. Composts have also been shown to suppress several diseases in the field, although the effects have been generally smaller and more variable than in container experiments. The disease suppressive effect of compost is generally increased with rate of application. Compost inclusion rates of at least 20% were normally required to consistently obtain a disease suppressive effect, particularly in peat-based media, but significant disease suppression has been found at lower inclusion rates in soil. Reported levels of disease suppression were variable, even using apparently similar composted materials at the same rates. Sterilization of composted materials generally resulted in a loss in disease suppressiveness, indicating that the mechanism was often or predominantly biological, although chemical and physical factors have also been implicated. The inoculation of composts with biological control agents may improve the efficacy and reliability of disease control obtained (Noble and Coventry, 2005).

In one study by Entry, Strausbaugh and Sojka, they used wood chip polyacrylamide (PAM) cores to alter the soil environment in a greenhouse study to favor indigenous soil microorganisms in vegetable and manure compost to reduce *Verticillium dahliae* infection of potato (Solanum tuberosum L.) plants. Potato plants growing in soils amended with vegetable compost-wood chip-PAM cores had significantly less *Verticillium dahliae* infection ratings than control soils and soils with dairy or vegetable compost alone.

In another study, Varo-Suárez and colleagues tested 35 composted organic residues including olive waste compost, grape compost, cork compost, vermicompost, fulvic acids, humic acids, leonardite+compost, dairy waste (2.5% lactic acid), and manure of resp. poultry, sheep, pigs, cows, sewage sludge and compost tea, and in addition of 15 mixtures including some of the residues mixed with the non-pathogenic *Fusarium oxysporum* FO12. The various residues tested appeared to vary very strongly in their effects, from no effect to complete suppression. The two grape composts were able to suppress *Verticillium wilt* completely, while e.g. olive waste compost had only minor effects. On the other hand, olive waste compost mixed with 2.5% lactic acid from the dairy industry did show a very strong disease suppressive effect, stronger than when the lactic acid product was used alone. The authors suggest that the effects of grape compost were caused by the high concentrations of phenolic substances and volatile organic acids.

One downside and consideration when using compost to control *Verticillium wilt* is that compost made from crop residue may include plants that were infected with *Verticillium dahliae*, and because microsclerotia can survive in animal guts (Markakis, 2014), manure may be contaminated as well. Proper composting is required to ensure that no viable microsclerotia remain in the final product. In California certain regulatory groups have established regulations that require materials reach 55 °C (131°F) or higher for 15 days or longer with a minimum of five turnings of the windrow during this time, which should be sufficient to kill *Verticillium dahliae* microsclerotia in manure or crop residue (Lloyd and Gordon, 2014).

Green Manure

A green manure is a crop that is grown and then incorporated into the soil while still green. This practice was widely used to improve soils and provide nutrients to crops before synthetic fertilizers became available. In contrast to the low-input, low-management green manures of the past, mustard green manures require fertilizer, irrigation, and intensive management. They require a current understanding of soil ecology, soil-borne pests, plant biochemistry, and breeding and screening techniques. And unlike synthetic fertilizers, they can improve the soil's physical, chemical, and biological qualities (McGuire 2016). Fungal and bacterial diseases and parasitic nematodes have all been reduced by using green manure crops (Wiggins and Kinkel 2005). Majority of the studies available for green manure have been conducted on potato plants.

According to McGuire, with *Verticillium dahliae*, researchers have observed that when certain green manures (barley, mustard, rapeseed, sudangrass, and sweet corn) are incorporated with a chisel plow or disk before planting a potato crop, the level of infection by *Verticillium wilt* is low, even with high levels of the fungus still in the field. The green manure serves as an energy source for beneficial microorganisms. It is suspected that these organisms outcompete *Verticillium wilt* for energy and subsequently increase in number. Then, after the potato crop is planted, they possibly exclude *Verticillium wilt* from the area along the potato roots, called the rhizosphere. This is the only place where *Verticillium wilt* can infect potato plants.

In one study by Davis, Huisman, Westermann, Hafez, Everson, Sorensen and Schneider they conducted two field studies to investigate the effects of green manure treatments on *Verticillium wilt* (*V. dahliae*) of potato (Russet Burbank). Each study involved the use of a sudangrass (Sorghum vulgare var. sudanense 'Monarch') green manure treatment and a fallow treatment for either 2 or 3 years prior to growing potato. In addition to sudangrass, comparisons also were made with several green manure treatments, including Austrian winter pea (Pisum sativum 'Austrian winter'), two cultivars of rape (Brassica napus var. napus 'Dwarf Essex' and 'Bridger'), rye (Secale cereale), oat (Avena sativa 'Monida'), and corn (Zea mays 'Jubilee'). *Verticillium wilt* of potato was best controlled after green manure treatments of either sudangrass or corn; after these treatments, yields were increased above all other treatments. *Verticillium wilt* was most severe when potato followed the fallow treatment and intermediate following rape, Austrian winter pea, oat, and rye.

When used in certain cropping systems, green manure crops have been able to replace expensive fumigants (McGuire, 2003). However, the degree and duration of these beneficial effects depend on many factors, such as soil texture, temperature and moisture, plant age and species, climate, tillage practices, pest species and levels, and crop rotation (Larkin et al., 2011). Therefore, the benefits of green manures may differ between systems and between fields.

Summary of Outcomes, Discussions, and Recommendations

Extensive literature searches were conducted on all of the potential alternative control methods mentioned above. It was not difficult to find publications, research and studies conducted specifically on *Verticillium wilt* because it is one of the more common soil-borne diseases. Because of the environmental, regulatory, economic, and political concerns of using synthetic, highly toxic agrochemicals, agricultural industry and research teams are attempting to find viable alternative control methods. Most studies were conducted on small scales and some occurred within greenhouses so more insight is needed into potential control methods that can be used on a bigger scale within crop and vegetable fields. The lack of a specific control method that can be used across the board highlights a significant gap in knowledge on *Verticillium wilt* and readily available sources of control. Future studies on one specific alternative control method would help farmers ensure their yields are drastically impacted from the disease.

Discussion of Alternative Control Methods

A few of the control methods investigated (mustard incorporation, compost, green manure) do not appear to be completely effective at eliminating *Verticillium wilt*. Mustard incorporation and the glucosinolates in the cover crop has been shown to be effective for preventing *Verticillium wilt* and other soil-borne diseases, but it should not be the sole control method because biofumigation efficacy will decrease as the season continues. As suggested from the research, HGM and biofumigation from cover cropping should be used as part of an integrative approach to maintaining healthy crops.

Two control methods investigated (compost and green manure) have the potential to host and transfer *Verticillium wilt* if the crop residues include plants that were infected. Because microsclerotia can survive in animal guts the manure may be contaminated as well. Proper composting is required to ensure that no viable microsclerotia remain in the final product. The widespread availability of compost and green manure along with the soil improvement properties are appealing to growers, but they need information on its use and effectiveness relative to the control of economically important root diseases in specific crops. The degree and duration of the beneficial effects depends on many factors, such as soil texture, temperature and moisture, plant age and species, climate, tillage practices, pest species and levels, and crop rotation. Therefore, the benefits of composts and green manures may differ between systems and between fields.

Recommendations for Future Research

Future research needs have been identified that could provide extremely beneficial information on alternative control methods of *Verticillium wilt.*

Anaerobic soil disinfection (ASD) seems to be a viable solution and alternative to the use of pesticides to control soil-borne diseases. Future research needs to focus on how to optimize the technique (in terms of carbon source used, temperature and degree of anaerobiosis attained) to control specific sets of pathogens, and to better which mechanism(s) are responsible for disease control in different situations. The role of observed microbial community shifts as a result of ASD in immediate disease control and long term disease suppression needs to be more fully explored. Further reductions in the costs of ASD compared to fumigant use will help increase adoption of the technique which is currently limited by cost and uncertainty about its effectiveness at controlling different pathogens across a range of environments.

Soil solarization has been an effective nonchemical method to effectively controlling *Verticillium wilt* and weeds with the only downfall being the weather needs to be sunny or warm majority of the time. The research concluded that a specific type of tarp, a transparent polyethylene plastic, was highly effective in reducing soil disease population and increasing crop yields. It was effective against a wide variety of soil-borne diseases on multiple different crops and vegetables. In some of the experiments the *Verticillium wilt* control and reduction in pathogen population extended into the second year after tarping. Through the research and studies examined it has proven to be an effective method for controlling soil-borne diseases, which is simple, nonhazardous, and does not involve toxic materials.

Incorporating broccoli residues have demonstrated its effectiveness in significantly reducing populations of *Verticillium dahliae*. As recommended by researchers, if sufficient volumes of broccoli residue are used as a regular component of crop rotation cycles, the suppressive activity may be even further heightened. This technique is economical and effective because it does not require the harvestable heads of the broccoli; the head generates revenue, and the remaining residues contribute to disease control. Broccoli residues are natural materials and pose no threat to the environment, surrounding crops, wildlife or people. Majority of the studies concluded that the disease incidence and severity were consistently and significantly reduced in the broccoli residue plots when compared with no broccoli.

Combined control methods, along with good environmental control programs and proper monitoring, may prove to be the most effective strategy to minimize the presence of *Verticillium wilt.*

References

Berlanger, I. & Powelson, M.L. (2000).Verticillium wilt. *The Plant Health Instructor*. doi:10.1094/phi-i-2000-0801-01

Bhat, R. G., & Subbarao, K. V. (2001). Reaction of broccoli to isolates of Verticillium dahliae from various hosts. *The American Phytopathological Society*. 85 (2), 141-146.

Blok, W. J., Lamers, J. G., Termorshuizen, A. J., and Bollen, G. J. (2000). Control of soilborne plant pathogens by incorporating fresh organic amendments followed by tarping. *Phytopathology*. 90 (3), 253-259.

Bolda, M., & Koike, S. (2013). Verticillium Wilt in strawberries: California 2013 Update. Retrieved from https://ucanr.edu/blogs/blogcore/postdetail.cfm?postnum=10993

Brown, J. & Morra M. J. (2005). Glucosinolate-containing seed meal as a soil amendment to control plant pests. National Renewable Energy Laboratory. University of Idaho, Moscow, Idaho.

Carroll, C. L., Carter, C. A., Goodhue, R. E., Lawell, C. C., & Subbarao, K. V. (2017). The economics of managing Verticillium wilt, an imported disease in California lettuce. *California Agriculture.* doi:10.3733/ca.2017a0028.

Darby, H., & Gupta, A. (2017). Using High Glucosinolate Mustard as a Cover Crop to Reduce Weeds and Disease. Retrieved from http://www.uvm.edu/extension/cropsoil/wp-content/uploads/HGM-manual-final.pdf

Davis, J. R., Huisman, O. C., Westermann, D. T., Hafez, S. L., Everson, D. O., Sorensen, L. H., and Schneider, A. T. (1996). Effects of green manures on Verticillium wilt of potato. *Phytopathology*. 86 (5), 444-453.

Dupont, T. (2015). Reducing Soil Borne Diseases with Cover Crops. Retrieved from https://extension.psu.edu/reducing-soil-borne-diseases-with-cover-crops

Entry, James & A. Strausbaugh, Carl & E. Sojka, R. (2013). Compost Amendments Decrease Verticillium dahliae Infection on Potato. Compost Science & Utilization. doi:10.1080/1065657X.2005.10702216.

Fradin, E., & Thomma, B. (2006). Physiology and molecular aspects of Verticillium wilt diseases caused by V. dahliae and V. albo-atrum. *Mol Plant Pathol*. doi:10.1111/j.1364-3703.2006.00323.

Koike, S. & Subbarao, K. V. (2000). Broccoli Residues Can Control Verticillium Wilt of Cauliflower. *California Agriculture*. 54 (3), 30-33.

Larkin, R., Honeycutt, C., and Olanya, O. (2011). Management of Verticillium wilt of potato with disease-suppressive green manures and as affected by previous cropping history. *Plant Disease.* 95 (5), 568-576.

Larkin, R. (2013). Green manures and plant disease management. *CAB Review*. 8.037, 1-10.

López Escudero J. & Mercado-Blanco, J. (2011). Verticillium wilt of olive: A case study to implement an integrated strategy to control a soil-borne pathogen. *Plant and Soil.* doi:10.1007/s11104-010-0629-2.

Lloyd, M., & Gordon, T. (2014). Verticillium wilt and Compost Amendments. Retrieved from https://ucanr.edu/blogs/blogcore/postdetail.cfm?postnum=15560

Markakis, E. A. (2014). Survival, persistence and infection efficiency of Verticillium dahliae passed through the digestive system of sheep. *Plant Disease.*

Mazzola, M. (2004). Assessment and management of soil microbial community structure for disease suppression. *Annual Review of Phytopathology.* 42, 35-59.

McCarty, D., (2012). Anaerobic Soil Disinfestation: Evaluation of Anaerobic Soil Disinfestation (ASD) for Warm-Season Vegetable Production in Tennessee. Master's Thesis, University of Tennessee. Retrieved from http://trace.tennessee.edu/utk_gradthes/1393

McGuire, A.M. (2003). Mustard Green Manures Replace Fumigant and Improve Infiltration in Potato Cropping System. *Crop Management.*

McGuire, A. (2016). Using Green Manures in Potato Cropping Systems. Retrieved from http://cru.cahe.wsu.edu/CEPublications/eb1951e/EB1951E.pdf

National Agricultural Statistics Service. (2017). Vegetables 2016 Summary. http://usda.mannlib.cornell.edu/usda/current/VegeSumm/Vege-Summ-02-22-2017_revision.pdf

Noble, R., & Coventry, E. (2005). Suppression of soil-borne plant diseases with composts: A review. *Biocontrol Science and Technology*. 15 (1), 3-20.

Olsen, M. W. (2011). Verticillium Wilt. Retrieved from https://extension.arizona.edu/sites/extension.arizona.edu/files/pubs/az1034.pdf

Palm M. E. (2011). Systematics and the impact of invasive fungi on agriculture in the United States. *BioScience*. 51, 141–47.

Pullman, G. S., DeVay, J. E., Garber, R. H., and Weinhold, A. R. (1981). Soil solarization: Effects on Verticillium wilt of cotton and soilborne populations of Verticillium dahliae, Pythium spp., Rhizoctonia solani, and Thielaviopsis basicola. *Phytopathology*. 71, 954-959.

Rossman A. (2009). The Impact of Invasive Fungi on Agricultural Ecosystems in the United States. *Biol Invasions.* 11, 97–107.

Shetty, K. G., Subbarao, K. V., Huisman, O. C., and Hubbard, J. C. (2000). Mechanism of broccoli-mediated Verticillium wilt reduction in cauliflower. *Phytopathology.* 90, 305-310.

Shrestha, U., Wszelaki, A. L., & Butler, D. M. (2014). Implementing Anaerobic Soil Disinfestation in Tennessee. Retrieved from https://extension.tennessee.edu/publications/Documents/SP765-B.pdf

Shrestha, U., Wszelaki, A. L., & Butler, D. M. (2014). Introduction to Anaerobic Soil Disinfestation as a Fumigant Alternative. Retrieved from https://extension.tennessee.edu/publications/Documents/SP765-A.pdf

Subbarao, K.V. (2011). Biology and epidemiology of Verticillium wilt of lettuce. Annual Lettuce Research Report. Crop Year 2010. California Leafy Greens Research Board, Salinas.

Testen, A. L., & Miller, S. A. (2017). Anaerobic Soil Disinfection for Management of Soilborne Diseases in Midwestern Vegetable Production. Retrieved from https://ohioline.osu.edu/factsheet/hyg-3315

Testen, A. L., & Miller, S. A. (2017). Identification and Management of soilborne diseases of tomato. Retrieved from https://ohioline.osu.edu/factsheet/hyg-3314

University of Illinois. (1997). Verticillium Wilt Disease. Retrieved from https://ipm.illinois.edu/diseases/rpds/1010.pdf

Wiggins, B.E. & L.L. Kinkel. (2005). Green Manures and Crop Sequences Influence Alfalfa Root Rot and Pathogen Inhibitory Activity among Soil-Borne Streptomycetes. *Plant and Soil.* 268 (1–2), 271–83.

Woodward, J. (2014). Texas Cotton: Seedling Diseases, Nematodes, and Verticillium Wilt. Retrieved from https://agfax.com/2014/03/18/texas-cotton-seedling-diseases-nematodes-and-verticillium-wilt/

Varo-Suárez, A., Raya-Ortega, M., Agustí-Brisach, C., García-Ortiz-Civantos, C., Fernández-Hernández, A., Mulero-Aparicio, A., & Trapero, A. (2017). Evaluation of organic amendments from agro-industry waste for the control of verticillium wilt of olive. *Plant Pathology*, *67(4)*, 860-870. doi:10.1111/ppa.12798.

Vilsack, T., & Clark, C. (2009). United States Department of Agriculture. Retrieved from https://www.nass.usda.gov/Publications/AgCensus/2007/

Xiao, C. L., Subbarao, K. V., Schulbach, K. F., and Koike, S. T. (1998). Effects of crop rotation and irrigation on Verticillium dahliae microsclerotia in soil and wilt in cauliflower. *Phytopathology*. 88, 1046-1055.