A Comprehensive Assessment of Verticillium Wilt of Potato: Present Status and Future Prospective

Shreejana KC[1,2,*], Amrit Poudel[1], Dipiza Oli[1], Shirish Ghimire[2], Prodipto Bishnu Angon[3]

[1]Department of Plant Sciences and Plant Pathology, Faculty of Plant Science, Montana State University, Bozeman, Montana, USA

[2]Institute of Agriculture and animal Science, Gokuleshwor College, Baitadi, Nepal

[3]Faculty of Agriculture, Bangladesh Agricultural University, Mymensingh 2202, Bangladesh

*Corresponding author: sreezaa20@gmail.com

Abstract

The fungal disease Verticillium wilt is a soil-borne pathogen that is caused by *Verticillium dahliae*. This disease affects a wide range of crops and can cause significant yield losses. Recent findings suggest that *Verticillium* wilt has been affecting potato crops in abundant demesne 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 may be 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 variegate depending on the ferocity of the disease and the local growing circumstances. Overall, the recent findings of Verticillium wilt in potatoes underscore the importance of continued monitoring and research to better understand the disease and develop effective management strategies. This review paper is written with the intention of consolidating and disseminating up-to-date information on Verticillium wilt and management strategies. By providing a comprehensive assessment, the paper contributes to the scientific community's understanding of this devastating plant disease.

Keywords: Plant pathology; Pathogen; Pathogenicity; Verticillium wilt; Symptoms; Disease management.

1. Introduction

The fungus of genus *Verticillium* is soil-borne fungi [1], [2] that can cause plant diseases in a spacious range of host plants like maple [3], ash, redbud, dogwood, catalpa, magnolia, and Solanaceae crops [4], [5]. 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 [6]. 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 [7]. 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 [8]. Regional studies and crop-specific reports can provide more specific information on the prevalence and impact of Verticillium wilt in specific areas or crops [9]. Verticillium wilt is a widespread malady that influences over 300 species of plant in the global world of the United States of America [10]. In susceptible crops such as potatoes and tomatoes, 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 [11]. The range of losses eventuate depending on the extremity of the infection, the pathogen can cause a yield loss of about 10-50% [12]. 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 [13].

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 potatoes. 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.

2. About Verticillium Wilt

2.1 Common species

There are a number of *Verticillium* species, like *Verticillium theobromae, V. fusisporum, V. nonalfalfae, V. luteoalbum, V. affinae, and V. lecanii.* However, the two most common species are *Verticillium dahliae* and *Verticillium albo-atrum* [14]. These fungi infect plants via the roots and proliferate in the plant's water-conducting tissues, producing symptoms like wilting, and necrosis.

Verticillium dahliae is the most quotidian race concurrent with verticillium wilt in a wide horizon of plant species, including potato, eggplant, tomato, strawberry, olive, cotton, and many other crops and ornamental plants. This species is known to be highly virulent and can cause significant yield losses in affected crops.

Verticillium albo-atrum is also known to cause wilt in a range of host plants, although it is generally considered to be less virulent than *V. dahliae*. However, a study by Harvey suggests that *V. albo-atrum* cause severe wilting. This species is often associated with trees and shrubs and can engender significant defilement to forests and landscapes.

Both species of Verticillium can produce microsclerotia that can subsist in the soil for manifold years, making them strenuous to control. Effective management of verticillium wilt typically involves a combination of cultural practices and chemical control measures. Cultural practices include the activities such as crop rotation, terracing, lay farming and the use of resistant cultivars. Chemical control measures involve soil fumigation and fungicide applications.

2.2 Biology of *Verticillium*

The *Verticillium* fungi produce microsclerotia, which are small, hard, and dark structures that can endure 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.

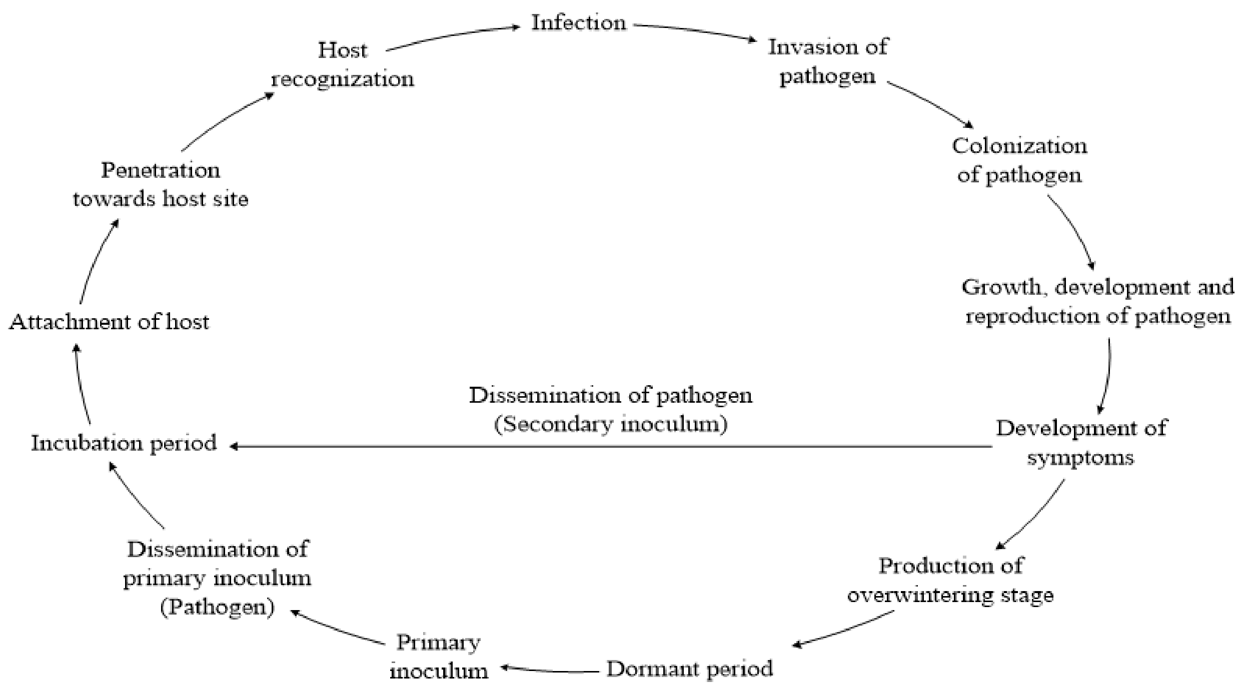

Figure 1. Disease cycle of *Verticillium*

2.3 Life cycle of *Verticillium*

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 subsist 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 cambium 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 stewardship 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.

2.5 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 [15]. A model of critical parameters associated with potato Verticillium wilt revealed that the model accounted for 49% of tuber yield [16].

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 [17]. 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: Potatoes infected with Verticillium wilt may have reduced storability, which can lead to additional losses for growers and processors [18]. 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 potatoes unmarketable.

Increased production costs: Controlling Verticillium wilt can be expensive, as it may require additional inputs such as fungicides, crop rotation, and soil fumigation [19].

Limitations on potato production: In severe cases, Verticillium wilt can limit the production of potatoes in certain regions [20], 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.

2.6 Etiology

The etiology of Verticillium wilt involves the soil-borne fungi of the genus *Verticillium*, which are the causal agents of this disease [21]. 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 [14].

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 [22]. The fungi also produce a range of molecules that can suppress the plant's defense responses, making it more susceptible to infection [23]. 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 favored 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.

2.7 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 caused by fungi of the genus Verticillium affecting the capacious range of host plants. 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 [24].

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 [10]. 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 [25].
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.

2.8 Symptoms

Verticillium can cause vascular wilting in a variety of crops, including tomatoes, potatoes, strawberries, eggplants, peppers, 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 [26].

Symptomatology of Verticillium wilt in potatoes 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 [27].

3. **Stunted growth**: Verticillium wilt can cause stunted growth and reduced yields (Figure 2) [28].

4. **Vascular discoloration:** The fungi that cause 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 [27].

5. **Necrosis**: Verticillium wilt can cause necrosis or death of the infected tissues (Figure 2). This can lead to the development of cankers or other types of damage [29].

6. **Chlorosis and curling**: Verticillium wilt can cause distinct leaf symptoms, such as chlorosis, curling, or mottling (Figure 2) [30].

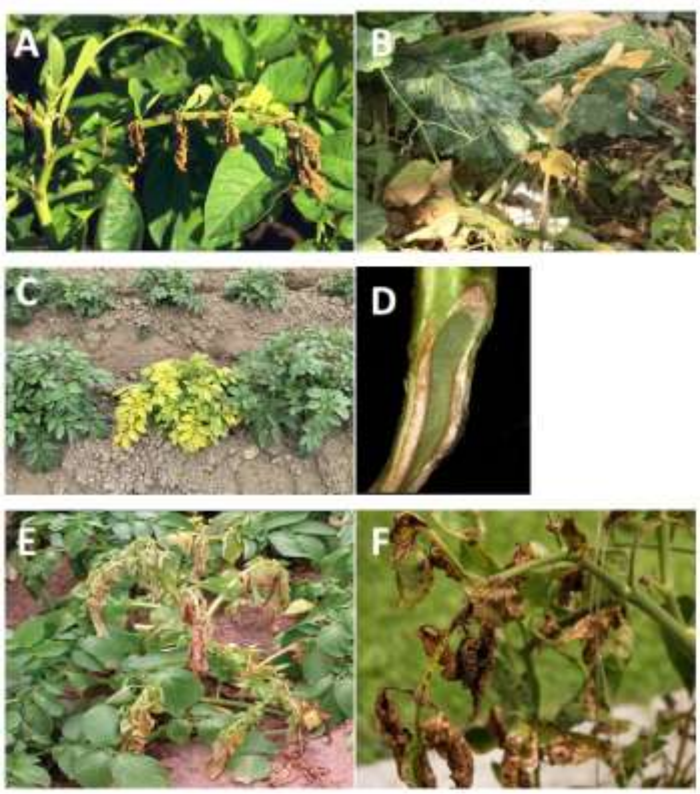

Figure 2: Symptoms of vascular wilt. A. Wilting B. Yellowing C. Stunted growth D. Vascular discoloration E. Necrosis F. Chlorosis and curling. (Field picture, 2022)

It is important to note that some of these symptoms can also be caused by other plant diseases or environmental factors, so an accurate diagnosis of Verticillium wilt requires laboratory analysis. In general, a combination of symptoms, along with laboratory analysis, is needed to confirm the presence of Verticillium wilt in a plant.

Effective management of Verticillium wilt involves understanding the epidemiology of the disease and implementing appropriate control measures to limit its spread and impact. Crop rotation, the use of resistant cultivars, and chemical control measures are all important components of an integrated approach to managing Verticillium wilt.

3. Present status of management practices

The study of Verticillium wilt in potatoes 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 [26], [31]. 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 [32], [33]. 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.

3.1 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 fungal 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: 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 [34]. This approach increases the soil temperature, thus killing the soil pathogen and reducing the population.

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 [35].

Irrigation management: Overhead irrigation can spread fungal spores and promote disease development. Using drip irrigation or other forms of irrigation that do not wet the foliage can help to reduce disease spread [36].

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 of *V. dahlia* [37]. Using the less virulent isolate Vn-1 to make potatoes resistant to verticillium is a promising way to advance agricultural sustainability [20]. Research conducted on 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 [38]. Similarly, Bannock Russet is slightly resistant to Verticilium wilt [16]. 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 [39], [40]. Verticillium fungi grow best in alkaline soils [8]. Maintaining soil pH between 6.0 and 6.5 can help to minimize the prevalence of Verticillium wilt.

3.2 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.

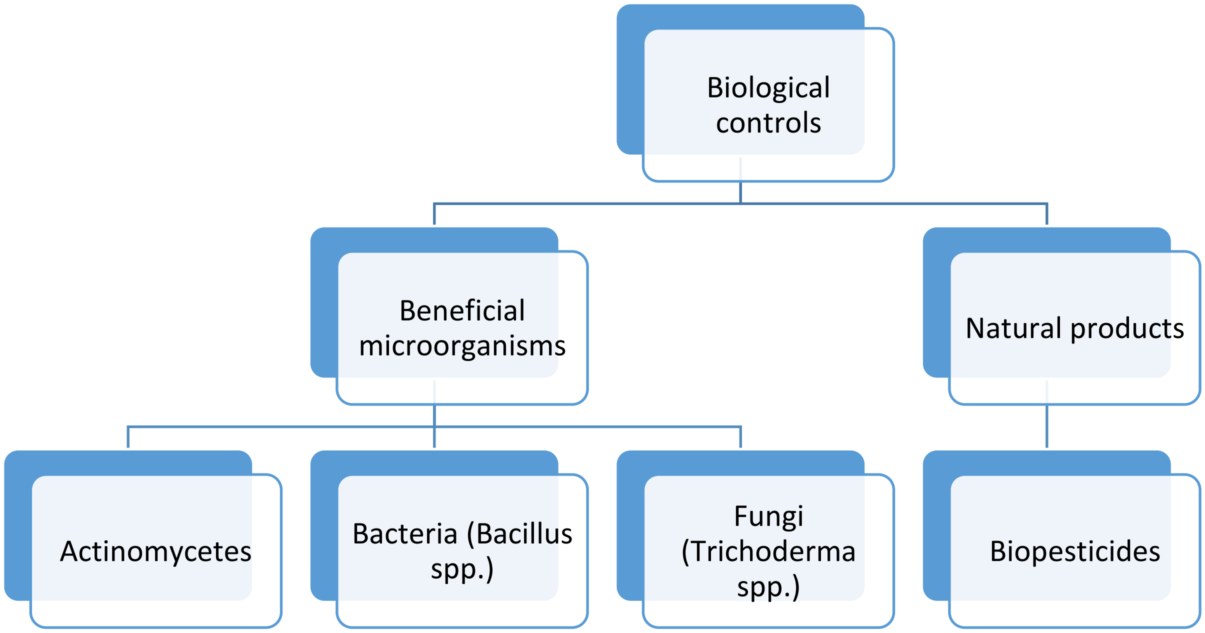

Figure 3: category showing the biological controls methods

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 the 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 contra 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 [41]. 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 [42]. 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 [43].

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 training 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* [44].

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* [45].

3.3 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.

3.4 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* [32]. 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 [31]. 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 [46].

3.5 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 [47].
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 [48].

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.

4. Advancements and Future Hypotheses in Verticillium Wilt Research: Enhancing Disease

Potatoes are the most important vegetable crop consumed throughout the world. However, its production is being challenged by 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 [49]. 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 to decrease the infection of Verticillium wilt [50]. 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.

5. 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 steam to leaves to fruits. It degrades the self-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. It can affect a wide variety of plants like potatoes, tomatoes, eggplant, strawberry, sunflower, mint, olive, cotton, and ornamental species (maple, ash, redbud, dogwood, catalpa, magnolia, and many others). 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 the 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. 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 of endophytic fungi and using genetic engineering to develop transgenic plants.

References

[1] F. J. López-Escudero and J. Mercado-Blanco, "Verticillium wilt of olive: a case study to implement an integrated strategy to control a soil-borne pathogen," *Plant Soil*, vol. 344, pp. 1–50, 2011.

[2] M. Lykogianni, E.-A. Papadopoulou, A. Sapalidis, D. Tsiourvas, Z. Sideratou, and K. A. Aliferis, "Metabolomics reveals differential mechanisms of toxicity of hyperbranched poly (ethyleneimine)-derived nanoparticles to the soil-borne fungus Verticillium dahliae Kleb," *Pestic. Biochem. Physiol.*, vol. 165, p. 104535, 2020.

[3] R. K. Brooks, K. L. Wickert, A. Baudoin, M. T. Kasson, and S. Salom, "Field-inoculated Ailanthus altissima stands reveal the biological control potential of Verticillium nonalfalfae in the mid-Atlantic region of the United States," *Biol. Control*, vol. 148, p. 104298, 2020.

[4] C. X. Hong, M. A. Hansen, E. A. Bush, E. R. Day, A. Del-Pozo, and J. F. Derr, "2021 Home Grounds and Animals PMG-Home Ornamentals," 2021.

[5] D. Smitley, "Elsner, Michigan State University Extension; Joy N. Landis, Michigan State University IPM; Paula M. Shrewsbury, University of Maryland Department of Entomology; Daniel A. Herms, The Davey Tree Expert Company, Kent, Ohio; and Cristi L Palmer, IR-4 Project Rutgers University.," 2019.

[6] H. Dhouib *et al.*, "Potential of a novel endophytic Bacillus velezensis in tomato growth promotion and protection against Verticillium wilt disease," *Biol. Control*, vol. 139, p. 104092, 2019.

[7] J. G. Ramírez-Gil, D. Castañeda-Sánchez, and J. G. Morales-Osorio, "Edaphic factors associated with the development of avocado wilt complex and implementation of a GIS tool for risk visualization," *Sci. Hortic.*, vol. 288, p. 110316, 2021.

[8] L. Liu *et al.*, "Biological characteristics of Verticillium dahliae MAT1-1 and MAT1-2 strains," *Int. J. Mol. Sci.*, vol. 22, no. 13, p. 7148, 2021.

[9] G. F. Pegg and B. L. Brady, *Verticillium wilts*. CABI, 2002.

[10] N. Goldberg, "Verticillium wilt," *Compend. Pepper Dis. Am. Phytopathol. Soc. Press St Paul Minn.*, pp. 21–22, 2003.

[11] J. R. Depotter *et al.*, "Verticillium longisporum, the invisible threat to oilseed rape and other brassicaceous plant hosts," *Mol. Plant Pathol.*, vol. 17, no. 7, p. 1004, 2016.

[12] R. Jing *et al.*, "Verticillium wilt caused by Verticillium dahliae and V. nonalfalfae in potato in northern China," *Plant Dis.*, vol. 102, no. 10, pp. 1958–1964, 2018.

[13] A. G. Ayele, T. A. Wheeler, and J. K. Dever, "Impacts of verticillium wilt on photosynthesis rate, lint production, and fiber quality of greenhouse-grown cotton (Gossypium hirsutum)," *Plants*, vol. 9, no. 7, p. 857, 2020.

[14] M. J. Umer *et al.*, "Insights to Gossypium defense response against Verticillium dahliae: the Cotton Cancer," *Funct. Integr. Genomics*, vol. 23, no. 2, p. 142, 2023.

[15] J. Davis, O. Huisman, D. Everson, and A. Schneider, “Verticillium wilt of potato: a model of key factors related to disease severity and tuber yield in southeastern Idaho,” *Am. J. Potato Res.*, vol. 78, pp. 291–300, 2001.
[16] D. A. Johnson and J. K. Dung, “Verticillium wilt of potato–the pathogen, disease and management,” *Can. J. Plant Pathol.*, vol. 32, no. 1, pp. 58–67, 2010.
[17] J. K. Dung, P. B. Hamm, J. E. Eggers, and D. A. Johnson, “Incidence and impact of Verticillium dahliae in soil associated with certified potato seed lots,” *Phytopathology*, vol. 103, no. 1, pp. 55–63, 2013.
[18] S. Desotell, *Evaluation of Management Programs for Control of Potato Early Die (PED) and Sensitivity of Helminthosporium Solani to Three Classes of Fungicides*. Michigan State University, 2020.
[19] D. Wang *et al.*, “Different appearance period of Verticillium wilt symptoms affects sunflower growth and production,” *J. Plant Pathol.*, vol. 103, pp. 513–517, 2021.
[20] J. Hao, D. Wang, Y. Wang, and H. Zhou, “Attenuated Isolate Gibellulopsis nigrescens Vn-1 Enhances Resistance against Verticillium dahliae in Potato,” *Agronomy*, vol. 12, no. 12, p. 3082, 2022.
[21] F. Gao *et al.*, “Deacetylation of chitin oligomers increases virulence in soil-borne fungal pathogens,” *Nat. Plants*, vol. 5, no. 11, pp. 1167–1176, 2019.
[22] G. Wang *et al.*, “Cotton peroxisome-localized lysophospholipase counteracts the toxic effects of Verticillium dahliae NLP1 and confers wilt resistance,” *Plant J.*, 2023.
[23] J. Zhou *et al.*, “CGTase, a novel antimicrobial protein from Bacillus cereus YUPP-10, suppresses Verticillium dahliae and mediates plant defence responses,” *Mol. Plant Pathol.*, vol. 22, no. 1, pp. 130–144, 2021.
[24] L. Tsror, “Epidemiology and control of Verticillium wilt on olive,” *Isr. J. Plant Sci.*, vol. 59, no. 1, pp. 59–69, 2011.
[25] G. E. Vallad, Q.-M. Qin, and K. V. Subbarao, “Verticillium wilt of cool season vegetable crops: their distribution, impact and management,” *Recent Res. Dev. Plant Pathol.*, vol. 3, pp. 189–210, 2004.
[26] E. F. Fradin and B. P. Thomma, “Physiology and molecular aspects of Verticillium wilt diseases caused by V. dahliae and V. albo-atrum,” *Mol. Plant Pathol.*, vol. 7, no. 2, pp. 71–86, 2006.
[27] W. Yan, B. Li, A. Chai, Y. Shi, J. Shi, and X. Zhang, “First report of Verticillium wilt on cultivated radish caused by Verticillium dahliae Kleb. in China,” *J. Plant Pathol.*, vol. 101, pp. 777–777, 2019.
[28] A. M. Höfer *et al.*, “The velvet protein Vel1 controls initial plant root colonization and conidia formation for xylem distribution in Verticillium wilt,” *PLoS Genet.*, vol. 17, no. 3, p. e1009434, 2021.
[29] N. Liu, X. Ma, Y. Sun, Y. Hou, X. Zhang, and F. Li, “Necrotizing Activity of Verticillium dahliae and Fusarium oxysporum f. sp. vasinfectum Endopolygalacturonases in Cotton,” *Plant Dis.*, vol. 101, no. 7, pp. 1128–1138, 2017.
[30] G. L. Bruno, S. Sermani, M. Triozzi, and F. Tommasi, “Physiological response of two olive cultivars to secondary metabolites of Verticillium dahliae Kleb.,” *Plant Physiol. Biochem.*, vol. 151, pp. 292–298, 2020.
[31] J. K. Dung, “Verticillium wilt of mint in the United States of America,” *Plants*, vol. 9, no. 11, p. 1602, 2020.
[32] M.-Y. Shin, C. G. Viejo, E. Tongson, T. Wiechel, P. W. Taylor, and S. Fuentes, “Early detection of Verticillium wilt of potatoes using near-infrared spectroscopy and machine learning modeling,” *Comput. Electron. Agric.*, vol. 204, p. 107567, 2023.
[33] D. Zhang, X. Dai, S. J. Klosterman, K. V. Subbarao, and J. Chen, “The secretome of Verticillium dahliae in collusion with plant defence responses modulates Verticillium wilt symptoms,” *Biol. Rev.*, vol. 97, no. 5, pp. 1810–1822, 2022.
[34] N. Volesky, M. Murray, and C. Nischwitz, “Fusarium and Verticillium Wilts of Vegetables,” 2022.

[35] K. Pfaff and S. Jansky, “Effect of time and storage temperature on survival of Verticillium dahliae microsclerotia in dried potato stem tissue,” *Am. J. Potato Res.*, vol. 84, pp. 271–273, 2007.
[36] M. Pérez-Rodríguez, N. Serrano, O. Arquero, F. Orgaz, J. Moral, and F. J. López-Escudero, “The effect of short irrigation frequencies on the development of Verticillium wilt in the susceptible olive cultivar ‘Picual’under field conditions,” *Plant Dis.*, vol. 100, no. 9, pp. 1880–1888, 2016.
[37] A. Nachmias, J. Orenstein, M. Tal, and M. Goren, “Reactions to a Verticillium dahliae phytotoxin in tissue cultures derived from susceptible and tolerant potato,” *Plant Sci.*, vol. 68, no. 1, pp. 123–130, 1990.
[38] H. Li *et al.*, “Assessment of resistance in potato cultivars to Verticillium wilt caused by Verticillium dahliae and Verticillium nonalfalfae,” *Plant Dis.*, vol. 103, no. 6, pp. 1357–1362, 2019.
[39] K. Hills, H. Collins, G. Yorgey, A. McGuire, and C. Kruger, “Improving soil health in pacific northwest potato production: A review,” *Am. J. Potato Res.*, vol. 97, pp. 1–22, 2020.
[40] A. O. Ogundeji *et al.*, “Eggplant by grafting enhanced with biochar recruits specific microbes for disease suppression of Verticillium wilt,” *Appl. Soil Ecol.*, vol. 163, p. 103912, 2021.
[41] D. Castro, M. Torres, I. Sampedro, F. Martínez-Checa, B. Torres, and V. Béjar, “Biological control of Verticillium wilt on olive trees by the salt-tolerant strain Bacillus velezensis XT1,” *Microorganisms*, vol. 8, no. 7, p. 1080, 2020.
[42] Q. Zhang *et al.*, “Transcriptome Analysis Reveals That C17 Mycosubtilin Antagonizes Verticillium dahliae by Interfering with Multiple Functional Pathways of Fungi,” *Biology*, vol. 12, no. 4, p. 513, 2023.
[43] A. Uppal, A. El Hadrami, L. Adam, M. Tenuta, and F. Daayf, “Biological control of potato Verticillium wilt under controlled and field conditions using selected bacterial antagonists and plant extracts,” *Biol. Control*, vol. 44, no. 1, pp. 90–100, 2008.
[44] D. Pei, Q. Zhang, X. Zhu, and L. Zhang, “Biological Control of Verticillium Wilt and Growth Promotion in Tomato by Rhizospheric Soil-Derived Bacillus amyloliquefaciens Oj-2.16,” *Pathogens*, vol. 12, no. 1, p. 37, 2023.
[45] K. Shreejana, R. Thapa, A. Lamsal, S. Ghimire, K. Kurunju, and P. Shrestha, “Urtica Dioica: A OSTRACIZED NEGLECTED PLANT IN AGRICULTURE SERVING AS A BEST MEDICINAL AND INSECTICIDAL PROPERTY,” *Trop. Agrobiodiversity TRAB*, vol. 3, no. 1, pp. 08–11, 2022.
[46] J. Amini, “Induced resistance in potato plants against verticillium wilt invoked by chitosan and Acibenzolar-S-methyl,” *Aust. J. Crop Sci.*, vol. 9, no. 6, pp. 570–576, 2015.
[47] G. Bubici, A. D. Marsico, L. Gaber, and L. Tsror, “Evaluation of thiophanate-methyl in controlling Verticillium wilt of potato and artichoke,” *Crop Prot.*, vol. 119, pp. 1–8, 2019.
[48] I. Opatovsky *et al.*, “Control of lettuce big-vein disease by application of fungicides and crop covers,” *Plant Pathol.*, vol. 68, no. 4, pp. 790–795, 2019.
[49] P. B. Angon and U. Habiba, “Application of the CRISPR/Cas9 Gene-editing System and Its Participation in Plant and Medical Science,” *Curr. Appl. Sci. Technol.*, pp. 10–55003, 2023.
[50] P. B. Angon, N. Anjum, M. Akter, S. KC, R. P. Suma, and S. Jannat, “An Overview of the Impact of Tillage and Cropping Systems on Soil Health in Agricultural Practices,” *Adv. Agric.*, vol. 2023, 2023.