Asian Journal of Mycology 7(2): 21–36 (2024) ISSN 2651-1339
www.asianjournalofmycology.org

Article
Doi 10.5943/ajom/7/2/3

Fusarium oxysporum f. sp. *lycopersici,* the causal agent of vascular wilt disease of tomatoes: From its taxonomy to disease management

Rhouma A[1*], Hajji-Hedfi L[1], Atallaoui K[2], Kouadri AM[3] and Khrieba MI[4]

[1]Regional Centre of Agricultural Research of Sidi Bouzid, CRRA, Gafsa Road Km 6, B.P. 357, 9100, Sidi Bouzid, Tunisia
[2]Department of Natural and Life Sciences, University of Djelfa, Algeria
[3]Laboratory of Research on Biological Systems and Geomatics, Department of Agronomy, Faculty of Life and Natural Sciences, University Mustapha Stambouli of Mascara, Algeria
[4]National Center for Biotechnology Damascus, Syria

Rhouma A, Hajji-Hedfi L, Atallaoui K, Kouadri AM, Khrieba MI 2024 – *Fusarium oxysporum f. sp. lycopersici*, the causal agent of vascular wilt disease of tomatoes: From its taxonomy to disease management. Asian Journal of Mycology 7(2), 21–36, Doi 10.5943/ajom/7/2/3

Abstract

Tomato (*Solanum lycopersicum*) is one of the world's most vital vegetable crops, holding immense agricultural, nutritional, and research significance. However, the Fusarium wilt disease, caused by *Fusarium oxysporum* f. sp. *lycopersici*, poses a severe threat to its global cultivation. This review paper focuses on the comprehensive management of Fusarium wilt disease and the associated taxonomic framework. It highlights the global significance of tomatoes, emphasizing their importance around the world. The review covers various aspects, including taxonomy and genetic variation of the pathogen, host range, disease symptoms, economic implications, factors affecting epidemiology, geographical distribution, disease cycle, and various management strategies. Moreover, it explores different management approaches, including chemical control, biological control, cultural practices, resistance breeding, soil solarization, and grafting. This comprehensive review underscores the strategies needed to protect tomato crops, ensuring food security on a global scale despite the challenges posed by Fusarium wilt.

Keywords – Fusarium wilt – management practice – *Solanum lycopersicum* – sustainable

Introduction

Tomato (*Solanum lycopersicum* L.) is the second-most important solanaceous crop worldwide after potato (*Solanum tuberosum* L.) (Quinet et al. 2019). This crop originated in western South America and is now cultivated across the globe, either for local consumption or as a vital export commodity (Kumar et al. 2022). Tomato production and consumption have witnessed remarkable growth in recent years (Pan et al. 2023). They are valued not only for their agricultural prominence but also for their impressive nutritional profile, offering a rich source of vitamin C and phytochemical lycopene (Kumar et al. 2022).

They are also used in culinary applications, from salads, raw additions, and crisps to key ingredients in various prepared dishes and even as the base for ubiquitous products like canned tomatoes, tomato juice, ketchup, puree, and "sun-dried" tomatoes (Kumar et al. 2022, Włodarczyk et al. 2023). Beyond their culinary importance, tomatoes are considered a model fruit-bearing crop for essential research, further underscoring their significance in agriculture and scientific

Submitted 12 December 2023, Accepted 26 August 2024, Published 26 September 2024
Corresponding Author: Abdelhak Rhouma – e-mail – abdelhak.rhouma@gmail.com

exploration (Makhadmeh et al. 2022).

Vascular wilt, caused by *F. oxysporum* f. sp. *lycopersici*, stands as a major threat to tomato cultivation worldwide (Muhorakeye et al. 2024). This soil-borne pathogen can persist in the soil in the form of dormant chlamydospores, which germinate upon contact with host roots. Once established, it colonizes the xylem vessels and releases toxins (Latifah et al. 2023). This colonization results in vessel blockage, severe water stress, and the appearance of characteristic wilt symptoms, ultimately leading to reduced crop yields and sometimes plant death. The fungus can spread through contaminated soil and equipment and even over long distances via infected transplants (Rippa et al. 2023). This disease can cause substantial economic losses, reaching a 60% to 70% reduction in fruit yield (Latifah et al. 2023, Rippa et al. 2023).

Therefore, it is imperative to understand and effectively manage *F. oxysporum* and vascular wilt to ensure global food security and sustainable tomato production. This review aims to provide a comprehensive overview of the strategies and approaches for managing vascular wilt disease caused by *F. oxysporum* f. sp. *lycopersici* in tomato plants.

Taxonomy and genetic variation

Taxonomy is crucial for identifying and categorizing different strains or pathotypes of pathogens causing vascular wilt diseases. Accurate species identification is paramount in plant pathology for effectively identifying disease-causing agents. Species names serve as a concise communication tool and play a critical role in plant quarantine efforts, preventing the introduction of novel pathogens into new territories. However, challenges arise within genera containing numerous species, particularly those where disagreements exist regarding species concepts. This can lead to the identification of numerous "cryptic species" previously classified under various designations, such as *formae speciales* (specialized forms), subspecies, or pathotypes (Manawasinghe et al. 2021). In the case of *Fusarium oxysporum*, various *forma specialis* (f. sp.) are identified based on their host specificity. Identifying the specific *forma specialis* allows researchers to focus on understanding the interactions between the pathogen and the host plant (Ribeiro et al. 2022). For example, in the context of tomato vascular wilt caused by *Fusarium oxysporum* f. sp. *lycopersici* (Saccardo) Snyder & Hansen, the complete classification might look as follows: Kingdom: Fungi; Phylum: Ascomycota; Subphylum: Pezizomycotina; Class: Sordariomycetes; Subclass: Hypocreomycetidae; Order: Hypocreales; and Family: Nectriaceae (Chitwood-Brown et al. 2021).

Genetic variation within a pathogen population can have significant implications for the development of disease, host specificity, and the effectiveness of management strategies. Understanding genetic diversity helps researchers track disease spread and evolution (Hernández-Aparicio et al. 2021, Ribeiro et al. 2022, González-García et al. 2023). Genetic variation can lead to differences in pathogenicity and virulence among pathogen strains. Some strains might be more aggressive, leading to more severe disease symptoms, while others might be less virulent (Nirmaladevi et al. 2016). Genetic variation can determine the pathogen's ability to infect different host plant species or cultivars. Some strains might be specialized to infect specific hosts, while others might have a broader host range (Arie 2019, López et al. 2021). Nirmaladevi et al. (2016) employed 69 strains of *F. oxysporum* f. sp. *lycopersici*, which were evaluated for their ability to infect and cause disease in five susceptible tomato varieties. The findings revealed a significant proportion of virulent strains, with 45% exhibiting high virulence and an additional 30% demonstrating moderate virulence. Genetic variation in host plants can lead to variations in resistance or tolerance to the pathogen. Some plants might have natural resistance mechanisms that prevent or limit pathogen invasion (Gao et al. 1995, Chitwood-Brown et al. 2021). Understanding the genetic variation in pathogen populations is essential for developing effective management strategies. For example, if a pathogen population shows a high level of genetic diversity, it might be less susceptible to control measures that target specific genetic traits (Haruna et al. 2024). Genetic variation contributes to the evolution and adaptation of pathogens. In response to selective pressures like fungicides or resistant plant varieties, pathogens can evolve to overcome these challenges (Nirmaladevi et al. 2016).

Studying the genetic variation within pathogen populations and the genetic traits of host plants provides insights into the dynamics of disease outbreaks, the development of new strains, and the potential for long-term disease management (Ribeiro et al. 2022). In summary, both taxonomy and genetic variation are critical aspects of understanding vascular wilt diseases caused by pathogens like *F. oxysporum* f. sp. *lycopersici*. They help researchers classify and identify pathogen strains, understand disease development, and develop effective strategies for disease management and control.

Identification of *Fusarium oxysporum* f. sp. *lycopersici*

Traditionally, morphological characteristics (Macroscopic and microscopic features) have been the primary method for species identification within the *Fusarium* genus. These characteristics include the structure and abundance of asexual reproductive structures (macroconidia, microconidia, phialides, and chlamydospores) and cultural characteristics (aroma, color, and colony texture). For example, *F. oxysporum* is distinguished by specific features such as non-septate microconidia, 3-septate macroconidia, and smooth or rough-walled chlamydospores. However, this approach has limitations due to inherent variability between isolates, influenced by both genetic and environmental factors (Crous et al. 2021, Zhou et al. 2021, Darvishnia et al. 2023). This variability can hinder accurate species identification and may not provide sufficient resolution for newly discovered species. DNA sequencing for phylogenetic analysis has emerged as a more reliable and informative approach, overcoming the limitations of morphological criteria. This method has revealed that *F. oxysporum* is a complex of distinct lineages, supporting the view that it encompasses multiple species (Hafizi et al. 2013, Darvishnia et al. 2023).

Accurate and rapid detection and identification of diverse Fusarium wilt pathogens are crucial for effective disease management strategies. The availability of reference genomes has significantly enhanced this process, enabling cost-effective and reliable diagnosis of plant pathogens (Haegi et al. 2013, O'Donnell et al. 2015, Xia et al. 2019). Furthermore, various molecular methods based on DNA polymorphisms have been established for Fusarium wilt pathogen detection and differentiation (Adhikari et al. 2020). These methods include insertion-deletion, random amplified polymorphic DNA, simple sequence repeat, and amplified fragment length polymorphism analyses (Nirmaladevi et al. 2016, Arie 2019, Hassan 2020, Dholu et al. 2021, Ekwomadu & Mwanza 2023). Additionally, loop-mediated isothermal amplification, single-nucleotide polymorphism genotyping, and specific gene sequence targeting (e.g., elongation factor-1 alpha, calmodulin, β-tubulin, and internal transcribed spacer) have emerged as powerful tools for Fusarium wilt pathogen identification (Lievens et al. 2009, Xia et al. 2019).

Economic importance

Fusarium wilt has significant economic importance due to its impact on tomato crops. The disease can lead to substantial losses in tomato production and have far-reaching effects on the agricultural industry, as well as on local economies. Here are some key points highlighting the economic importance of this disease (Chitwood-Brown et al. 2021, Hernández-Aparicio et al. 2021, Mostafa et al. 2022, Ribeiro et al. 2022, Rippa et al. 2023).

Yield losses: Fusarium wilt can cause severe wilting, stunting, and premature death of infected tomato plants. This led to reduced fruit production and lower yields, resulting in financial losses for farmers and reduced tomato availability for consumers (Ribeiro et al. 2022).

Quality reduction: Even if plants survive the infection, they may not produce high-quality fruits. The stress caused by the disease can lead to smaller, unripe, or misshapen tomatoes that are less marketable and command lower prices (Panno et al. 2021).

Market value reduction: The presence of Fusarium wilt symptoms on tomato crops can lower their market value. Consumers often prefer healthy, disease-free produce, and affected tomatoes might be unsuitable for certain markets or processing (Inami et al. 2014).

Crop management costs: Managing Fusarium wilt requires implementing various control strategies, such as crop rotation, soil fumigation, and application of fungicides. These practices can involve additional costs for farmers, including the purchase of fungicides and the labor required for disease management (McGovern 2015, Hassan 2020).

Loss of planting material: Fusarium wilt can lead to the loss of planting material, such as seeds or transplants, if they are contaminated with the pathogen. This can increase the costs of acquiring disease-free planting material (Panno et al. 2021).

Trade and export restrictions: Some regions or countries might impose trade restrictions on tomatoes originating from areas with known Fusarium wilt outbreaks. This can impact international trade and limit market access for affected producers (Ribeiro et al. 2022).

Farmers' income reduction: The combination of reduced yields, lower-quality produce, and increased management costs can lead to decreased income for tomato growers (Panno et al. 2021).

Risk to the tomato industry: If Fusarium wilt becomes widespread in a region, it poses a significant risk to the sustainability of the local tomato industry. Small-scale and large-scale farmers alike can be affected, which can disrupt the tomato supply chain and lead to market instability (Inami et al. 2014, Ribeiro et al. 2022).

Long-term effects: Repeated infections of Fusarium wilt can lead to the build-up of the pathogen's population in the soil, making it challenging to grow susceptible crops in affected fields for several growing seasons. This can have lasting economic consequences for farmers and the Tunisian agricultural sector (Hassan 2020, Ribeiro et al. 2022).

Given these economic impacts, research efforts are focused on developing resistant tomato varieties, improving disease management practices, and enhancing our understanding of the pathogen's biology and interactions with host plants. These efforts are aimed at minimizing the economic losses caused by Fusarium wilt in tomato crops.

Geographical distribution of *Fusarium oxysporum* f. sp. *lycopersici*

Fusarium oxysporum f. sp. *lycopersici* has a global distribution. It can be found in various regions where tomatoes are cultivated. The disease's occurrence, prevalence, and impact can vary based on factors such as climate, cultural practices, host susceptibility, and pathogen populations. Here's a general overview of its geographical distribution (Hernández-Aparicio et al. 2021, Attia et al. 2022, González-García et al. 2023).

Tropical and subtropical regions: Fusarium wilt of tomatoes is particularly problematic in tropical and subtropical regions where warm temperatures and high humidity create favorable conditions for disease development (Bawa 2016).

Mediterranean climates: Areas with Mediterranean climates characterized by dry, hot summers and mild, wet winters can also support the disease's spread, especially if irrigation practices contribute to soil moisture (Aydi-Ben-Abdallah et al. 2020).

Global tomato production areas: Fusarium wilt can be found in major tomato-producing regions around the world, including countries in North America, Europe, Asia, Africa, and Oceania (Alkhalifah et al. 2023).

Intensive agriculture regions: In regions with intensive tomato cultivation, where susceptible tomato varieties are grown frequently, the pathogen can build up in the soil and become a significant concern (Chitwood-Brown et al. 2021, Ribeiro et al. 2022).

Greenhouses and protected cultivation: The disease is a major threat in greenhouse and protected cultivation systems, where the controlled environment can facilitate disease development (Song et al. 2004, Adhikari et al. 2020).

The distribution of the disease can change over time due to factors like trade, changing agricultural practices, and global movement of plant material. In regions where the disease is prevalent, growers often implement management strategies such as using resistant tomato varieties, practicing crop rotation, and employing soil sanitation measures to mitigate its impact (Dholu et al.

2021, McGovern 2015).

Host range

The host range of the vascular wilt disease caused by *F. oxysporum* f. sp. *lycopersici*, which infects *S. lycopersicum* (tomato plants), is typically limited to tomatoes and closely related plant species within the *Solanaceae* family (González-García et al. 2023). This form of *F. oxysporum* specifically targets tomato plants and can cause the disease commonly known as "Fusarium wilt of tomato" or "tomato wilt" (Mousa et al. 2021). The specificity of this *forma specialis* is a result of the co-evolution between the pathogen and its host plant, which has led to the development of a unique set of interactions between them (Yan et al. 2023).

It is worth noting that different *formae speciales* of *F. oxysporum* exist, each adapted to infect different host plants. These specialized *formae speciales* have evolved to exploit specific host plants' vulnerabilities and interact with their unique physiological and biochemical characteristics. As a result, the host range of each *forma specialis* is relatively narrow (Attia et al. 2022).

Understanding the host range of a pathogen is crucial for effective disease management. In the case of Fusarium wilt in tomatoes, this understanding allows farmers and researchers to implement strategies such as crop rotation, the use of resistant tomato varieties (Big Beef x Supernatural, Green Zebra x Supernatural, Big Beef x Arnold), soil sanitation (soil solarization, soil fumigation, etc.), and other practices (chemical and biological controls) that help prevent the disease and its spread (Mostafa et al. 2022).

Disease symptoms

Fusarium wilt can lead to significant yield losses and tomato plant mortality (Mousa et al. 2021, Attia et al. 2022, Aydi-Ben-Abdallah et al. 2020, Dong et al. 2023, Latifah et al. 2023). The symptoms of Fusarium wilt in tomato plants typically include wilting and yellowing leaves, which is one of the most noticeable symptoms, especially in hot weather. The wilting usually starts with the lower leaves and progresses upward. The leaves may turn pale green or yellow before wilting completely (Aydi-Ben-Abdallah et al. 2020, Attia et al. 2022, Dong et al. 2023, Latifah et al. 2023). As the disease progresses, the affected leaves may show symptoms of necrosis (tissue death) along the edges and between veins. This necrosis can spread and cause the entire leaf to dry up (Mousa et al. 2021, Dong et al. 2023, Latifah et al. 2023). Furthermore, the vascular tissues (xylem) of the plant, responsible for water and nutrient transport, often show characteristic discoloration. The xylem vessels can turn brown or black due to the blockage of water flow caused by the pathogen's colonization. As the disease progresses, the vascular tissues within the stem can turn yellow and eventually brown or black. This is a clear indication of the pathogen's presence and activity in the plant's vascular system (Aydi-Ben-Abdallah et al. 2020, Mousa et al. 2021, Attia et al. 2022, Dong et al. 2023, Latifah et al. 2023).

Infected plants often exhibit stunted growth due to the disruption of water and nutrient transport within the plant. This can result in reduced plant height and overall size (Mousa et al. 2021, Latifah et al. 2023). Infected plants might drop their flowers or develop fruits prematurely due to the decreased water uptake and nutrient supply (Aydi-Ben-Abdallah et al. 2020, Attia et al. 2022, Dong et al. 2023). In some cases, Fusarium wilt can lead to root rot, causing decay of the root system. This further impairs the plant's ability to take up water and nutrients (Aydi-Ben-Abdallah et al. 2020, Attia et al. 2022, Latifah et al. 2023).

It's important to note that the symptoms of Fusarium wilt can be similar to those of other wilt-causing pathogens or environmental stress factors. Proper diagnosis is essential to accurately identify the cause of the symptoms. Diagnostic tools include visual assessment, laboratory tests, and molecular techniques (Panno et al. 2021, Latifah et al. 2023).

Preventive measures, such as using disease-resistant tomato varieties (Chitwood-Brown et al. 2021, Hernández-Aparicio et al. 2021, Ribeiro et al. 2022), practicing proper crop rotation (Ajilogba & Babalola 2013, Bawa 2016), using antagonistic micro-organisms (Weng et al. 2022, Yan et al. 2023, Ma et al. 2023, Sachdev et al. 2023), and maintaining good soil health (Mawar et al. 2022, Ma et al. 2023), can help manage Fusarium wilt and reduce its impact on tomato plants (Mauro et al. 2020, Latifah et al. 2023).

Disease cycle

The disease cycle of Fusarium wilt in tomatoes involves a complex interplay between the pathogen, the host plant, and environmental factors. Here's an overview of the disease cycle and host-pathogen interactions (Bawa 2016, Chitwood-Brown et al. 2021, Dholu et al. 2021, Hernández-Aparicio et al. 2021) (Fig. 1).

Initial infection: The pathogen *F. oxysporum* f. sp. *lycopersici* resides in the soil as survival structures (chlamydospores). When conditions are favorable, the pathogen germinates and produces infective hyphae (Bawa 2016, Chitwood-Brown et al. 2021, Dholu et al. 2021, Hernández-Aparicio et al. 2021) (Fig. 1).

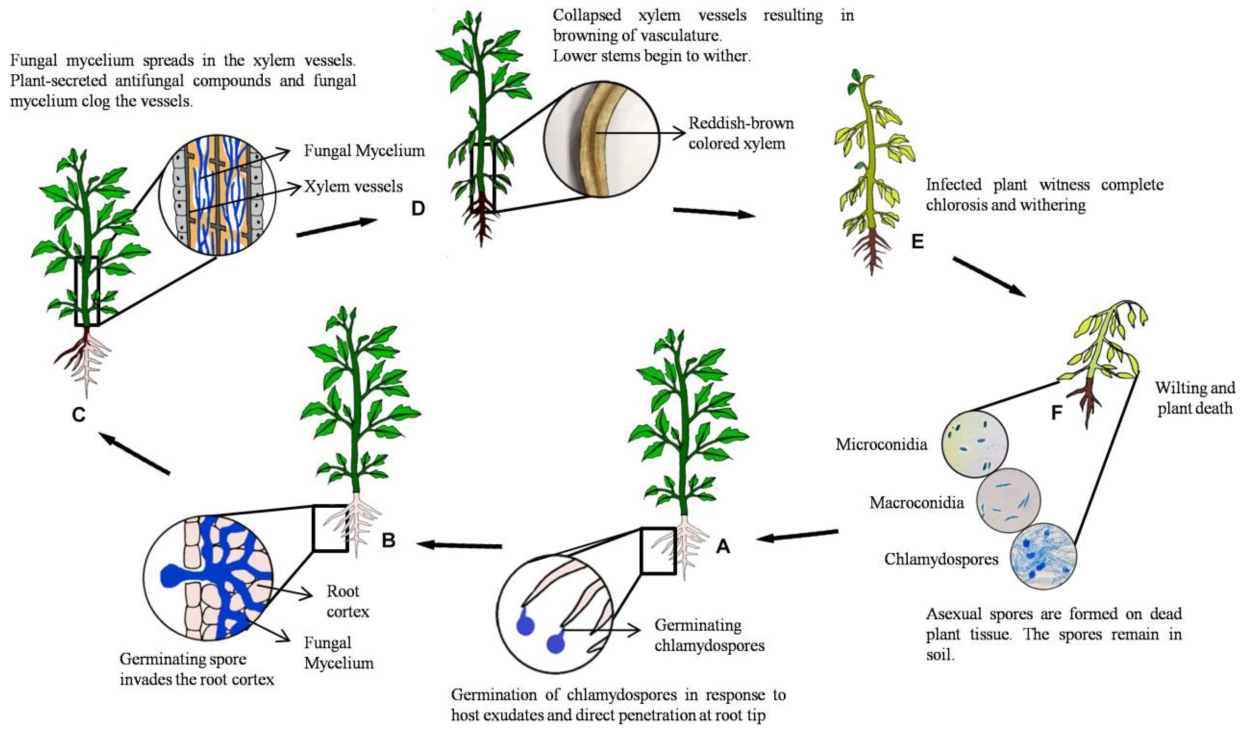

Fig. 1 – Disease cycle of tomato vascular wilt disease caused by *Fusarium oxysporum* f. sp. *lycopersici* (Jangir et al. 2021)

Root invasion: The infective hyphae of the pathogen penetrate the root tissues of susceptible tomato plants. The pathogen uses enzymes to break down the plant cell walls, allowing it to enter the vascular system through the root cortex (Bawa 2016, Chitwood-Brown et al. 2021, Dholu et al. 2021, Hernández-Aparicio et al. 2021) (Fig. 1).

Vascular system colonization: Once inside the plant, the pathogen spreads within the vascular system (xylem vessels), blocking water and nutrient transport. This leads to wilting, stunting, and other disease symptoms (Bawa 2016, Chitwood-Brown et al. 2021, Dholu et al. 2021, Hernández-Aparicio et al. 2021) (Fig. 1).

Pathogen multiplication: The pathogen reproduces and forms spores (conidia) within the vascular system. These spores can further colonize the plant and contribute to the spread of the disease (Bawa 2016, Chitwood-Brown et al. 2021, Dholu et al. 2021, Hernández-Aparicio et al. 2021) (Fig. 1).

Symptom development: As the vascular system becomes blocked and water uptake is impaired, wilting of leaves occurs. The leaves may be yellow and show signs of necrosis along the margins (Bawa 2016, Chitwood-Brown et al. 2021, Dholu et al. 2021, Hernández-Aparicio et al. 2021) (Fig. 1).

Plant death and spore dispersal: In severe cases, the plant succumbs to the infection, and the pathogen produces more spores. These spores are released into the soil, completing the disease cycle (Bawa 2016, Chitwood-Brown et al. 2021, Dholu et al. 2021, Hernández-Aparicio et al. 2021) (Fig. 1).

Understanding the disease cycle and host-pathogen interactions is essential for developing strategies to manage Fusarium wilt. By targeting various stages of the disease cycle and considering the interactions between the pathogen, host, and environment, growers can minimize the impact of the disease and maintain healthy tomato crops (Adhikari et al. 2020, Aydi-Ben-Abdallah et al. 2020, Alkhalifah et al. 2023).

Factors affecting the epidemiology

The epidemiology of tomato vascular wilt is influenced by various factors that contribute to the disease's spread, development, and impact. These factors can interact and vary based on environmental conditions, pathogen characteristics, and host-plant interactions. Here are some key factors affecting the epidemiology of Fusarium wilt in tomatoes (Aydi-Ben-Abdallah et al. 2020, Campos et al. 2023, Dong et al. 2023, González-García et al. 2023, Yan et al. 2023).

Pathogen survival and persistence: Fusarium oxysporum f. sp. *lycopersici* can survive in the soil for several years, even in the absence of its host, due to its ability to form resting structures like chlamydospores (Panno et al. 2021, González-García et al. 2023).

Host susceptibility and resistance: The susceptibility or resistance of tomato varieties to Fusarium wilt affects disease severity and spread. The use of resistant tomato cultivars can greatly reduce disease incidence and limit pathogen propagation (Chitwood-Brown et al. 2021, Ribeiro et al. 2022).

Pathogen dispersal and transmission: Fusarium oxysporum f. sp. *lycopersici* primarily spreads through contaminated soil, water, and plant debris. Movement of infected soil, tools, and equipment can introduce the pathogen to new areas (Ekwomadu & Mwanza 2023, Karačić et al. 2024).

Environmental conditions: Higher temperatures and high soil moisture can facilitate pathogen growth, infection, and disease development. The disease is more severe in soils with high organic matter content (Hibar et al. 2006, Dholu et al. 2021).

Crop management practices: Continuous planting of susceptible crops can lead to pathogen build-up. Nonetheless, proper crop rotation can help reduce disease incidence. Removing and destroying infected plant debris can limit the pathogen's survival and spread (Aydi-Ben-Abdallah et al. 2020).

Introduction of infected plant material: Infected seeds, transplants, or seedlings can introduce the pathogen to new fields. Plants may carry the pathogen without showing symptoms, making it challenging to identify and prevent its spread (Dholu et al. 2021, Ekwomadu & Mwanza 2023, Karačić et al. 2024).

Weed hosts: Some weeds can harbor and spread the pathogen, contributing to its persistence (Dholu et al. 2021). These weed species include *Agropyron repens*, *A. trachycaulum*, *Agrostis stolonifera*, *Bromus inermis*, *Calamagrostis canadensis*, *Capsella bursa-pastoris*, *Echinocloa crusgalli*, *Fallopia convolvulus*, *Poa annua*, *Tripleurospermum inodorum*, and *Viola arvensis* (Inch & Gilbert 2003, Matelionienė et al. 2022, Zavtrikovienė et al. 2022).

Disease-inducing practices: Conditions that stress the plant, such as waterlogging or nutrient imbalances, can make it more susceptible to infection. Overhead irrigation or using contaminated water sources can facilitate pathogen dispersal (Dholu et al. 2021, Ekwomadu & Mwanza 2023, Karačić et al. 2024).

Pathogen variation: Variability in the pathogen population can affect disease severity and the effectiveness of resistant varieties (Chitwood-Brown et al. 2021, Ribeiro et al. 2022). Rust fungi, like wheat stem rust, are highly adaptable due to their extensive genetic diversity. This adaptability has enabled them to repeatedly outmaneuver disease-resistant wheat varieties. A prime example is the Ug99 race group of wheat stem rust, which is highly virulent and capable of causing substantial crop losses. The global wheat industry faces a significant threat from this pathogen (Karelov et al. 2022, Patpour et al. 2022, Shahin et al. 2022). Powdery mildew fungi, notorious for their high genetic diversity, have evolved new strains that can circumvent even resistant crop varieties like strawberries (Lynn et al. 2024), barley (Dreiseitl 2020), wheat (Gruner et al. 2020), cucurbits (Liu et al. 2021, Yadav et al. 2021), tomato (Yan et al. 2021) and grapevine (LaPlante et al. 2021).

Understanding these factors and their interactions is crucial for developing effective disease management strategies. Integrated approaches, including the use of resistant varieties, proper crop rotation, soil management, and sanitary practices, can help mitigate the impact of Fusarium wilt in tomato crops (Nedelcu & Alexandri 1995, Jahanshir & Dzhalilov 2010, Ajilogba & Babalola 2013, Mauro et al. 2020, Latifah et al. 2023).

Management of tomato vascular wilt disease

Chemical control of tomato vascular wilt disease was evaluated repeatedly under laboratory, greenhouse, and field conditions. Several fungicides (prochloraz-Mn, thiram, imazalil, captafol, and benomyl) have been used to manage numerous plant pathogens, such as tomato vascular wilt, and powerful fungicides with minimal environmental impact are rare (Nusret & Steven 2004, Jahanshir & Dzhalilov 2010).

Inducing resistance in susceptible tomato plants is how compounds like copper chloride, ferric chloride, and manganese sulfate control *F. oxysporum* f. sp. *lycopersici*. Moreover, Jahanshir & Dzhalilov (2010) revealed that prochloraz and bromuconazole were the most effective fungicides against *F. oxysporum* f. sp. *lycopersici* under laboratory and greenhouse conditions, followed by benomyl and carbendazim. Benomyl has been suggested to control *F. oxysporum* through the dip remedy method (Jahanshir & Dzhalilov 2010). This technique is prolonged to use carbendazium in tomato seedlings infected with Fusarium wilt and might increase yield by as much as 24% (Weitang et al. 2004). The effect of a mixture of metamidoxime and copper oxychloride on *F. oxysporum* was tested *in vitro*, and the results showed that these fungicides had a strong synergistic effect. A new product aimed at controlling tomato diseases could be developed based on these fungicides (Nedelcu & Alexandri 1995).

The treatment of tomato seeds with fungicides notably decreases the severity of vascular wilt disease. El-Shami et al. (1993) found the application of Vitavax-thiuram and Vitavax-captan as fungicidal seed treatments were successful in controlling Fusarium wilt disease. Therefore, Vitavax-captan provided superior disease control than Vitavax-thiuram. Thiram and Topsin-M were found to be the most effective at 800 mg/g soil, resulting in a reduction in *F. oxysporum* f. sp. *lycopersici* populations by 83.4% (Dwivedai et al. 1995).

Fungicides have a greater carcinogenic risk than insecticides and herbicides combined, according to a National Academy of Sciences report in 1986 on pesticide residues in food. Safer alternatives should be found immediately due to the suspicion of synthetic fungicides in our food chain (Hajji-Hedfi et al. 2022). The ineffectiveness of fungicides due to pathogen resistance has rendered alternative modes of action. Moreover, fungicides are expensive and can cause environmental and human dangers (Hajji-Hedfi et al. 2023). Therefore, alternative, green technique remedies for the management of tomato vascular wilt disease are needed (Rhouma et al. 2023a, b).

Crop rotation can be used to control Fusarium wilt, and it is recommended not to plant the tomato crop for at least four years if the disease attack is severe. Thus, the vegetation recommended for rotation is made up of grasses and cereals (Ajilogba & Babalola 2013). Tomatoes affected by Fusarium wilt should be removed immediately (Rhouma et al. 2024). Used farm equipment must be disinfected, and wiped clean earlier than reuse (Rhouma et al. 2023c). The use of sterile shoes and clothing on the farm can also help reduce the transfer of infested soil between pastures (Rhouma et al. 2021). Following is another approach to handle *F. oxysporum* f. sp. *lycopersici*. It is advisable to exercise during the summer months to allow high temperatures and excessive drying to reduce the population of *F. oxysporum* f. sp. *lycopersici* in soil (Rhouma et al. 2023b). Plants that are healthy and vigorous and are grown under a good nutritional program and suitable sanitary conditions are less prone to Fusarium wilt infection than those grown under nutritional stress (Bawa 2016). The protection of tomatoes against Fusarium wilt disease and other pests is achieved through good weed control during planting and throughout the growing season (Ma et al. 2023). Disease pathogens can be destroyed, and crop residue can be broken down by tillage after harvest and before planting (Ajilogba & Babalola 2013).

Tomato vascular wilt can be mitigated by using grafting technology as one of the best alternatives. Tomato grafting has been intended to provide resistance to soil-borne diseases. Fusarium wilt, bacterial wilt, Verticillium wilt, Monosporascus root rot, and nematodes are among the tomato diseases treated by grafting (Mauro et al. 2020). The use of grafting in tomatoes against soil-borne phytopathogens has the potential to decrease disease severity and enhance agronomic aspects, product quality, and nutrient contents (Mauro et al. 2020, Latifah et al. 2023). It's interesting to note that grafting Big Beef and Green Zebra (tomato varieties) onto Supernatural rootstock led to an increase in antioxidant capacity. Additionally, the phenolic content of Big Beef grafted onto Arnold and Big Beef and Green Zebra grafted onto Supernatural was modified (Greathouse et al. 2021).

Soil solarization is considered a physical method for disinfecting soils in which the population of soil pathogens, including *F. oxysporum* f. sp. *lycopersici* is decreased (Ma et al. 2023). This is done by spreading plastic film over the soil for several weeks. This facilitates increased temperature and humidity in the soil, which inhibits soil-borne diseases, nematodes, insects and many weed seeds. This is generally done during the summer season when the air temperature is high, and there is significant radiation (Mawar et al. 2022). A satisfying soil treatment can be achieved through a natural and sustainable solar energy practice, which overcomes the major limitation of traditional solarization: application time (Rippa et al. 2023).

The efforts to develop tomato cultivars resistant to *F. oxysporum* f. sp. *lycopersici* first appeared in the 1900s at research stations in the United States, and some of the first tests were conducted in Florida in 1905 (Ribeiro et al. 2022). Wild tomato accessions showed resistance to the three races of *F. oxysporum* f. sp. *lycopersici*. Several of these have been utilized to study resistance, and some have been introduced into tomato cultivars for tomato production regions worldwide (Ribeiro et al. 2022). Cultivars resistant to or tolerant to Fusarium wilt are available for tomato crops (Hernández-Aparicio et al. 2021). Nonetheless, a cultivar that is resistant to a particular form expert might not be resistant to the opportunity races of the same forma specialis (Chitwood-Brown et al. 2021).

Biological control provides a greater opportunity to reduce the use of chemicals. It uses antagonistic micro-organisms to fight against diseases (Yan et al. 2023, Ma et al. 2023). *Trichoderma asperellum*, *T. harzianum*, *T. virens*, *T. viride*, *T. hamatum*, *Aspergillus flavus*, *A. niger*, *Mucor circinelloides*, and *Pencillium oxalicum* are used in competition to manipulate various soil-borne pathogens. These filamentous fungi are widespread in nature, with immoderate population densities in soil (Attia et al. 2022, Sachdev et al. 2023). *Bacillus amyloliquefaciens*, *B. subtilis*, *B. pasteurii*, *B. cereus*, *B. pumilus*, *B. mycoides*, and *B. sphaericus* elicit reductions in the disease severity (Yang et al. 2023). Mousa et al. (2021) found that tomato seedlings treated separately with peppermint oil and *B. amyloliquefaciens* decreased tomato Fusarium wilt severity greater than peppermint oil + *B. amyloliquefaciens* in combination. Ma et al. (2023) stated that *Peudomonas flourescens*, *P. putida*, *P. chlororaphis*, *Bacillus subtilis*, *Streptomyces pulcher*, *S. corchorusii*, and *S. mutabilis* have promising biocontrol activities against Fusarium wilt. These may also act without delay as biofertilizers and biostimulants through the manufacturing of plant boom hormones together with indole acetic acid, gibberellin, cytokinin, and ethylene (Asif et al. 2023). Du et al. (2022) documented that *P. polymyxa*, *B. amyloliquefaciens*, *B. Olei*, *B. aryabhattai*, *Pseudomonas putida*, and *B. subtilis* are effective plant-growth-promoting rhizosphere bacteria and also biocontrol agents of *F. oxysporum* f. sp. *lycopersici*, which can significantly enhance the resistance of tomato to Fusarium wilt.

Some microorganisms suppress pathogens by producing antibiotic metabolites, while others can immediately stimulate nutrient uptake, promoting rhizobial and mycorrhizal symbiosis or by immediately fixing atmospheric nitrogen (Dong et al. 2023). Cota-Ungson et al. (2023) revealed that the antioxidant system of tomatoes was enhanced by increasing the content of anthocyanins, flavonoids, and glutathione, and the activity of phenylalanine ammonium lyase, catalase, glutathione peroxidase. The elicitation of induced systemic resistance in tomato plants using microorganisms was approved under greenhouses or field conditions (Campos et al. 2023). *Stenotrophomonas maltophilia*, *Serratia marcescens*, and *Bacillus* sp. exhibited a positive phosphate solubilization activity and capacities for hydrogen cyanide, pectinase, protease, and chitinase production (Aydi-Ben-Abdallah et al. 2020).

To provide an effective tomato Fusarium wilt management system, the use of beneficial microorganisms represents an ecological disease management strategy. As stated by Ma et al. (2023), several isolates of non-pathogenic *Fusarium* spp. (*F. oxysporum* and *Neocosmospora solani*) are able to effectively manage Fusarium wilt under greenhouse trials.

Arbuscular mycorrhizal fungi were potent against *F. oxysporum* f. sp. *lycopersici*. Wang et al. (2022) found that *Rhizophagus irregularis* colonization significantly lowered the severity of tomato Fusarium wilt and increased the shoot dry weight, Phosphorus content, net photosynthetic rate, polyphenol oxidase, and phenylalanine ammonia lyase activities, and induced expression of lipoxygenase D gene and allene oxide cyclase gene. Weng et al. (2022) showed that arbuscular mycorrhizal fungi decreased disease incidence of tomato Fusarium wilt, enhanced phytohormone concentrations, induced signal substrate production and gene expression regulation, and improved protein production under greenhouse and field conditions.

The treatment of tomato plants with essential oils and plant extracts generated the highest disease damage reduction and the production of catalase and peroxidase activities, superoxide dismutase, polyphenol-oxidase, total phenolic content, and total sugars (Abo-Elyousr et al. 2020, Matrood & Rhouma 2021, Mostafa et al. 2022, Ahmed et al. 2023, Okon et al. 2023, Hajji-Hedfi et al. 2024). Mostafa et al. (2022) evaluated the efficacy of macroalgae extracts against tomato Fusarium wilt. These authors revealed that macroalgae extracts significantly decreased the disease incidence. Jin et al. (2023) found that biochar (at concentrations of 1 and 2%) suppressed the Fusarium wilt of tomato, which could be related to the change in the rhizosphere microbial community structure, and increased the abundance of potential beneficial microorganisms. González-García et al. (2023) reported the ability of UV-A Radiation to reduce the severity of tomato Fusarium wilt and increase the contents of secondary metabolites and photosynthetic pigments.

Conclusions

Fusarium wilt, caused by *F. oxysporum* f. sp. *lycopersici*, remains a significant challenge in tomato cultivation worldwide. This review underscores the importance of the different approaches to disease management. Effective management strategies include chemical control using fungicides, biological control employing antagonistic microorganisms, cultural practices such as crop rotation and soil hygiene, resistance breeding to develop resistant tomato cultivars, soil solarization, and grafting onto resistant rootstocks. Each method contributes to reducing disease incidence and minimizing economic losses. As global food security and sustainable tomato production are paramount, ongoing research and implementation of integrated disease management practices are essential. Combining these strategies and adapting them to specific regions and conditions will help ensure the continued success of tomato cultivation while mitigating the impact of Fusarium wilt.

Conflicts of interest

The authors declare that they have no conflict of interest. All authors have approved the manuscript for submission.

Funding statement

This research was funded by the SIRAM (Sustainable Innovations for Regenerative Agriculture in the Mediterranean Area) project, affiliated with the PRIMA program.

References

Abo-Elyousr KAM, Almasoudi NM, Abdelmagid AWM, Roberto SR et al. 2020 – Plant extract treatments induce resistance to bacterial spot by tomato plants for a sustainable system. Horticulturae 6(2), 36. Doi 10.3390/horticulturae6020036

Adhikari TB, Gao A, Ingram T, Louws FJ. 2020 – Pathogenomics characterization of an emerging fungal pathogen, *Fusarium oxysporum* f. sp. *lycopersici,* in greenhouse tomato production systems. Frontiers in Microbiology 11, 1995. Doi 10.3389/fmicb.2020.01995

Ahmed HFA, Seleiman MF, Mohamed IAA, Taha RS et al. 2023 – Activity of essential oils and plant extracts as biofungicides for suppression of soil-borne fungi associated with root rot and wilt of marigold (*Calendula officinalis* L.). Horticulturae 9(2), 222. Doi 10.3390/horticulturae9020222

Ajilogba CF, Babalola OO. 2013 – Integrated management strategies for tomato Fusarium wilt. Biocontrol Science 18, 117-127. Doi 10.4265/bio.18.117

Alkhalifah DHM, Damra E, Melhem MB, Hozzein WN. 2023 – Fungus under a changing climate: Modelling the current and future global distribution of *Fusarium oxysporum* using geographical information system data. Microorganisms 11(2), 468. Doi 10.3390/microorganisms11020468

Arie T. 2019 – *Fusarium* diseases of cultivated plants, control, diagnosis, and molecular and genetic studies. Journal of Pesticide Science 44(4), 275–281. Doi 10.1584/jpestics.J19-03

Asif R, Siddique MH, Hayat S, Rasul I, Nadeem H, Faisal M, Waseem M, Zakki SA, Zitouni A, Muzammil S. 2023 – Efficacy of *Saccharothrix algeriensis* NRRL B-24137 to suppress *Fusarium oxysporum f.sp. vasinfectum* induced wilt disease in cotton. Peer Journal 11, e14754. https://doi.org/10.7717/peerj.14754

Attia MS, Abdelaziz AM, Al-Askar AA, Arishi AA et al. 2022 – Plant growth-promoting fungi as biocontrol tool against Fusarium wilt disease of tomato plant. Journal Fungi 8, 775. Doi 10.3390/jof8080775

Aydi-Ben-Abdallah R, Jabnoun-Khiareddine H, Daami-Remadi M. 2020 – Fusarium wilt biocontrol and tomato growth stimulation, using endophytic bacteria naturally associated with *Solanum sodomaeum* and *S. bonariense* plants. Egyptian Journal of Biological Pest Control 30, 113. Doi 10.1186/s41938-020-00313-1

Bawa I. 2016 – Management strategies of Fusarium wilt disease of tomato incited by *Fusarium oxysporum* f. sp. *lycopersici* (Sacc.): A review. International Journal of Advanced Academic Research 2, 32–42.

Campos MD, Varanda C, Patanita M, Amaro Ribeiro J et al. 2023 – A TaqMan® assay allows an accurate detection and quantification of *Fusarium* spp., the causal agents of tomato wilt and rot diseases. Biology 12, 268. Doi 10.3390/biology12020268

Chitwood-Brown J, Vallad GE, Lee TG, Hutton SF. 2021 – Breeding for resistance to Fusarium wilt of tomato: A review. Genes 12(11), 1673. Doi 10.3390/genes12111673

Cota-Ungson D, González-García Y, Cadenas-Pliego G, Alpuche-Solís ÁG et al. 2023 – Graphene–Cu nanocomposites induce tolerance against *Fusarium oxysporum*, increase antioxidant activity, and decrease stress in tomato plants. Plants 12(12), 2270. Doi 10.3390/plants12122270

Crous PW, Lombard L, Sandoval-Denis M, Seifert KA et al. 2021 – *Fusarium*: more than a node or a foot-shaped basal cell. Studies in Mycology 98, 100116. Doi 10.1016/j.simyco.2021.100116

Darvishnia M, Hasanvand E, Pakbaz S. 2023 – Morphological and molecular identification of Fusarium associated with beans in Selseleh county. Journal of Genetic Resources 9(2), 222–231. Doi 10.22080/jgr.2023.26023.1372

Dholu D, Shete PP, Faraaz Ahmed M, Dhaval P. 2021 – Wilt (*Fusarium oxysporum f. sp. lycopersici*) etiology, morphology, epidemiology and management of tomato: Review article. The Pharma Innovation Journal 10(5), 174–178.

Dong H, Gao R, Dong Y, Yao Q, Zhu H. 2023 – *Bacillus velezensis* RC116 inhibits the pathogens of bacterial wilt and Fusarium wilt in tomato with multiple biocontrol traits. International Journal of Molecular Sciences 24, 8527. Doi 10.3390/ijms24108527

Dreiseitl A. 2020 – Specific resistance of barley to powdery mildew, its use and beyond: A concise critical review. Genes 11(9), 971. https://doi.org/10.3390/genes11090971

Du N, Guo H, Fu R, Dong X et al. 2022 – Comparative transcriptome analysis and genetic methods revealed the biocontrol mechanism of *Paenibacillus polymyxa* NSY50 against tomato Fusarium wilt. International Journal of Molecular Sciences 23(18), 10907. Doi 10.3390/ijms231810907

Dwivedai SK, Dwivedi RS, Ambasht RS. 1995 – Effect of fungicides on population dynamics of Fusarium wilt pathogens of two economic. Journal of Mycopathological Research 33, 49–52.

Ekwomadu TI, Mwanza M. 2023 – *Fusarium* fungi pathogens, identification, adverse effects, disease management, and global food security: A review of the latest research. Agriculture 13(9), 1810. Doi 10.3390/agriculture13091810

El-Shami MA, Awad NGH, Abdel-Nour NAR. 1993 – Effect of fungicides and herbicides interactions on tomato damping-off and plant growth. Egyptian Journal of Agricultural Research 71, 641–658.

Gao H, Beckman CH, Mueller WC. 1995 – The nature of tolerance to *Fusarium oxysporum f. sp. lycopersici* in polygenically field-resistant marglobe tomato plants. Physiological and Molecular Plant Pathology 46, 401–412. Doi 10.1006/pmpp.1995.1031

González-García Y, Escobar-Hernández DI, Benavides-Mendoza A, Morales-Díaz AB et al. 2023 – UV-A Radiation stimulates tolerance against *Fusarium oxysporum* f. sp. *lycopersici* in tomato plants. Horticulturae 9(4), 499. Doi 10.3390/horticulturae9040499

Greathouse J, Henning S, Soendergaard M. 2021 – Effect of grafting rootstock on the antioxidant capacity and content of heirloom tomatoes (*Solanum lycopersicum* L.) in hydroponic culture. Plants 10(5), 965. Doi 10.3390/plants10050965

Gruner K, Esser T, Acevedo-Garcia J, Freh M et al. 2020 – Evidence for allele-specific levels of enhanced susceptibility of wheat mlo mutants to the hemibiotrophic fungal pathogen *Magnaporthe oryzae* pv. *Triticum*. Genes 11(5), 517. https://doi.org/10.3390/genes11050517

Haegi A, Catalano V, Luongo L, Vitale S et al. 2013 – A newly developed Real-Time PCR assay for detection and quantification of *Fusarium oxysporum* and its use in compatible and incompatible interactions with grafted melon genotypes. Phytopathology 103, 802–810. Doi 10.1094/PHYTO-11-12-0293-R

Hafizi R, Salleh B, Latiffah Z. 2013 – Morphological and molecular characterization of *Fusarium solani* and *F. oxysporum* associated with crown disease of oil palm. Brazilian Journal of Microbiology 44(3), 959–968. Doi 10.1590/S1517-83822013000300047

Hajji-Hedfi L, Hlaoua W, Al-Judaibi AA, Rhouma A et al. 2022 – Comparative effectiveness of filamentous fungi in biocontrol of *Meloidogyne javanica* and activated defense mechanisms on tomato. Journal of Fungi 9(1), 37. Doi 10.3390/jof9010037

Hajji-Hedfi L, Rhouma A, Hajlaoui H, Hajlaoui F et al. 2023 – Understanding the influence of applying two culture filtrates to control gray mold disease (*Botrytis cinerea*) in tomato. Agronomy 13(7), 1774. Doi 10.3390/agronomy13071774

Hajji-Hedfi L, Rhouma A, Hlaoua W, Dmitry KE et al. 2024 – Phytochemical characterization of forest leaves extracts and application to control apple postharvest diseases. Scientific Reports 14, 2014. Doi 10.1038/s41598-024-52474-w

Haruna SG, Yahuza L, Tijjani I. 2024 – Management of Fusarium wilt of tomato (*Fusarium oxysporum* f. sp. *lycopersici*) and related soil-borne diseases using eco-friendly methods: A review. Asian Journal of Research in Crop Science 9(1), 154–168. Doi 10.9734/ajrcs/2024/v9i1257

Hassan HA. 2020 – Biology and integrated control of tomato wilt caused by *Fusarium oxysporum lycopersici*: A comprehensive review under the light of recent advancements. Journal of the Botanical Research 3, 84–99. Doi 10.36959/771/565

Hernández-Aparicio F, Lisón P, Rodrigo I, Bellés JM et al. 2021 – Signaling in the tomato immunity against *Fusarium oxysporum*. Molecules 26(7), 1818. Doi 10.3390/molecules26071818

Hibar K, Daami-Remadi M, Jabnoun-Khiareddine H, El Mahjoub M. 2006 – Temperature effect on mycelial growth and on disease incidence of *Fusarium oxysporum* f. sp. *radicis-lycopersici*. Plant Pathology Journal 5, 233–238. Doi 10.3923/ppj.2006.233.238

Inami K, Kashiwa T, Kawabe M, Onokubo-Okabe A et al. 2014 – The tomato wilt fungus *Fusarium oxysporum* f. sp. *lycopersici* shares common ancestors with non-pathogenic *F. oxysporum* isolated from wild tomatoes in the Peruvian Andes. Microbes and Environments 29, 200–210. Doi 10.1264/jsme2.me13184

Inch S, Gilbert J. 2003 – The incidence of *Fusarium* species recovered from inflorescences of wild grasses in southern Manitoba. Plant Pathology 25, 379–383. https://doi.org/10.1080/07060660309507093

Jahanshir A, Dzhalilov FS. 2010 – The effects of fungicides on *Fusarium oxysporum* f. sp. *lycopersici* associated with Fusarium wilt of tomato. Journal of Plant Protection Research 50(2), 172–178. Doi 10.2478/v10045-010-0029-x

Jangir P, Mehra N, Sharma K, Singh N et al. 2021 – Secreted in xylem genes: Drivers of host adaptation in *Fusarium oxysporum*. Frontiers in Plant Science 12, 628611. Doi 10.3389/fpls.2021.628611

Jin X, Zhou X, Wu F, Xiang W et al. 2023 – Biochar amendment suppressed Fusarium Wilt and altered the rhizosphere microbial composition of tomatoes. Agronomy 13(7), 1811. Doi 10.3390/agronomy13071811

Karačić V, Miljaković D, Marinković J, Ignjatov M et al. 2024 – *Bacillus* species: Excellent biocontrol agents against tomato diseases. Microorganisms 12(3), 457. Doi 10.3390/microorganisms12030457

Karelov A, Kozub N, Sozinova O, Pirko Y et al. 2022 – Wheat genes associated with different types of resistance against stem rust (*Puccinia graminis* Pers.). Pathogens 11(10), 1157. Doi 10.3390/pathogens11101157

Kumar M, Chandran D, Tomar M, Bhuyan DJ et al. 2022 – Valorization potential of tomato (*Solanum lycopersicum* L.) seed: Nutraceutical quality, food properties, safety aspects, and application as a health-promoting ingredient in foods. Horticulturae 8(3), 265. Doi 10.3390/horticulturae8030265

LaPlante ER, Fleming MB, Migicovsky Z, Weber MG. 2021 – Genome-wide association study reveals a genomic region associated with mite-recruitment phenotypes in the domesticated grapevine (*Vitis vinifera*). Genes 12(7), 1013. Doi 10.3390/genes12071013

Latifah E, Antarlina SS, Sugiono S, Handayati W et al. 2023 – Grafting technology with locally selected eggplant rootstocks for improvement in tomato performance. Sustainability 15(1), 855. Doi 10.3390/su15010855

Lievens B, Houterman PM, Rep M. 2009 – Effector gene screening allows unambiguous identification of *Fusarium oxysporum* f. sp. *lycopersici* races and discrimination from other formae speciales. FEMS Microbiology Letters 300, 201–215. Doi 10.1111/j.1574-6968.2009.01783.x

Liu X, Gu X, Lu H, Liu P et al. 2021 – Identification of novel loci and candidate genes for resistance to powdery mildew in a resequenced cucumber germplasm. Genes 12(4), 584. https://doi.org/10.3390/genes12040584

López WR, Garcia-Jaramillo DJ, Ceballos-Aguirre N, Castaño-Zapata J et al. 2021 – Transcriptional responses to *Fusarium oxysporum* f. sp. *lycopersici* (Sacc.) Snyder & Hansen infection in three Colombian tomato cultivars. BMC Plant Biology 21, 412. Doi 10.1186/s12870-021-03187-z

Lynn SC, Dunwell JM, Whitehouse AB, Cockerton HM. 2024 – Genetic loci associated with tissue-specific resistance to powdery mildew in octoploid strawberry (*Fragaria* × *Ananassa*). Frontiers in Plant Science 15, 1376061. https://doi.org/10.3389/fpls.2024.1376061

Ma M, Taylor PWJ, Chen D, Vaghefi N et al. 2023 – Major soilborne pathogens of field processing tomatoes and management strategies. Microorganisms 11(2), 263. Doi 10.3390/microorganisms11020263

Makhadmeh I, Albalasmeh AA, Ali M, Thabet SG et al. 2022 – Molecular characterization of tomato (*Solanum lycopersicum* L.) accessions under drought stress. Horticulturae 8(7), 600. Doi 10.3390/horticulturae8070600

Manawasinghe IS, Phillips AJL, Xu J, Balasuriya A et al. 2021 – Defining a species in fungal plant pathology: Beyond the species level. Fungal Diversity 109, 267–282. Doi 10.1007/s13225-021-00481-x

Matelionienė N, Supronienė S, Shamshitov A, Zavtrikovienė E et al. 2022 – Weeds in cereal crop rotations may host *Fusarium* species that cause Fusarium head blight and grain weight losses in wheat. Agronomy 12(11), 2741. https://doi.org/10.3390/agronomy12112741

Matrood AAA, Rhouma A. 2021 – Evaluating eco-friendly botanicals as alternatives to synthetic fungicides against the causal agent of early blight of *Solanum melongena*. Journal of Plant Diseases and Protection 128, 1517–1530. Doi 10.1007/s41348-021-00530-2

Mauro RP, Agnello M, Distefano M, Sabatino L et al. 2020 – Chlorophyll fluorescence, photosynthesis and growth of tomato plants as affected by long-term oxygen root zone deprivation and grafting. Agronomy 10(1), 137. Doi 10.3390/agronomy10010137

Mawar R, Lodha S, Ranawat M, El Enshasy HA et al. 2022 – Combined effects of biosolarization and *Brassica* amendments on survival of biocontrol agents and inhibition of *Fusarium oxysporum*. Agronomy 12(8), 1752. Doi 10.3390/agronomy12081752

McGovern RJ. 2015 – Management of tomato diseases caused by *Fusarium oxysporum*. Crop Protection 73, 78-92. Doi 10.1016/j.cropro.2015.02.021

Mostafa YS, Alamri SA, Alrumman SA, Hashem M et al. 2022 – In vitro and in vivo biocontrol of tomato Fusarium wilt by extracts from brown, red, and green macroalgae. Agriculture 12(3), 345. Doi 10.3390/agriculture12030345

Mousa MAA, Abo-Elyousr KAM, Abdel Alal AMK, Alshareef NO. 2021 – Management Fusarium wilt disease in tomato by combinations of *Bacillus amyloliquefaciens* and peppermint oil. Agronomy 11(12), 2536. Doi 10.3390/agronomy11122536

Muhorakeye MC, Namikoye ES, Khamis FM et al. 2024 – Biostimulant and antagonistic potential of endophytic fungi against Fusarium wilt pathogen of tomato *Fusarium oxysporum* f. sp. *lycopersici*. Scientific Reports 14, 15365. Doi 10.1038/s41598-024-66101-1

Nedelcu L, Alexandri AA. 1995 – Synergistic effect between metamidoxime and copper oxychloride. Probleme de Protectia Plantelor 23(1), 13–21.

Nirmaladevi D, Venkataramana M, Srivastava R, Uppalapati SR et al. 2016 – Molecular phylogeny, pathogenicity and toxigenicity of *Fusarium oxysporum* f. sp. *lycopersici*. Scientific Reports 6, 21367. Doi 10.1038/srep21367

Nusret O, Steven EN. 2004 – Fusarium crown and root rot of tomato and control methods. Plant Pathology Journal 3, 9–18. Doi 10.3923/ppj.2004.9.18

O'Donnell K, Ward TJ, Robert VARG, Crous PW et al. 2015 – DNA sequence-based identification of Fusarium: Current status and future directions. Phytoparasitica 43, 583–595. Doi 10.1007/s12600-015-0484-z

Okon OG, Rhouma A, Ismaila U, Matrood AAA et al. 2023 – Biological control of fruit rot of postharvest orange (*Citrus aurantium*) by aqueous plant extracts. Indian Journal of Agricultural Sciences 93(11), 1243–1247. Doi 10.56093/ijas.v93i11.141146

Pan F, Li X, Zhong D, Lu X et al. 2023 – Eceriferum Genes in tomato (*Solanum lycopersicum*): Genome-wide identification and expression analysis reveal their potential functions during domestication. Horticulturae 9(7), 748. Doi 10.3390/horticulturae9070748

Panno S, Davino S, Caruso AG, Bertacca S et al. 2021 – A review of the most common and economically important diseases that undermine the cultivation of tomato crops in the Mediterranean Basin. Agronomy 11(11), 2188. Doi 10.3390/agronomy11112188

Patpour M, Hovmøller MS, Rodriguez-Algaba J, Randazzo B et al. 2022 – Wheat stem rust back in Europe: Diversity, prevalence and impact on host resistance. Frontiers in Plant Science 13, 882440. https://doi.org/10.3389/fpls.2022.882440

Quinet M, Angosto T, Yuste-Lisbona FJ, Blanchard-Gros R et al. 2019 – Tomato fruit development and metabolism. Frontiers in Plant Science 10, 1554. Doi 10.3389/fpls.2019.01554

Rhouma A, Khrieba MI, Salih YA, Atallaoui K et al. 2021 – Technical document on downy mildew of soybeans. Asian Journal of Plant and Soil Sciences 6(1), 130–135.

Rhouma A, Mehaoua MS, Mougou I, Rhouma H et al. 2023a – Combining melon varieties with chemical fungicides for integrated powdery mildew control in Tunisia. European Journal of Plant Pathology 165, 189–201. Doi 10.1007/s10658-022-02599-3

Rhouma A, Hajji-Hedfi L, El Amine Kouadri M, Atallaoui K et al. 2023b – Verticillium wilt of olive and its control caused by the hemibiotrophic soil-borne fungus *Verticillium dahliae*. Microbial Biosystems 8(2), 25–36. Doi 10.21608/MB.2024.255400.1089

Rhouma A, Hajji-Hedfi L, Salih YA, Bousselma A et al. 2023c. Ascochyta leaf spot of wheat: Disease profile and management. Microbial Biosystems 8(1), 26–32. Doi 10.21608/MB.2023.230326.1077

Rhouma A, Hajji-Hedfi L, El Amine Kouadri M, Chihani-Hammas N et al. 2024 – Investigating plant growth promoting and antifungal potential of *Metarhizium* spp. against Fusarium wilt in tomato. Nova Hedwigia 119(1-2), 117–139. Doi 10.1127/nova_hedwigia/2024/0958

Ribeiro JA, Albuquerque A, Materatski P, Patanita M et al. 2022 – Tomato response to *Fusarium* spp. infection under field conditions: Study of potential genes involved. Horticulturae 8(5), 433. Doi 10.3390/horticulturae8050433

Rippa M, Yan C, Liu Q, Tucci E et al. 2023 – Comparison between an Innovative Solarization System and Dazomet-Based Fumigation. Soil Systems 7(1), 20. Doi 10.3390/soilsystems7010020

Sachdev S, Bauddh K, Singh RP. 2023 – Native rhizospheric microbes mediated management of biotic stress and growth promotion of tomato. Sustainability 15(1), 593. Doi 10.3390/su15010593

Shahin A, Mazrou YSA, Omara RI, Hermas G et al. 2022 – Geographical correlation and genetic diversity of newly emerged races within the Ug99 lineage of stem rust pathogen, *Puccinia graminis* f. sp. *Tritici*, in different wheat-producing areas. Journal of Fungi 8(10), 1041. https://doi.org/10.3390/jof8101041

Song W, Zhou L, Yang C, Cao X et al. 2004 – Tomato Fusarium wilt and its chemical control strategies in a hydroponic system. Crop Protection 23(3), 243–247. Doi 10.1016/j.cropro.2003.08.007

Wang H, Hao Z, Zhang X, Xie W et al. 2022 – Arbuscular mycorrhizal fungi induced plant resistance against Fusarium wilt in jasmonate biosynthesis defective mutant and wild type of tomato. Journal of Fungi 8(5), 422. Doi 10.3390/jof8050422

Weitang S, Ligang Z, Chengzong Y, Xiaodong C et al. 2004 – Tomato Fusarium wilt and its chemical control strategies in a hydroponic system. Crop Protection 23(3), 243–247. Doi 10.1016/j.cropro.2003.08.007

Weng W, Yan J, Zhou M, Yao X et al. 2022 – Roles of arbuscular mycorrhizal fungi as a biocontrol agent in the control of plant diseases. Microorganisms 10(7), 1266. Doi 10.3390/microorganisms10071266

Włodarczyk K, Smolińska B, Majak I. 2023 – The antioxidant potential of tomato plants (*Solanum lycopersicum* L.) under nano-zno treatment. International Journal of Molecular Sciences 24(14), 11833. Doi 10.3390/ijms241411833

Xia JW, Sandoval-Denis M, Crous PW, Zhang XG et al. 2019 – Numbers to names - restyling the *Fusarium incarnatum-equiseti* species complex. Persoonia - Molecular Phylogeny and Evolution of Fungi 43, 186–221. Doi 10.3767/persoonia.2019.43.05

Yadav V, Wang Z, Yang X, Wei C et al. 2021 – Comparative analysis, characterization and evolutionary study of dirigent gene family in *Cucurbitaceae* and expression of novel dirigent peptide against powdery mildew stress. Genes 12(3), 326. Doi 10.3390/genes12030326

Yan Z, Appiano M, van Tuinen A, Meijer-Dekens F et al. 2021 – Discovery and characterization of a novel tomato mlo mutant from an EMS mutagenized micro-tom population. Genes 12(5), 719. https://doi.org/10.3390/genes12050719

Yan X, Guo S, Gao K, Sun S et al. 2023 – The impact of the soil survival of the pathogen of Fusarium wilt on soil nutrient cycling mediated by microorganisms. Microorganisms 11(9), 2207. Doi 10.3390/microorganisms11092207

Yang F, Jiang H, Chang G, Liang S et al. 2023 – Effects of rhizosphere microbial communities on cucumber Fusarium wilt disease suppression. Microorganisms 11(6), 1576. Doi 10.3390/microorganisms11061576

Zavtrikovienė E, Gorash A, Kadžienė G, Matelionienė N et al. 2022 – Pathogenicity of asymptomatically residing *Fusarium* species in non-gramineous plants and weeds to spring wheat under greenhouse conditions. Pathogens 11(12), 1467. Doi 10.3390/pathogens11121467

Zhou Q, Yang Y, Wang Y, Jones C et al. 2021 – Phylogenetic, phenotypic and host range characterization of five *Fusarium* species isolated from chickpea in Alberta, Canada. Canadian Journal of Plant Pathology 43(5), 651–657. Doi 10.1080/07060661.2020.1869830