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# A COMPREHENSIVE ASSESSMENT OF VERTICILLIUM WILT OF POTATO: PRESENT STATUS AND FUTURE PROSPECTIVE

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**ABSTRACT**

The fungal disease *Verticillium* wilt is caused by a soil-borne pathogen, *Verticillium dahliae* which affects the yield of a wide range of agricultural crops. Recent findings suggest that *Verticillium* wilt has been affecting potato crops in abundant domains around the global world, including in North America, parts of Europe, and Asia. In some cases, the disease has been observed in fields where it has not been previously reported, indicating that it has been spreading. Farmers and researchers are working to manage the disease through a variety of measures, including rotation of crops, the use of resistant varieties of potato developed from resistant strains, and the application of fungicides. However, the potency of these measures can vary depending on the ferocity of the disease and the local growing circumstances. Overall, the recent findings of *Verticillium* wilt in potato underscore the importance of continued monitoring and research to better understand the disease and develop effective management strategies. This review has highlighted the up-to-date information on Verticillium wilt and management strategies. The study also helps the scientific community understand this devastating plant disease by offering a thorough review of the situation.

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## INTRODUCTION

The fungus of genus *Verticillium* is soil-borne fungi (López-Escudero and Mercado-Blanco 2011; Lykogianni *et al.*, 2020) that can cause plant diseases in a wild range of host plants like maple (Brooks *et al.*, 2020), ash, redbud, dogwood, catalpa, magnolia, and Solanaceae crops (Hong *et al.*, 2021; Smitley, 2019). This soil-borne pathogen is capable of causing destructive disease, namely *Verticillium* wilt. It can cause a significant threat to growing crops, like low yields both in terms of quality and quantity, impacting farmers worldwide (Dhouib *et al.*, 2019). The number of plants affected by *Verticillium* wilt each year can vary extensively depending on the topographical condition, geographical region, host plant species, and predominant environmental conditions (Ramírez-Gil, Castañeda-Sánchez, and Morales-Osorio 2021). It is challenging to provide a precise assessment of the exact number of affected plants globally or annually. However, *Verticillium* wilt is notorious for influencing a broad range of economically dominant crops, including vegetables like potato and tomato, fruits like strawberry, and ornamentals like mint, cotton, and sunflower, as well as trees and woody plants. However, the damage is significantly noticeable in potato (Liu *et al.*, 2021). Regional studies and crop-specific reports can provide more specific information on the prevalence and impact of *Verticillium* wilt in specific areas or crops (Pegg and Brady 2002). *Verticillium* wilt is a widespread malady that influences over 300 species of plant in the global world of the United States of America (Goldberg 2003). In susceptible crops such as potato and tomato, yield losses ranging from 10% to 15% and even can reach up to 60% or even complete crop failure has been reported in severely affected fields (Depotter *et al*., 2016). The range of losses eventuate depending on the extremity of the infection, the pathogen can cause a yield loss of about 10-50% (Jing *et al*., 2018). In one of the studies conducted on cotton, it is observed that there is a significant loss in yield and quality of the fiber worldwide due to *Verticillium* wilt (Ayele, Wheeler, and Dever, 2020).

The study of *Verticillium* wilt presents a comprehensive overview encompassing the etiology, disease cycle, colonization of the vascular system, and subsequent plant symptoms, along with modern management strategies by which growers can effectively mitigate the impact of *Verticillium* wilt on their growing crops. It serves as a valuable resource for the agricultural community, including farmers, agronomists, breeders, pathologists, and researchers. Despite extensive research efforts, several knowledge gaps still exist regarding the complex interactions between the pathogen, the host plant, and environmental factors. This comprehensive assessment aims to consolidate the existing knowledge, address these gaps, and provide valuable insights into the holistic management of *Verticillium* wilt in potato. The study of the wilt in potato provides practical guidance in the management of its disease, reduces yield loss, and promotes sustainable agricultural practices. Farmers facing challenges associated with *Verticillium* wilt will gain insights into the disease cycle, enabling them to identify symptoms and implement appropriate management strategies. Agronomists and researchers can utilize the information presented in this paper to develop improved control methods. Plant breeders can incorporate new breeding techniques to release resistant cultivars and advance research on *Verticillium* wilt. Ultimately, the broader community benefits from increased agricultural productivity, sustainable farming practices, and improved food security.

## About Verticillium Wilt

### Life cycle of *Verticillium*

The *Verticillium* fungi produce microsclerotia, which are small, hard, and dark structures that can stay viable for multiple years in the soil (Figure 1). These microsclerotia are the predominant method of survival and dissemination for the fungi, and they can infect plants over a wide area.

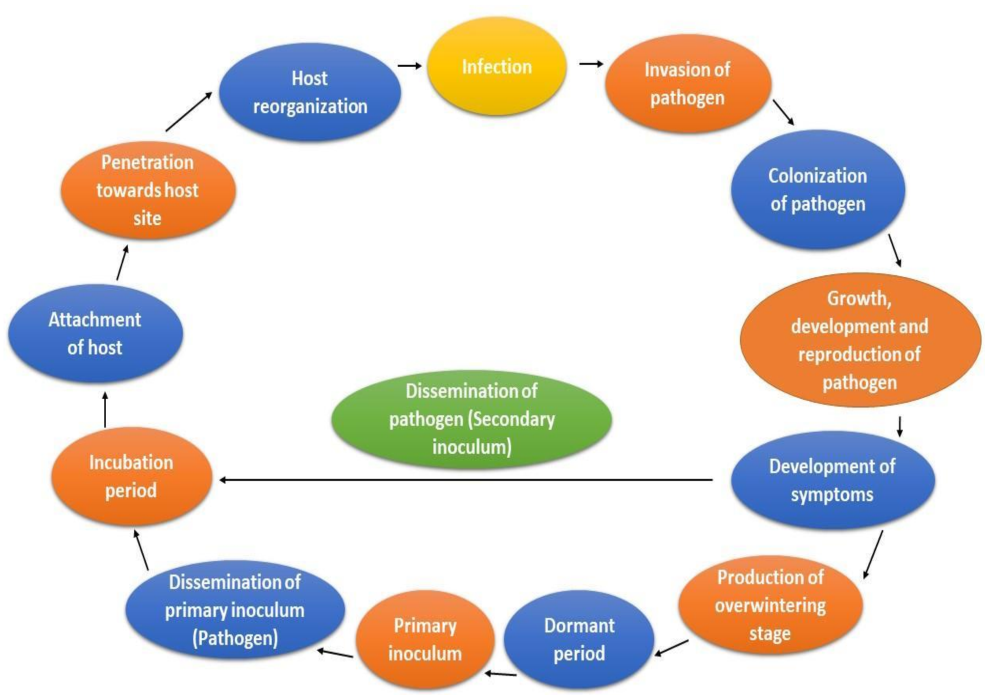


Figure 1. Life cycle of *Verticillium* (Dhar *et al*., 2020).

The life cycle of *Verticillium* wilt of potato, caused by the soil-borne pathogen involves several stages that can occur over several years in the soil. Here are the key stages of the life cycle:

**Survival of the fungi**

Fungi of *Verticillium* survive in the soil as small, hard, and dark structures known as microsclerotia, which can exist viable for several years.

**Infection of potato plants**

The fungi can infect potato plants through the roots, and grow in the xylem of the plant, causing symptoms like wilting, yellowing and necrosis.

**Production of microsclerotia**

As the fungi grow and reproduce within the potato plant, they produce microsclerotia within the infected tissues.

**Release of microsclerotia**

When the infected plant tissues break down, the microsclerotia are divulged into the soil, where they can exist viable for a couple of years.

**Infection of new potato plants**

When a susceptible potato plant is grown in soil containing viable microsclerotia, the fungi can infect the plant, and the cycle starts anew.

The life cycle of *Verticillium* wilt in potato can also involve additional stages, such as the infection of other host plants, which can serve as a reservoir for the fungi in the soil. Effective strategies for the wilt of potato caused by *Verticillium* typically involve a combination of cultural practices and chemical control measures, such as soil fumigation and fungicide applications.

## Economic Importance of *Verticillium*

The soil-borne pathogen *Verticillium dahliae* and *V. albo-atrum* causing *Verticillium* wilt of potato is an economically important disease that can cause consequential losses in potato production. Here are some of the ways in which this disease can impact the potato industry:

**Reduced yield**

*Verticillium* wilt can cause significant reductions in potato yield, with losses ranging from 10-70% depending on the severity of the disease (Davis *et al*., 2001). A model of critical parameters associated with potato *Verticillium* wilt revealed that the model accounted for 49% of tuber yield (Johnson and Dung, 2010).

**Reduced quality**

In addition, to yield losses, *Verticillium* wilt can also lead to lower-quality potatoes, with increased incidence of misshapen, discolored, and cracked tubers (Dung *et al*., 2013). The wilt can cause discoloration at the end of the stem and a decrease in the quality of tuber for the table stock.

**Reduced storability**

Potato infected with *Verticillium* wilt may have reduced qualities for storage, which can lead to additional losses for growers and processors (Desotell, 2020). The infected tubers tend to deteriorate at a faster rate resulting in shorter storage life. The tuber can experience soft rot, internal necrosis, and altered textures which can render potato unmarketable.

**Increased production costs**

Controlling *Verticillium* wilt can be expensive, as it may require additional inputs such as fungicides, crop rotation, and soil fumigation (Wang *et al*., 2021).

**Limitations on potato production**

In severe cases, *Verticillium* wilt can limit the production of potato in certain regions (Hao *et al*., 2022), which can have broader economic impacts on the potato industry.

Overall, *Verticillium* wilt of potato is a disease that can have significant economic impacts on growers and processors. Effective management strategies are needed to minimize losses and maintain the health and productivity of potato crops.

**Etiology**

The etiology of *Verticillium* wilt involves the soil-borne fungi of the genus *Verticillium*, which are the causal agents of this disease (Gao *et al*., 2019). *Verticillium* wilt is a vascular disease that causes wilting by fungal growth clogging vascular bundles especially the xylem and the plant trying to restrict the movement of the pathogen by obstructing the annexed vascular bundles (Umer *et al*., 2023).

The fungi that cause *Verticillium* wilt have a complex life cycle that involves several stages, including the production of microsclerotia, which are small, hard, and dark architecture that can remain viable in the soil for a couple of years. When a susceptible host plant is grown in soil containing viable microsclerotia, the fungi can infect the plant through the roots and accelerates in the vascular bundles especially the xylem tissue of the plant. *Verticillium* fungi produce a range of enzymes and toxins that can damage plant tissues and interfere with the plant's normal physiology (Wang *et al*., 2023). The fungi also produce a range of molecules that can suppress the plant's defense responses, making it more susceptible to infection (Zhou *et al*., 2021). In addition to infecting the roots and water-conducting tissues of the plant, the *Verticillium* fungi can also produce microsclerotia within the infected tissues. When the infected plant tissues break down, the microsclerotia are liberated into the soil, where they can survive for more than a year, perpetuating the disease cycle. The disease is caused by environmental stress in crops that are either induced by heat, moisture, drought, deficiency of nutrients along with entomological stress like insect damage. Infection is via the roots infecting the entire cambium system and management of the disease is arduous. Effective management of *Verticillium* wilt typically involves a combination of cultural practices, such as lay farming, alley cropping, alternating the crops with non-host plants, and use of resistant cultivars incorporating genetic engineering, as well as chemical control measures such as soil fumigation and fungicide applications.

**Epidemiology**

The epidemiology of *Verticillium* wilt involves the study of the factors that govern the occurrence like rainfall, intensity of light, air temperature and flow, humidity spread, genetic composition, and severity of the disease in agricultural and horticultural systems. The disease is manifested spare in plants under stress, especially water scarcity, and can engender premature death of the plant, reducing yield and size of tuber (Tsror, 2011). (simplify the sentence and make it meaningful)

The epidemiology of *Verticillium* wilt is influenced by a range of factors, including:

1. **Soil characteristics:** *Verticillium* fungi can sustain in the soil for several years in the form of microsclerotia. The presence of microsclerotia in the soil is a key factor in the epidemiology of *Verticillium* wilt.
2. **Host plant susceptibility:** Different plant species and cultivars have varying levels of susceptibility to *Verticillium* infection. Highly susceptible cultivars are more likely to develop wilt symptoms and suffer yield losses.
3. **Environmental conditions:** Environmental factors such as temperature, humidity, and soil moisture can influence the occurrence and severity of *Verticillium* wilt. For example, high soil moisture levels can favor the development and spread of the disease. Optimal temperatures for disease progress typically range between 20 to 30 degrees Celsius or 70 degrees F to 85 degrees F (Goldberg, 2003). Soil moisture, pH levels, and nutrient availability can also impact disease severity. Stress factors such as drought, excessive irrigation, and high soil salinity can exacerbate the disease (Vallad, Qin, and Subbarao, 2004).
4. **Crop management practices:** Practices like crop rotation, irrigation fertilization, post-harvest storage, the use of resistant cultivars, and chemical control measures can all influence *Verticillium* wilt epidemiology.
5. **Spread of the disease:** *Verticillium* wilt can spread from infected plant material, soil, or irrigation water. The use of contaminated planting material, the spread of the fungus by machinery, and the movement of soil are all factors that can contribute to the spread of the disease.

**Symptoms**

*Verticillium* can cause vascular wilting in a variety of crops, including tomato, potato, strawberry, eggplant, pepper, and many ornamental plants. The symptoms of *Verticillium* infection can be difficult to distinguish from those of other plant diseases, but they typically include yellowing, stunting, and wilting of the plant, as well as premature leaf drop necrosis, and vein clearing (Fradin and Thomma, 2006).

Symptomatology of *Verticillium* wilt in potato is characterized by gradual foliar wilting, yellowing, and necrosis. However, symptom expression may vary depending on the potato cultivar, environmental conditions, and the specific *Verticillium* species involved. Several research investigations have focused on the phenotypic characterization of resistant and susceptible potato cultivars, seeking to identify key morphological and physiological traits associated with resistance.

The symptoms of *Verticillium* wilt can vary depending on the host plant, but typically include the following:

1. **Wilting:** *Verticillium* wilt causes a rapid wilting of the leaves, stems, and branches of infected plants. The wilting can be sudden or gradual, and it may affect either a certain part or cover the entire part of the plant (Figure 2).
2. **Yellowing:** As the severity of the disease goes on increasing, the leaves of injured plants may yellow and drop off (Figure 2). This can lead to defoliation and a significant reduction in plant growth (Yan *et al*., 2019).
3. **Stunted growth**: *Verticillium* wilt can cause stunted

growth and reduced yields (Figure 2) (Höfer *et al*., 2021).

4. **Vascular discoloration:** The fungi that causes *Verticillium* wilt to grow in the xylem tissues of the plant, resulting in discoloration of the vascular tissues (Figure 2). The discoloration is usually dark brown or black and can be seen in the stem and roots of infected plants (Yan *et al*., 2019).
6. **Necrosis**: *Verticillium* wilt can cause necrosis or death of the infected plant (Figure 2). This can lead to the development of cankers or other types of damage (Liu *et al*., 2017).
7. **Chlorosis and curling**: *Verticillium* wilt can cause distinct leaf symptoms, such as chlorosis, curling, or mottling (Figure 2) (Bruno *et al*., 2020).

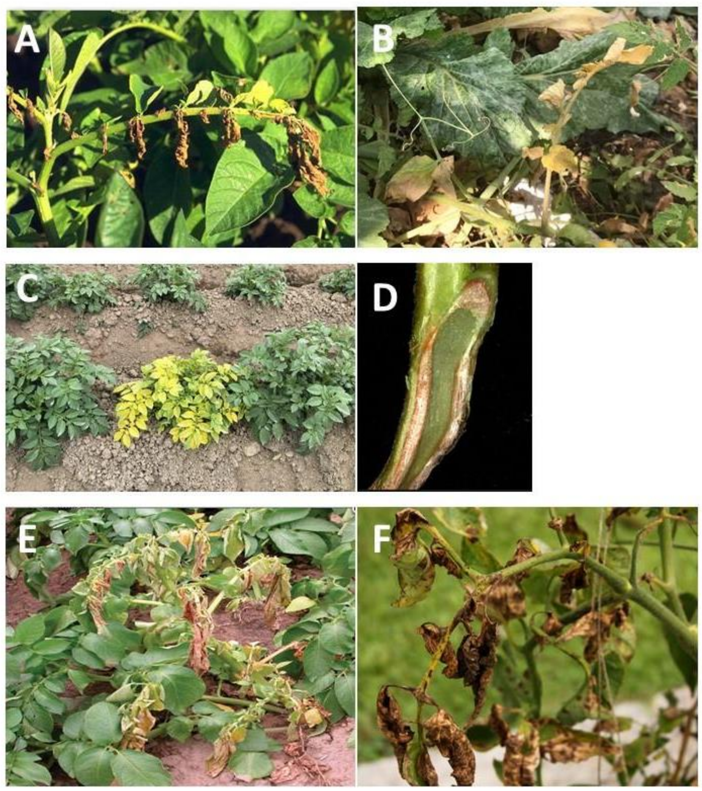


Figure 2. Symptoms of vascular wilt. A. Wilting B. Yellowing C. Stunted growth D. Vascular discoloration E. Necrosis F. Chlorosis and curling (Höfer *et al*., 2021; Yan *et al*., 2019).

Due to potential misunderstanding with water stress or Fusarium wilt, *Verticillium* wilt is difficult to diagnose (Blum *et al*., 2018). Necrotic lesions at the root cap or vascular discolorations within the root before the pathogen colonization may be the first signs to be seen on different plants affected by *Verticillium* wilt (Blum *et al*., 2018). When Fusarium wilt first appears, the leaves have chlorotic plaques between the major veins, but the remainder of the leaves are still green. Gradually, the leaves get necrotic, vascular tissue turn into brown discoloration and fall off the stem (Man *et al*., 2022). *Verticillium* wilt-affected plants typically exhibit distinctive brownish discoloration in their vascular tissues and limited growth, and it can cause defoliation, the slow wilting and death of subsequent branches, or the sudden collapse and death of the entire plant (Blum *et al*., 2018). However, there are no specific signs that all plants exhibit, and laboratory testing should be used to confirm the disease diagnosis.

Disease incidence and severity can vary greatly depending on the sowing time due to factors like as host resistance, cultural practices, and pathogen aggressiveness (Lizarazo *et al*., 2023). An integrated strategy for managing *Verticillium* wilt should include crop rotation, the adoption of resistant cultivars, and chemical management methods (Tsror, 2011). Effective management of *Verticillium* wilt involves understanding the epidemiology of the disease and implementing appropriate control measures to limit its spread and impact (Jimenez-Diaz *et al*., 2012).

**Present status of Management Practices**

The study of *Verticillium* wilt in potato has garnered substantial attention in recent years. Previous research has shed light on various aspects of the disease, ranging from the pathogen's survival in the soil to its entry into the plant and subsequent colonization of the vascular system (Dung, 2020; Fradin and Thomma, 2006). Notable studies have elucidated the molecular innards concealed the pathogenesis of *Verticillium* wilt, revealing the role of toxins, enzymes that will degrade the cell wall, and effector proteins in manipulating plant defense responses. The pathogen colonizes the vascular bundle and shows symptoms, so management is crucial to reducing the disease's impact. Its management requires an integrated approach combining all cultural, biological, and chemical control strategies, as chemical control is not a standalone control strategy. Recently, advancements in research have contributed to the understanding and supervision of *Verticillium* wilt (Shin *et al*., 2023; Zhang *et al*., 2022). Molecular techniques, such as DNA-based detection methods and genomics, have aided in the identification and characterization of *Verticillium* wilt pathogens, via which breeders develop resistant cultivars using techniques like the introduction of transgenes, and researchers target specific genes involved in host-pathogen interactions, leading to the development of resistant varieties. Integrated Disease Management (IDM) is a holistic approach involving the integration of cultural practices, resistant varieties, chemical control only if necessary, and biological control methods. This integration provides a more sustainable and long-term solution for disease management. This approach minimizes reliance on a single control method and maximizes the effectiveness of disease management strategies.

*Verticillium* can be managed through cultural practices such as crop rotation to break the continuous disease cycle, the use of resistant cultivars active compositing, and soil solarization. In severe cases, chemical control may be necessary, but this is not always effective. Proper diagnosis and management of *Verticillium* can help prevent crop losses and maintain the health of plants in agricultural and ornamental settings.

**Cultural management practices of *Verticillium***

Cultural management methods can be a potent strategy to minimize the impact of *Verticillium* wilt in agricultural and horticultural systems. Some of the key cultural management methods for controlling *Verticillium* wilt include.

**Sanitation and crop rotation**

Infected plant material and debris should be removed from the field and destroyed to shrink the number of microsclerotia and not spores present in the soil, a potential source of inoculum. Crop rotation can help reduce the prevalence of *Verticillium* wilt by reducing the integer of susceptible hosts in the field. Rotating to non-host crops or crops with different susceptibilities to the disease can help break the disease cycle.

**Soil solarization**

Soil solarization is a hydrothermal process that raises soil temperature under transparent plastic to create unfavorable condition for weeds, insects, and soilborne plant diseases (Baysal-Gurel, Kabir, and Liyanapathiranage, 2019). In this method, solar energy is utilized to heat the soil which as a result kills soil-borne pathogen, including *Verticillium* fungi. This method involves covering moist soil with clear plastic sheeting for several weeks during the hot summer months (Volesky, Murray, and Nischwitz, 2022). This approach increases the soil temperature, thus killing the soil pathogen and reducing the population. It has been reported that *Verticillium sp.* needs to be controlled at temperatures higher than 42° C (Ramírez-Gil and Morales-Osorio, 2021). It has been experimentally demonstrated to be effective in eradicating *V. dahliae* microsclerotia that are present at soil depths of 10 and 20 cm at a temperature of 48° C (Kowalska, 2021). Solarization may be less successful in areas like the southeastern of the United States where there are frequent rain showers and high summer temperatures since the rain lowers the temperature and reduces solar radiation passes through the plastic (Baysal-Gurel *et al*., 2019).

**Storage requirement**

Deterioration of infected tubers can be slowed down if they are stored properly. This includes keeping them in cool, dry, and well-ventilated conditions, ideally at a temperature of about 45-50°F (7-10°C) and with a relative humidity of 85-90%. Microsclerotia, the resting structures of *Verticillium dahliae*, had the lowest long-term survival in samples maintained at ambient temperature (Pfaff and Jansky, 2007).

**Irrigation management**

One of the practices that has the biggest impact on the severity of a disease is irrigation, which can either create favorable or unfavorable conditions for pathogens. It is particularly significant when growing vegetables, which typically require frequent, intensive irrigation (Cabral, Marouelli, and Café-Filho, 2020). There is a strong correlation between the frequency of verticillium wilts caused by the soilborne pathogen *Verticillium dahliae Kleb.* and the irrigation practices of many of their hosts, including potato plants (Pérez-Rodríguez *et al*., 2016). Overhead irrigation can spread fungal spores and promote disease development (Díaz-Rueda *et al*., 2022). The use of infected planting materials, improper agronomic techniques, and drip irrigation all contribute to the development of infectious propagules (Díaz-Rueda *et al*., 2022). Excessive N fertilization, especially when combined with high irrigation rates or frequent watering periods that encourage rapid vegetative development, might enhance the frequency and severity of *V. dahliae* infections. Using drip irrigation or other forms of irrigation that do not wet the foliage can help to reduce disease spread (Pérez-Rodríguez *et al*., 2016).

**Resistant cultivars**

Planting resistant cultivars can help to reduce the impact of *Verticillium* wilt. Many species of potato have been bred for resistance to the disease, and the selection of the resistant cultivars is a crucial component of an IDMS where IDMS stands for Integrated Disease Management Strategy. Breeds like Blanka are very tolerant to *V. dahlia* (Nachmias *et al*., 1990). Using the less virulent isolate Vn-1 to make potato resistant to *Verticillium* is a promising way to advance agricultural sustainability (Hao *et al*., 2022). Research conducted in China identified 5 resistant varieties i.e. Qingshu 9, Zhongshu 18, Longshu 8, and Zhongshu 19 which were resistant to both pathogen that causes *Verticillium* wilt in potato i.e. *V. dahliae* and *V. nonalfalfae* (Li *et al*., 2019). Similarly, Bannock Russet is slightly resistant to Verticilium wilt (Johnson and Dung, 2010). Through breeding programs, resistant varieties have been developed for potato, providing an effective tool for disease control. These resistant cultivars offer an inherent ability to resist or tolerate the pathogen, reducing the severity of *Verticillium* wilt. Effective cultural management of *Verticillium* wilt typically involves a combination of these methods, as well as careful monitoring and disease scouting to detect and manage outbreaks.

**Soil amendments**

Certain organic and inorganic soil amendments can stimulate the growth of beneficial microorganisms and suppress the growth of *Verticillium* fungi. Compost acts as a suppressive material against *Verticillium*. For example, some studies have shown that compost and biochar amendments can minimize the occurrence of *Verticillium* wilt in potato and eggplant (Hills *et al*., 2020; Ogundeji *et al*., 2021). *Verticillium* fungi grow best in alkaline soils (Liu *et al*., 2021). Maintaining soil pH between 6.0 and 6.5 can help to minimize the prevalence of *Verticillium* wilt.

**Biological control methods**

Biological control is another approach for managing *Verticillium* wilt, that involves using living organisms to minimize the prevalence and severity of the disease (Figure 3). Adding neem-based insecticides acts as an antagonist against *Verticillium*.

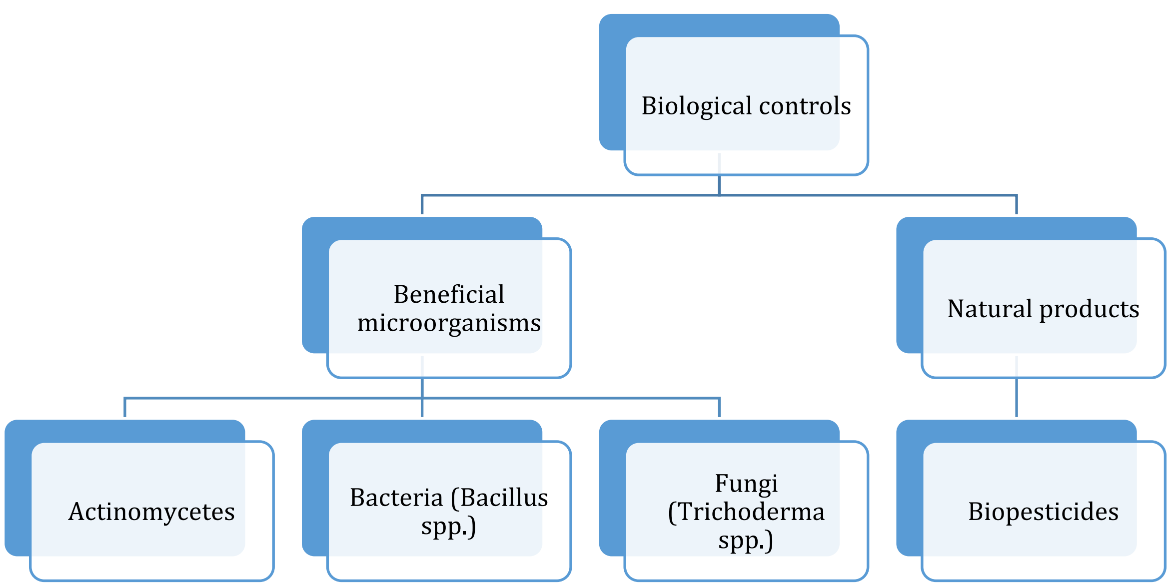


Figure 3. category showing the biological controls methods.

Some of the biological control methods that have been developed for controlling *Verticillium* wilt include:

**Microbial antagonists**

Certain soil-borne bacteria and fungi have been delineated to be efficacious antagonists of *Verticillium* wilt. These microbes can suppress the growth and development of fungi by producing toxic metabolites, competing for nutrients, or inducing plant resistance. The *B. velezensis* XT1 is tolerant to salt and it exhibits potent antifungal action in contrast to the extremely dangerous defoliating pathogen *V. dahliae* V024. This finding was proven in both in vitro, in the greenhouse and in field with both inhibitory and paregoric treatments (Castro *et al*., 2020). Transcriptome analysis demonstrated that C17 Mycosubtilin effectively counters *Verticillium dahliae* by disrupting multiple functional pathways within the fungal pathogen, highlighting its potential as a promising antagonist for managing *Verticillium* wilt (Zhang *et al*., 2023). Similarly, The Canada milkvetch extract is effective in reducing infestation in both moderately susceptible varieties i.e., Russet Burbank and Highly susceptible variety i.e. Kennebec (Uppal *et al*., 2008).

The methods used for assessment include fungicides like captan, azoxystrobin, benomyl, and carbendazim, as well as advantageous and antagonistic microorganisms like *Rhizoglomus fasciculatum* and *Trichoderma* sp., as well as physical, mechanical and cultural practices like soil solarization, proper irrigation and drainage, and the removal of diseased tissues, frequent pruning. The treatments T7fi and T8fi which includes activities like thinning and pruning, soil solarization, Trichoderma, mycorrhiza, sucrose, soil organic matter, and drainage resulted in a significant reduction of both the arena under the disease progression curve and the amount of *Verticillium dahliae* inoculate present in both plant tissue and soil. (Morales-osorio, 2021). *B. amyloliquefaciens* Oj-2.16 could be used as an auspicious aspirant for the biocontrol of *Verticillium* (Pei *et al*., 2023).

**Biocontrol agents**

Several commercial biocontrol agents have been developed to control *Verticillium* wilt. These include products based on the fungal antagonist Trichoderma spp. and the bacterium Bacillus subtilis. There have been reports of the genera Bacillus, Pseudomonas, Chryseomonas, Sphingomonas, Stenotrophomonas, and Serratia acting as biocontrol agents against vascular or soil-borne fungal diseases. During nursery propagation, root pretreatment with some isolates of *Pseudomonas fluorescens* can aid in the biocontrol of *V. dahlia* and reduce severity in potato. The *Verticillium* pathogen does not like the smell of Eucalyptus. A study shows that the infestation of the pathogen is lessened in the potato field with the application of Eucalyptus leaf or oil. Similarly, the application of Urtica dioica in the field also acts as an effective method to avoid pathogens. It creates a non-preference environment for the *V. dahlia* (Shreejana *et al*., 2022).

**Genetic control**

Approaches like Genetic engineering have been extensively used to modify genes and develop transgenic plants that are resistant to *Verticillium* wilt. These approaches involve the introduction of genes from other organisms that provide resistance to the disease.

Biological control methods can be an effective and sustainable way to manage *Verticillium* wilt, but they often require careful management and integration with other disease control methods.

**Mechanical method**

With the use of NIR spectroscopy and modeling, pilot detection of infection caused by *Verticillium* wilt is possible. This can be the turning point or point where the growers can focus on management practices like irrigation, and fertigation to reduce the impact of *V. dahliae* (Shin *et al*., 2023). The use of aerial imagery and GPS-enabled equipment enables the early detection and site-specific control of *Verticillium* wilt. Methods for controlling *V. dahliae* that are only now becoming clear include the utilization of biological control agents and techniques that promote the development of disease-suppressive soils (Dung, 2020). One of the study suggest that Acibenzolar-S-methyl and chitosan are promising in inducing esistivity in potato plant and protect tubers of potato against Potato *Verticillium* wilt (Amini, 2015).

**Chemical method**

Chemical control methods can also be acclimatized to manage *Verticillium* wilt. However, the efficacy of this control method is limited, and it should be used in combination with other management methods. Fungicides are the primary chemical control method for *Verticillium* wilt, and they work by inhibiting fungal growth and reducing disease severity. Some of the commonly used fungicides for *Verticillium* wilt include:

1. Chlorothalonil: Chlorothalonil is a broad-spectrum fungicide that is effective against *Verticillium* fungi.

It works by inhibiting fungal growth and spore production.

2. Propiconazole: Propiconazole is a systemic fungicide that is absorbed by the plant and translocated to the site of infection. It inhibits fungal growth and spore production and can provide long-term control of *Verticillium* wilt. *Verticillium* wilt was effectively controlled by propamocarb-hydrochloride; its effectiveness and that of polyversum were comparable and least effective than benomyl, but still considerably disparate from the disease control.
3. Thiophanate-methyl: Thiophanate-methyl is a systemic fungicide that is absorbed by the plant and translocated to the site of infection. It inhibits fungal growth and spore production and can provide long-term control of *Verticillium* wilt (Bubici *et al*., 2019).
4. Azoxystrobin: Azoxystrobin is a broad-continuum fungicide that operates by impeding mitochondrial respiration in the fungal corpuscle. It can provide both preventative and curative control of *Verticillium* wilt.
5. Fluazinam: Fluazinam is a fungicide that works by inhibiting fungal growth and spore production. It can provide both preventative and curative control of *Verticillium* wilt that affects the crops (Opatovsky *et al*., 2019).

It is important to note that fungicides should be used in accordance with label instructions and regulations to minimize the risk of environmental contamination and the development of fungicide-resistant strains of *Verticillium*. In addition, the use of fungicides should be integrated with additional management strategies to achieve everlasting and sustainable control of *Verticillium* wilt.

**Advancements and Future Hypotheses in *Verticillium* Wilt Research: Enhancing Disease**

Potato is the most important vegetable crop consumed throughout the world. However, its production is being challenged by a number of pathogen and diseases including *Verticillium* wilt. As *Verticillium* wilt continues to challenge agricultural productivity, ongoing research, and future hypotheses hold the potential to revolutionize disease management strategies. By focusing on genetic resistance, microbiome manipulation, host-pathogen interactions, and integrated disease management, researchers can contribute to sustainable agricultural practices and mitigate the impact of *Verticillium* wilt. In the genetic field, CRISPR technology can make an extensive change (Angon and Habiba, 2023). Similarly, using modern agricultural techniques like remote sensing and data analytics and integrating them with disease monitoring and decision support systems helps to optimize management practices. Exploring novel control agents, understanding soil health and microbial interactions, and considering climate change impacts will further enrich the research landscape, enhance disease management approaches, and develop adaptive management strategies. Tillage and specific cropping system may play a vital role in decreasing the infection of *Verticillium* wilt (Angon *et al*., 2023). The minimal environmental impact of novel control agents like biopesticides can lead to the development of eco-friendly and sustainable control options. However, despite these advancements, challenges persist in effectively managing *Verticillium* wilt in potato crops. The emergence of new pathogen strains shifts in pathogen populations, and the complexity of soil-plant interactions necessitate continued research efforts to refine and optimize disease management strategies.

**CONCLUSION**

Overall, the compressive study of *verticillium* is not enough for this present scenario. The disease is so destructive that it causes both economic and genetic damage. It causes losses in whole parts of plants, from stems to leaves to fruits. It degrades the shelf-life of fruits. Yellowing, stunted growth, vascular discoloration, necrosis of the leaf, and wilting of the whole plant are the major symptoms that may seem similar to other nutritional deficiencies. Little, rigid, and dark structures called microsclerotia, which are produced by the fungus *Verticillium* can endure for a couple of years in the soil. The main means of survival and spread for the fungi is microsclerotia, which can infect plants throughout a wide geographic range. The life cycle includes infecting the host plant, producing microsclerotia, and releasing microsclerotia to infect other plants. *Verticillium* can be effectively managed by cultural methods such as the rotation of crops, the use of resistant varieties, and soil solarization. Chemical control may be necessary in extreme circumstances, but it is not always a reliable answer. It has always been necessary to have an integrated strategy for *Verticillium* management. *Verticillium* can be effectively diagnosed and managed in agricultural settings to help reduce crop losses and maintain plant health. Controlling *Verticillium* through a biological agent is also one of the best alternative ways to control *Verticillium* which is eco-friendly and helps to protect the soil health as well as plant and human health. It includes using endophytic fungi and using genetic engineering to develop transgenic plants. We have discussed the several epidemiological variables that have influenced the prevalence and present significance of *Verticillium* Wilt. Some of these variables are the results of ineffective crop management and/or plant propagation techniques, while others may be connected to recent modifications in potato cultivation systems, such as irrigation and fertilizer, and still others depend on a variety of variable environmental circumstances. Additionally, these factors may interact together in ways that overlap or synergistic ways. There is a need for extensive, long-term investigations because many of them are not fully understood. The precise and accurate identification of *V. dahliae* pathotypes that infect potato plants has substantially progressed because of the development of molecular detection techniques. These processes greatly aid in identifying pathogen-free propagation and planting materials. The development of molecular methods to evaluate *V. dahliae* group population structure and estimate in-soil inoculum potential will aid in risk assessment studies and the choice of new planting sites. Future studies should substantially build on current findings in order to better combat potato *Verticillium* wilt. Growers may only be able to stay ahead of the pathogen and avoid a situation in which yield loss due to disease surpasses potential yield with the continuing development of new techniques and a better understanding of *V. dahliae* genetics to quickly assess *Verticillium* wilt samples.

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