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Verticillium wilt of olive and its control caused by the hemibiotrophic soil-borne fungus *Verticillium dahliae*

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ABSTRACT

Verticillium wilt, caused by the soil-borne fungus *Verticillium dahliae* Kleb., poses a significant threat to olive (*Olea europaea* L.) cultivation worldwide. This review provides an in-depth comprehension of the disease and its management strategies. The genetic diversity of *V. dahliae*, comprising various pathotypes and races, has implications for virulence and host interactions. The fungus can affect a wide host range, including crops and trees. *V. dahliae* is responsible for many symptoms such as wilting, yellowing, stunted growth, necrosis, and vascular discoloration. Economic consequences caused by this pathogen include yield losses, low-quality olive oil, market restrictions, and increased production costs. *Verticillium* wilt thrives in warm temperatures and excessive soil moisture. Chemical and biological controls and cultural practices are evaluated as potential measures. However, the search for resistant cultivars stands out as a significant solution. Insights from this review underscore the need for an interdisciplinary approach to managing the *Verticillium* wilt of olives. Integrated disease management strategies, resistant cultivars, and sustainable practices emerge as pivotal approaches for disease control.

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Introduction

Olive (*Olea europaea* L.) trees, native to the Mediterranean region, have been cultivated for an estimated 6,500 years, making them one of the oldest known cultivated tree species (Barazani et al., 2023). Olive trees are known for their robustness, longevity, and the exceptional product they yield in olives and oil. They have been an integral part of various cultures and economies across the globe (Cardoni et al., 2022). The total cultivated area for olive trees worldwide is estimated to be 10.1 million hectares as of 2023 (FAO, 2023; IOC, 2023).

While olive trees are renowned for their resilience, they are not impervious to the threats posed by plant diseases. Various pathogens, including bacteria and fungi, can cause diseases that have the potential to devastate olive production. These diseases can lead to reduced yields, poor fruit quality, and in severe cases, complete tree loss (Acharya et al., 2020; Montes-Osuna & Mercado-Blanco, 2020). One of the diseases that pose a threat to olive

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production is *Verticillium* wilt caused by *Verticillium dahliae* (Jeseničnik et al., 2023).

The hemibiotrophic, soil-borne fungus *V. dahliae* is responsible for substantial economic losses to 200 host species globally, including olive trees. *V. dahliae* thrives in the Mediterranean region known as the world's leading olive grower (Acharya et al., 2020; Song et al., 2020).

Despite the absence of comprehensive data, fragmented surveys offer crucial insights into the expanding reach and economic impact of *Verticillium* wilt of olive. Thanassoulopoulos et al. (1979) found a 2-3% infection rate in Greece, accompanied by a 1% drop in national olive production. In Spain, Blanco-López et al. (1984) conducted a more extensive survey between 1980 and 1983, revealing a staggering 38.5% incidence of *Verticillium* wilt of olive in 122 orchards located near the Guadalquivir valley. These fragmented studies, while geographically limited, highlight the potential severity of *Verticillium* wilt of olive threat and underscore the need for more comprehensive assessments. The geographic reach of *Verticillium* wilt of olive extended beyond its initial stomping grounds. Between 1994 and 1996, Sánchez-Hernández et al. (1998) documented a striking 39.5% incidence in newly established orchards, far from the disease's first sightings. This expansion wasn't an isolated incident. Subsequent reports by Jiménez-Díaz et al. (2009) and Rodríguez et al. (2009) revealed a worrying increase in both the frequency and severity of *Verticillium* wilt attacks across various olive-growing regions of Spain. The threat wasn't confined to Europe, as Al-Ahmad and Mosli (1993) estimated yield losses of 1-2.3% in Syria due to *Verticillium* wilt-infected trees. Serrhini and Zeroual (1995) showed a grim picture in Morocco, with *Verticillium* wilt of olive claiming 10-30% of trees in 60% of orchards. Algeria faces a similar plight, with Bellahcene et al. (2000) reporting the disease in most olive-growing areas, affecting up to 90% of surveyed orchards and averaging a 12% infection rate. Levin et al. (2003) estimated a devastating 75-89% reduction in susceptible olive production. The threat creeps even further, with Nigro et al. (2005) finding *V. dahliae* in 16% of olive fields and 50% of olive nurseries in Apulia, Italy. Dervis et al. (2010) added Turkey to the list, with *Verticillium* wilt of olive prevalent in 35% of orchards and a disease index of 3.1%. Even previously low-involved countries like Australia (Sergeeva & Spooner-Hart, 2009) and Argentina (Pérez et al., 2007) are now reporting the presence of the disease. Recent research revealed that fruits from infected olive trees produce oil demonstrated by poor sensory qualities, further diminishing their commercial value (Montes-Osuna & Mercado-Blanco, 2020).

The fungus can endure adverse conditions through stable microsclerotia structures that allow it to persist in the soil for several months to years. *V. dahliae* infects plants through the roots and colonizes the xylem, fostering *Verticillium* wilt, evident in symptoms like wilting, chlorosis, stunting, and necrosis (Chen et al., 2021). This pathogen not only causes tree mortality and decreased yields, but it also affects the organoleptic properties of olives, leading to a detrimental impact on the commercial value of olive oil on the market (Landa et al., 2019).

Two theories have emerged in the past six decades to explain the wilt's causation: vascular occlusion and toxin involvement (Castro et al., 2020; Mamalis et al., 2023). As the pathogen breaches the plant's defenses and establishes itself in the xylem, it triggers defensive reactions including the production of tyloses and a colloidal matrix, potentially leading to vascular occlusion and subsequent wilting (ElDesouki-Arafat et al., 2021). Alternatively, toxins may be delivered by the pathogen, inducing wilting via cytotoxicity (Cardoni et al., 2022; Markakis et al., 2022).

The possibility of toxin-driven wilting in *Verticillium* infections first gained traction with the observation that culture filtrates containing fungal chemicals could induce wilting symptoms. Since then, researchers have delved deeper into the potential role of toxins in the wilting mechanism (Stoddart & Carr, 1966; Meyer & Dubery, 1993). While compelling evidence supports a toxin-mediated wilting process, some studies have yielded inconclusive results, adding a layer of ambiguity to the issue (Fradin & Thomma, 2006). For instance, in potatoes, a low molecular weight polypeptide with phytotoxic properties was identified in the xylem of infected stems using immunofluorescent antibodies, suggesting its involvement in wilting symptoms. Nevertheless, further research is necessary to definitively establish the precise role and impact of toxins in *Verticillium*-induced foliar wilting (Nachmias et al., 1985). The discovery that a toxin could mimic the characteristic wilting in Arabidopsis thaliana seedlings provided further weight to the hypothesis of toxin-mediated wilt in *Verticillium* infections (Jing et al., 2005). Technological advancements in genomics and metabolomics have facilitated significant progress in unraveling the complex toxin profile. Researchers have identified diverse toxin components, including proteins with enzymatic or effector activity, potent metabolites, and even volatile compounds emitted by the fungus. These findings point towards a multifaceted arsenal of toxins employed by *Verticillium*, with further research necessary to fully understand their individual and combined roles in the wilting process (Klimes et al., 2015; Zhang et al., 2016, 2019; Li & Kang, 2018). The pathogenic arsenal of *V. dahliae* relies heavily on protein toxins secreted by the fungus. These toxins play a crucial role in the wilting of olive trees through various mechanisms, including the destruction of plant cell walls, the manipulation of host responses, and direct cytotoxicity (De Sain & Rep, 2015; Klimes et al., 2015; Chen et al., 2016). Research suggests that these secreted proteins target a diverse range of cellular components, including the cell wall, plasma membrane, and even intracellular structures (Meyer & Dubery, 1993; Zhao et al., 2020). Furthermore, recent studies have shown that protein toxins can induce cell wall degradation (VdEg-1, VdSSP1, VdPL3.1, VdPL3.3, VdCBM1, etc.), host immunity manipulation (VdAve1, VdISC1, Vd2LysM, VdCBM1, VdCP1, etc.), hormone homeostasis interference (VdAve1, VdISC1, VdCBM1, VdCP1, VdSCP126, etc.), cytotoxicity (VD18.5, VdNLP1, VdNLP2, VdXyn4, etc.), oxidative stress neutralization (VdSOD3, VdSOD5, VdSOD1, etc.), fungal nutrition (VdSSP1, VdXyn4, etc.), morphological development (VDH1, VdNLP1, Vd2LysM, VdASP F2, etc.), and microbiome manipulation (VdAve1, etc.) (Zhang et al., 2022).

Currently, effective protection measures against *Verticillium* wilt are limited, making its control a pressing challenge. Implementing fungicides and fumigants throughout the growing season is a common approach, though synthetic chemicals bring environmental concerns. Environmentally friendly alternatives to these treatments such as the use of resistant cultivars, are being pursued as sustainable solutions, aiming to mitigate the impact of this relentless pathogen on global agriculture (Montes-Osuna & Mercado-Blanco, 2020).

Taxonomy & genetic variation

Verticillium dahliae Kleb., which belongs to the domain *Eukaryota*, kingdom: Fungi, phylum: *Ascomycota*, subphylum: *Pezizomycotina*, class: *Sordariomycetes*, subclass: *Hypocreomycetidae*, order: *Glomerellales* and family: *Plectosphaerellaceae*. *V. dahliae* exhibits genetic variation, which means that different strains or isolates of the fungus may show genetic differences. This genetic diversity can lead to variations in various aspects of the pathogen, including its virulence, pathogenicity, and ability to adapt to different environments (Jeseničnik et al., 2023).

Genetic variation in *V. dahliae* has been extensively studied using molecular markers and sequencing techniques. These studies have revealed the existence of different pathotypes or races of the fungus, each capable of infecting specific plant hosts. The devastating virulence of *V. dahliae* varies dramatically depending on its two pathotypes: defoliating pathotype (D) and non-defoliating pathotype (ND). As their names suggest, the D pathotype unleashes a severe attack, causing leaves to wither and fall, while the ND pathotype operates stealthily within the plant without overt foliar symptoms. Understanding this link between pathotype and virulence is crucial for accurately predicting and combating *V. dahliae* infections (Bejarano-Alcázar et al., 1995; Göre et al., 2009; Le et al., 2020). Strains of *V. dahliae* can be classified into two races (races 1 and 2) based on the presence of the Ave 1 gene, a key virulence factor . Race 1 possesses the avirulence gene Ave1. However, race 2 lacks the avirulence gene Ave1 (Popov et al., 1972; Maruthachalam et al., 2010; De Jonge et al., 2012). Interestingly, Jiménez-Gasco et al. (2014) and Jiménez-Fernández et al. (2016) observed a strong correlation between pathotype and race in the strains of *V. dahliae*, with the majority of non-defoliating strains belonging to race 1 and defoliating ones belonging to race 2. This suggests a potential link between the Ave 1 gene and symptom expression (Baroudy et al., 2019; Godena et al., 2022). The genetic variability in *V. dahliae* is an important factor that contributes to the complexity of managing *Verticillium* wilt in many crops (Liu et al., 2021; Wu et al., 2023).

Understanding the genetic diversity of the pathogen is crucial for developing effective control strategies, such as breeding resistant plant varieties or implementing targeted management practices (Zhang et al., 2022). Additionally, studying the genetic variation of *V. dahliae* helps researchers and plant pathologists track the spread of specific strains and gain insights into their evolutionary history and epidemiology (Zhang et al., 2018).

Host range

Verticillium dahliae exhibits a remarkably broad host range, encompassing over 200 plant species across diverse taxonomic groups. Its pathogenic repertoire includes herbaceous and woody plants, spanning annuals (e.g., tomatoes, lettuce) and perennials (e.g., oak). Notably, *V. dahliae* effectively infects key agricultural crops like vegetables (tomatoes, potatoes, peppers), field crops (cotton, sunflower, flax), and fruit trees (apple, pear, peach). Ornamental plants (maples, roses, chrysanthemums) and even forest trees (oak, ash, willow) are not spared from its detrimental effects. This extensive host range highlights the significant economic and ecological impact of *V. dahliae*, necessitating comprehensive control strategies for diverse plant communities (Acharya et al., 2020; Song et al., 2020).

It is important to note that the host range of *V. dahliae* is extensive and not limited to the examples mentioned above. The ability of this pathogen to infect such a diverse range of plant species makes it a challenging pathogen to manage in agricultural and horticultural settings. Crop rotation, use of resistant varieties, and other preventive measures are essential in reducing the impact of *Verticillium* wilt on susceptible plants. By adopting these strategies, growers can better protect their crops and ornamental plants from the detrimental effects of this wide-ranging and formidable fungus (Zhang et al., 2022).

Symptoms

Symptoms of olive *Verticillium* wilt of olive can vary depending on the stage of infection, and environmental conditions. However, some common symptoms associated with *Verticillium* wilt of olive include (Figure 1) (Castro et al., 2020; ElDesouki-Arafat et al., 2021; Cardoni et al., 2022; Markakis et al., 2022; Mamalis et al., 2023):

Wilting: Affected trees may exhibit wilting, where leaves on one or more branches or the entire tree droop and lose turgidity even when the soil has adequate moisture.

Yellowing and rolling: Leaves may turn yellow or bronze, often starting at the margins or between the veins causing them to curl. The yellowing may progress upward from the lower leaves.

Stunted growth: Trees infected with *Verticillium* wilt of olive may show reduced growth and overall vigor.

Necrosis: In some cases, infected trees may display necrotic areas on the leaves or stems, which can lead to premature defoliation.

Vascular discoloration: If you cut a stem of an infected tree and observe the cross-section, you may notice brown to dark brown discoloration in the vascular tissues.

One-sided wilting: In some cases, only one side or branch of the tree may exhibit wilting, while the other side remains relatively unaffected.

Yellow V-shaped lesions: On some leaves, you might observe yellow V-shaped lesions pointing toward the leaf base.

Drying of branches: As the disease progresses, entire branches may dry up, and leaves may remain attached even when they are dead.

It's important to note that these symptoms can be caused by other biotic and abiotic factors as well, so proper diagnosis is essential to confirm *Verticillium* wilt of olive. To confirm the presence of *V. dahliae*, laboratory testing or diagnostic services may be necessary.

Keep in mind that different plant species and varieties may exhibit different symptom patterns, and the severity of symptoms can also vary based on the plant's susceptibility, the specific strain of the pathogen, and environmental factors. If you suspect *Verticillium* wilt in your olive trees, it is best to consult a local plant pathologist or agricultural extension office for accurate diagnosis and appropriate management strategies.

Favorable conditions for the establishment of the disease

Verticillium wilt of olive can establish and spread under specific favorable conditions. Understanding these conditions is crucial for implementing preventive measures and managing the disease effectively. The main factors that contribute to the establishment of *Verticillium* wilt of olive include:

Soil-borne pathogen: *V. dahliae* is a soil-borne fungus. The pathogen can persist in the soil for several years, especially in the form of resistant structures called microsclerotia. Infected tree debris, debris from pruned trees, crop residues, or weeds can serve as sources of inoculum, contributing to the disease's establishment in the soil (Santos-Rufo et al., 2022).

Fig 1. *Verticillium* wilt symptoms in olive trees.

Warm temperatures: Warm temperatures favor the growth and activity of *V. dahliae* in the soil. Soil temperatures between 20 to 30°C are generally conducive to disease development (Santos-Rufo et al., 2022).

Moisture: Soil moisture plays a significant role in the disease's establishment and spread. Excessively wet or waterlogged soils can promote the growth and spread of the pathogen, as well as the infection of olive tree roots (Santos-Rufo et al., 2022).

Olive tree susceptibility: Different olive tree varieties exhibit varying levels of susceptibility to *Verticillium* wilt. Some olive trees are highly susceptible, while others may show partial resistance or tolerance to the pathogen (Markakis et al., 2022).

Olive tree density: High olive tree densities, especially in monoculture or continuous cropping systems, can increase disease pressure as the pathogen spreads easily from one tree to another (Dias et al., 2022; Sobreiro et al., 2023).

Soil pH: Acidic soils (pH below 7) have been associated with increased disease severity, although the pathogen can still thrive in a wide range of soil pH levels (Santos-Rufo et al., 2022).
Stress factors: Environmental stressors, such as drought, high salinity, or nutrient deficiencies, can weaken plants' defenses, making them more susceptible to *Verticillium* wilt of olive (Montes-Osuna & Mercado-Blanco, 2020).
Field history: Fields with a history of *Verticillium* wilt of olive or where susceptible crops have been previously grown are more likely to have the pathogen present in the soil (Santos-Rufo et al., 2022).
Irrigation practices: Poor irrigation practices, such as overwatering or using contaminated water sources, can facilitate the spread of the pathogen in the soil (Pérez-Rodríguez et al., 2022).
Debris, residues, and weeds: Infected tree and crop residues, and debris from pruned trees left in the field or nearby weeds can serve as reservoirs for the pathogen, contributing to disease establishment and spread (Castro et al., 2020).
Imbalance in fertilization: *V. dahliae* infections are likely to occur due to fertilization imbalance, particularly N-K, or excessive N applications (Pérez-Rodríguez et al., 2022).

Life cycle & epidemiology

The epidemiology of *Verticillium* wilt involves the study of how the disease spreads, its impact on different host species, and the factors that influence its incidence and severity. The disease's epidemiology is influenced by factors such as the susceptibility of host plants, soil management, environmental conditions, and the presence of inoculum sources.

To manage *Verticillium* wilt effectively, understanding its life cycle and epidemiology is crucial. Implementing practices that reduce the initial inoculum levels in the soil, such as cover crops and intercropping with non-host crops, solarization, removing infected residues and debris, and using resistant varieties, can help minimize disease incidence. Additionally, practicing good soil and irrigation management can contribute to disease control and reduce its economic impact on agriculture and horticulture.

The life cycle and epidemiology of *Verticillium* wilt of olive involve several stages and factors that contribute to the disease's establishment and spread. Here's an overview of the life cycle and epidemiology of *V. dahliae* (Figure 2) (Montes-Osuna & Mercado-Blanco, 2020; Ostos et al., 2020; Sudip et al., 2020):

Survival and Overwintering: *V. dahliae* survives in the soil between growing seasons, mainly in the form of resilient structures called microsclerotia. These microsclerotia are the primary survival structures of the pathogen and can persist in the soil for several years, even in adverse conditions (Markakis et al., 2022).
Inoculum sources: The primary sources of inoculum for new infections are infected tree residues and debris, and weeds left in the field from previous growing seasons. These sources release microsclerotia, which can infect the roots of new susceptible trees (López-Moral et al., 2022).
Infection: The fungus enters the olive tree through the roots, primarily via root hairs or wounds. Once inside the root, the pathogen colonizes the xylem vessels, which are responsible for transporting water and nutrients throughout the tree (Landa et al., 2019).
Vascular colonization: The fungus multiplies and spreads within the vascular system of the tree, forming mycelial mats that block water and nutrient flow. This leads to wilting and yellowing of leaves, as well as other characteristic symptoms of olive *Verticillium* wilt (Zhang et al., 2022).
Reproduction and sporulation: Inside the tree, *V. dahliae* can produce conidia, which are asexual spores. These conidia may further contribute to disease spread within the tree or to nearby trees (ElDesouki-Arafat et al., 2021).
Disease development: The symptoms of olive *Verticillium* wilt become evident as the disease progresses. Affected trees show wilting, yellowing, and other characteristic symptoms, which can lead to reduced growth and yield losses (Fernández-González et al., 2020).
Disease dispersal: Infected trees can serve as sources of inoculum, and the pathogen can also spread through the soil, irrigation water, or equipment used in the field. Insects and nematodes have been suggested as possible vectors for the disease, contributing to its dissemination (Liu et al., 2021).
Environmental Factors: Environmental conditions, such as warm temperatures and adequate soil moisture, can favor the growth and activity of *V. dahliae* in the soil, leading to disease establishment and spread (López-Escudero & Mercado-Blanco, 2011).

Economic importance

Verticillium wilt is of significant economic importance due to its widespread distribution, broad host range, and potential to cause severe damage. Here are some key reasons why *Verticillium* wilt is economically important (Castro et al., 2020; ElDesouki-Arafat et al., 2021; Cardoni et al., 2022; Markakis et al., 2022; Mamalis et al., 2023):
Crop losses: *V. dahliae* can infect and cause wilt in a wide range of economically important crops, including olive trees. The disease can lead to yield losses, reduced quality of produce, and even complete crop failures, resulting in significant economic losses for farmers and growers (ElDesouki-Arafat et al., 2021).

Long-term impact: Once the pathogen is introduced into the soil, it can persist for years, making it challenging for farmers to cultivate susceptible varieties (high yielding and/or good-quality olive, and/or oil) on the same land. This limitation can prevent cover crops and intercropping and reduce overall agricultural productivity in affected areas (Castro et al., 2020).

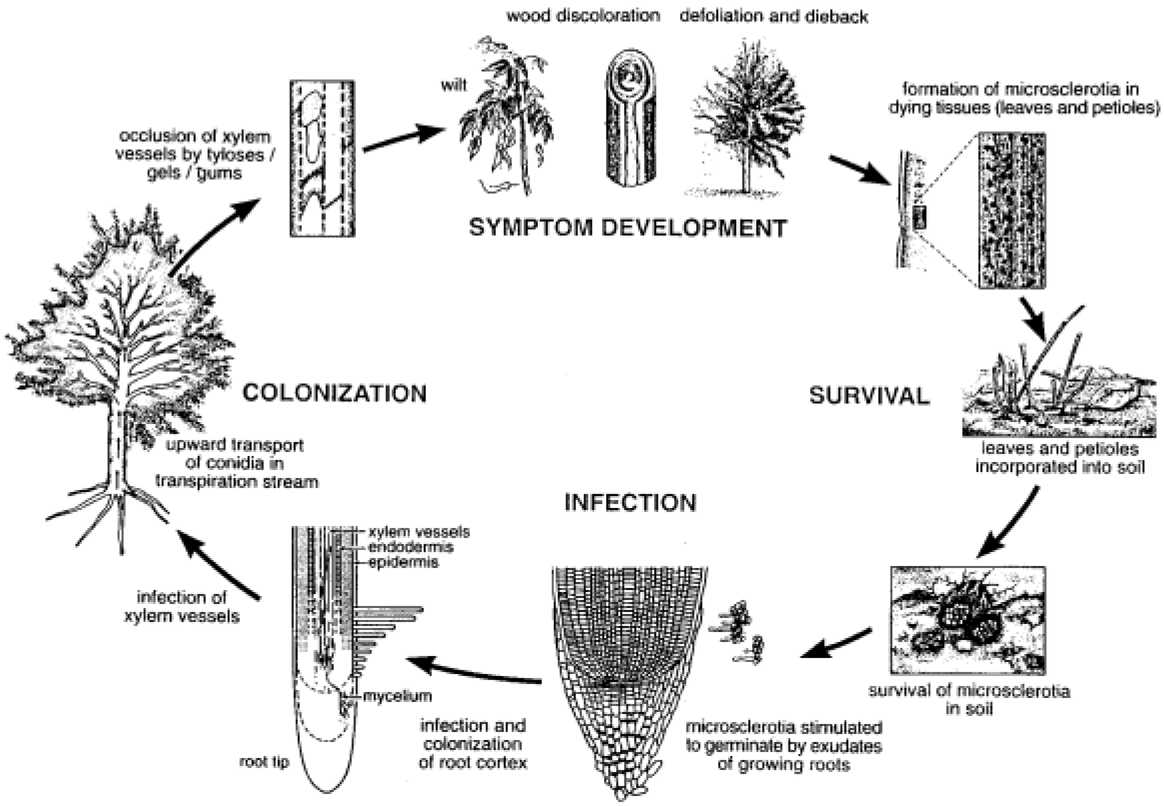

Fig 2. Life cycle of *Verticillium dahliae* in olive tree hosts.

Limited control measures: Managing *Verticillium* wilt can be difficult, as there are no complete control methods available. Although crop rotation, resistant varieties, and other management practices can help mitigate the impact, they are not always foolproof, especially in areas with high disease pressure (Cardoni et al., 2022).

Impact on nursery and landscaping industries: The disease can affect a wide range of olive trees used in decoration, including trees used in landscaping and nursery trade. Thus, infected nursery stock can lead to disease spread to new locations when planted, posing a threat to Tunisian agriculture since the olive tree is a strategic crop (Mamalis et al., 2023).

International trade restrictions: *Verticillium* wilt of olive is considered a quarantine pathogen in some regions, and its presence in crops can lead to trade restrictions and barriers for exporting countries. This can have a significant impact on the global trade of agricultural products (ElDesouki-Arafat et al., 2021).

Increased production costs: Farmers may need to invest in disease management practices, such as fumigation, chemical control, localized solarization, or other preventive measures, which can increase production costs (Cardoni et al., 2022).

Research and development: Given the economic importance of *Verticillium* wilt, research efforts are directed toward developing resistant varieties and sustainable management strategies. This requires investments in research and development, adding to the overall economic impact of the disease (Markakis et al., 2022).

Overall, *Verticillium* wilt of olive poses a significant economic threat to agriculture and horticulture industries worldwide. To reduce its economic impact, ongoing research, development of resistant cultivars, and implementation of integrated disease management practices are essential to minimize crop losses and ensure food security (Castro et al., 2020).

Management of *Verticillium* wilt on olive tree

There is currently no enough single control measure that is fully effective in managing *Verticillium* wilt of olive (Castro et al., 2020). Thus, the use of preventive measures is combined with an integrated disease management strategy. The risk because of pathogen spread, and subsequent infections of other trees can be mitigated by taking pre-planting control measures and post-planting measures (Ostos et al., 2020; Zhang et al., 2020).

Verticillium wilt of olive is regarded as one of the most serious diseases in olives (Song et al. 2020). An integrated controlling plan is necessary for active control of this disease, with the potential use of biological control as a tool (Ostos et al., 2020).

Verticillium wilt control is very difficult due to reasons that have been extensively reviewed elsewhere (Castro et al., 2020). The truth is that recent surveys and reports consistently inform about the spread of disease in new areas or increased incidence and severity in areas where the pathogen exists (Landa et al., 2019; ElDesouki-Arafat et al., 2021).

To achieve effective management, an integrated approach is necessary. This is usually a combination of cultural practices aimed at reducing disease (Montes-Osuna & Mercado-Blanco, 2020). The use of resistant cultivars and pre-plant soil treatments, such as soil fumigation or solarization, can reduce microsclerotia capability in soil (Montes-Osuna & Mercado-Blanco, 2020; Cardoni et al., 2022).

It is common to fumigate soil with chemicals such as methyl bromide and/or chloropicrin to combat *Verticillium* wilt of olive (Ziazia et al., 2021). Aureofungin, benomyl, captan, thiram, fosetyl-Al, azoxystrobin, trifloxystrobin, and acibenzolar-s-methyl show their effectiveness against *Verticillium* wilt of olive (López-Escudero & Mercado-Blanco, 2011). Yet, these fungicides have not shown satisfactory efficacy since *V. dahliae* aptitude to survive in the setting for a long time and to spread readily by way of various agricultural applications (Montes-Osuna & Mercado-Blanco, 2020; Ziazia et al., 2021). Hence, the possible dangers complicated in applying phytochemicals to olive trees for both the location and social health, composed of their narrow efficacy for controlling *Verticillium*-induced diseases, funding the want to find alternatives to trade their use or expand their ability (Hajji-Hedfi et al., 2023a; Rhouma et al., 2023a).

Cultural control combines lots of elements that must be put into practice: remove infected stems and leaves; remove all tree residues at pruning; make sure the soil contains enough NPK (avoid excess or deficiency); choose a tree density that allows good air movement; prune trees regularly to remove old and infected leaves and stems to aid air movement (Montes-Osuna & Mercado-Blanco, 2020; Ziazia et al., 2021; Sobreiro et al., 2023; Rhouma et al., 2023b).

Soil solarization is a powerful physical control method to reduce the population of soil-borne pathogens and consequently disinfest the soil via way of means of sun heating. The inoculum density of *V. dahliae* in soil may be decreased and *Verticillium* wilt may be managed in plants and trees through a pre-planting program (Calderón et al., 2015; Rippa et al., 2023). A post-planting soil solarization program is likewise feasible for woody hosts suffering from *V. dahliae* and has proven to be powerful in main healing in olive trees (Calderón et al., 2015). Covering the soil with transparent polyethylene films kills many soil-borne pathogens such as *V. dahliae* at lethal temperatures (35 and 60°C) (López-Escudero & Mercado-Blanco, 2011). Saremi et al. (2010) cautioned that olive soils experienced a decrease in the population density of *V. dahliae* from 1,600 CFU g^{-1} per soil to 300 CFU g^{-1} per soil. As stated by Otero et al. (2014), the effectiveness of soil solarization in terms of reducing *V. dahliae*'s population density and the severity of *Verticillium* wilt of olive was significant when combined with the use of *Trichoderma* spp., organic amendment, and chemical control. As far as we know, soil solarization as a pre-planting practice in commercial olive groves is not practicable, probably due to its high cost.

One of the organic strategies that can reduce the effect of vascular wilt sicknesses is the use of arbuscular mycorrhizal fungi (Villani et al., 2021). Arbuscular mycorrhizal fungi are either present or added to vegetation, resulting in many advantages for tree life (Ramírez-Gil & Morales-Osorio, 2021). Arbuscular mycorrhizal fungi's mycelial network recovers water and mineral uptake, primarily nitrogen and phosphorus, by increasing the soil volume available to the tree (Weng et al., 2021). Extra radical hyphae have a first-order capacity to absorb nutrients transported to the roots. Mycorrhizal symbiosis helped tree growth and lowered the population density of *V. dahliae* as well as the disease severity (Zhang et al., 2018; Goicoechea, 2020; Matrood & Rhouma, 2022; Okon et al., 2022).

Various fungi (*Trichoderma* spp., *Gliocladium* spp., *Chaetomium* spp., etc.) and bacteria (*Streptomyces* spp., *Pseudomonas* spp., *Bacillus* spp., etc.) have been described as effective biological control agents against a wide range of pathogens, not only through direct action but also through defense system activation. The use of microbial groups (fungi and microorganisms) isolated from the ecological niche of *V. dahliae* (soil of olive trees) showed significant results against the mycelial growth of *V. dahliae* and the disease severity (Fernández-González et al., 2020; Hajji-Hedfi et al., 2023b; Hajji-Hedfi et al., 2023c; Matrood et al., 2023). Gómez-Lama Cabanás et al. (2018), Castro et al. (2020), and Ziazia et al. (2021) pointed out that *Paenibacillus polymyxa*, *Paenibacillus terrae*, *Bacillus velezensis*, and *Pseudomonas putida* were highly significant in terms of the growth and germination inhibition rate of *V. dahliae* (under laboratory conditions), as well as the severity decreasing of *Verticillium* wilt of olive (under in vivo and field conditions). López-Moral et al. (2022) revealed that the combined treatment of olive tree (cv. Picual; *V. dahliae* resistant variety) with *Bacillus amyloliquefaciens*, copper phosphate, and olive stem extract were the most effective treatments in inhibiting conidia germination and hyphae growth of *V. dahliae*, and in decreasing the severity of *Verticillium* wilt of olive. Ramírez-Gil et al. (2021) found that the combination of beneficial and antagonistic microorganisms (*Trichoderma* spp. and *Rhizoglomus fasciculatum*), fungicides (benomyl, azoxystrobin, captan, and carbendazim), and physical and cultural practices (compost, organic amendment, solarization, drainage, removal of diseased debris and residues, and pruning) showed the highest reduction in *V. dahliae* inoculum and disease incidence under field conditions.

The use of resistant cultivars is prudent since it is an ecologically friendly (Rhouma et al., 2023a), and green manipulation for the *Verticillium* wilt of olive, as well as efforts to look for new genotypes and/or examine to be had cultivars have been reviewed. Santos-Rufo et al. (2023), and Markakis et al. (2022) found that 'Atsiholou', 'Koroneiki', 'Frantoio', and 'Tragolia' represent the most resistant varieties to *Verticillium* wilt in olive trees. However, 'Megaritiki', 'Mastoidis', 'Koutsourelia', 'Picual', 'Kothreiki', 'Chalkidikis', and 'Amfissis' revealed a significantly low level of resistance, suggesting an increased risk for the olive industry (Santos-Rufo et al. 2023; Markakis et al. 2022). Ostos et al. (2020) highlighted the efficacy of Frantoio cultivar (moderately resistant to *V. dahliae*) in combination with chemical weed control and soil solarization as a tool for *Verticillium* wilt control and its positive influence on the reduction of annual mortality compared to Picual cultivar (susceptible to *V. dahliae*).

Conclusions

This review delves into the importance and the challenges posed by *Verticillium* wilt caused by the soil-borne fungus *V. dahliae* in olive cultivation. The disease's widespread impact on *Verticillium* wilt severity, economic significance, and difficulty in control methods are thoroughly explored. The paper also highlights that the integrated approach, which combines preventive and post-planting measures, is essential to combat *Verticillium* wilt's persistent threat. The significance of research and development in finding sustainable solutions is needed, given the disease's long-lasting impact on agriculture and horticulture.

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