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Review Article

Insights into Fusarium Wilt of Tomato (*Fusarium oxysporum* f. sp. *lycopersici*) and its Management Strategies

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ABSTRACT

Tomato (*Lycopersicon esculentum*), a widely cultivated vegetable rich in vitamins, minerals, and health-promoting antioxidants like lycopene and vitamin C, faces significant production challenges. Among these, *Fusarium* wilt, caused by the soilborne fungus *Fusarium oxysporum* f.sp. *lycopersici* (FOL), is a prevalent and destructive disease in tomato-growing regions worldwide. FOL, a highly damaging ascomycete fungus, poses a serious threat alongside the large populations of nonpathogenic *F. oxysporum* (NPF) residing in various ecological niches. The disease manifests initially with yellowing of lower leaves, followed by progressive wilting. FOL invades the tomato plant, colonizing the vascular tissue and causing its discoloration to a dark brown hue. This discoloration extends upwards, ultimately leading to wilting, collapse, and plant death. The wilting syndrome is attributed to a complex interplay of factors induced by the fungus, including xylem blockage by fungal mycelia, production of mycotoxins, suppression of host defense mechanisms, and formation of tyloses (cellular outgrowths).. Managing *Fusarium* wilt is challenging due to the extended survival of the pathogen and its existence in diverse pathogenic races. Conventional approaches, such as deployment of resistant cultivars and application of synthetic fungicides have shown limited efficacy. Additionally, the potential environmental hazards associated with fungicides necessitate a cautious approach. This review explores the use of both chemical and biological control agents in *Fusarium* wilt management, acknowledging the limitations of single-method strategies. To achieve sustainable and environmentally friendly disease control, an integrated approach is recommended. This review aims to equip farmers with a diverse toolbox of management methods that can be combined into a comprehensive package to combat *Fusarium* wilt and related soil borne diseases.

Keywords: Tomato, Fusarium wilt, Molecular characterization, Management.

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INTRODUCTION

The increasing frequency and severity of plant disease outbreaks pose significant and growing threats to primary productivity, global food security, and biodiversity, especially in vulnerable regions (Nauman et al., 2023; Naqvi et al., 2024). These outbreaks result in considerable yield and ecological losses, with annual crop yield losses due to pathogens and pests alone estimated at US$220 biblon. This has a direct impact on food security, regional economies, and various interconnected socio-economic factors (Azeem et al., 2020; Ali et al., 2020; Anwaar et al., 2022; Rehman et al., 2023; Iftikhar et al., 2024). Agriculture is a cornerstone of Pakistan's economy, contributing nearly 22.9% to Gross Domestic Product (GDP) and employing over 37.4% of the workforce, ensures food security and provide raw material to the industrial sector according to Pakistan's Bureau of Statistics 2022-2023. However, recent decline in agricultural growth necessitates development strategies. The horticulture sector is prioritized as a key driver for future agricultural progress. This initiative aims for economic growth, enhanced food security, and sustainable practices (Ahmad, 2020). The global horticulture industry holds significant economic potential, with a market value exceeding USD 150 billion (Baiphethi & Jacobs, 2009). Pakistan seeks to capitalize on this by becoming a major player in the high-value agricultural product market. Pakistan's growing population and expanding middle class drive demand for high-value perishable goods like fruits and vegetables (Chandio et al., 2016). While the WHO recommends a yearly per capita vegetable intake of 73 kg, Pakistan's average is only 35.6 kg (Shaheen et al., 2011; Abedullah & Ahmad, 2006). Limited land area and lower yields contribute to this gap (Byerlee & White, 2000; Bakhsh et al., 2022). Tomato, (*Solanum lycopersicum L.*) holds economic significance as the second most widely cultivated vegetable crop globally (Ma et al., 2023). Its annual production reaches approximately 115.95 million tons (Hassan, 2020). Although tomatoes are one of the most significant crops that are widely farmed, different agroecological zones have shown differences in output (Bhutani & Kallo, 1983). Tomato has gained significant global significance in horticulture in terms of utilization, versatility, fresh commodity, nutritional value and culinary. Its incorporation as a vital constituent in various processed food items, and utilization in scientific investigations about plant growth and development principles. (Babalola et al., 2010) Assert that this particular crop possesses substantial economic and industrial importance in diverse geographical areas worldwide. Tomato, commonly recognized as fundamental component of Pakistan gastronomy, frequently employed as primary vegetable in prepared meals and as savory enhancements in condiments and salads. The demand for tomatoes strongly correlates with income elasticity. Consequently, the growth of population, expansion of the economy, and development of urban areas will lead to an augmented need for these vegetables (Losada et al., 2018). It is commonly employed as a daily staple food item and is a prominent component of the Pakistani food preparation tradition. The predominant application of this specific vegetable is primarily in its uncooked state, typically consumed as a raw commodity (Poti et al., 2015). Tomato exhibits a notable concentration of vitamin C (31 mg per 100g) alongside vitamin A, calcium, iron, and other vital nutrients. Lycopene, a prevalent antioxidant, is naturally present in tomatoes and has been discovered to exhibit anti-carcinogenic characteristics, effectively impeding the progression of various types of cancer (Adenuga et al., 2013). Small-scale agricultural enterprises predominantly undertake tomato cultivation in Pakistan. The cultivation of this particular crop offers producers the opportunity to generate relatively higher profits. It contributes to improve employment opportunities for rural laborers, primarily due to its labor-intensive characteristics. The tomato production in Pakistan reached a total of 536,217 tonnes in 2008. However, the crop's yield is comparatively inferior to the global benchmark. Study conducted by (Mari et al., 2007) suggests that the Lycopersicon genus demonstrates a remarkable ability to withstand various environmental and nutritional conditions. Numerous species have been subjected to hybridization techniques to create a wide array of varieties with the specific purpose of cultivating a singular harvest field crop or, mainly when cultivated under protective measures, yielding a continuous provision of fruit for the fresh market over an extended period. The mechanical harvesting of field tomatoes has become a viable option due to the joint endeavors of plant breeders and agricultural engineers. This technological development facilitates the production and processing of substantial volumes of tomatoes in a financially efficient manner (Fritsch et al., 2017). The products are employed in a wide range of canned, frozen, preserved, or dehydrated food items.

Fusarium wilt is a highly damaging and prevalent disease that causes significant yield losses in tomatoes (Srinivas et al. 2019; Haque et al. 2023). The causative agent, a soil-borne fungus named *Fusarium oxysporum f.sp. lycopersici* (FOL), invades the tomato plant's vascular system, leading to wilting and eventually death (Michielse et al. 2009; Srinivas et al. 2019). FOL is particularly challenging to manage due to its ability to survive in the soil for extended periods and its existence in diverse pathogenic races (SG, 2024).

Distribution

The Andean region spans Colombia, Ecuador, Peru, Bolivia, and Chile are widely recognized as the primary geographical area where the genus *Solanum* section *Lycopersicum* (formerly called the genus *Lycopersicon*) originated. The native distribution of all wild relatives of tomatoes is limited to this specific geographic region (Rick, 1973). The tomato is thought to have originated in the western seaboard of South America, where the presence of cold ocean currents is believed to play a role in moderating average air temperatures, even in regions near the equator. The nations of Ecuador and Peru demonstrate a significant prevalence of diverse species dispersed throughout the coastal plain and extending into the foothills of the Andes (Table 1). The genus's longitudinal distribution spans over 2000 km from central Ecuador to northern Chile. However, the average distance from the coastline is approximately 200 kilometers. According to historical analysis, it is postulated that the indigenous tomato species can be traced back to its origins in South America. It is hypothesized that the dispersion of tomato seeds towards the north, possibly facilitated by drainage canals, occurred, leading to their eventual arrival in Mexico. The fruit in this particular geographical area experienced a substantial surge in popularity, resulting in the emergence of multiple alternative terms for the word "tomato" in the indigenous languages. The conquistadors from Europe during the early 16th century introduced seeds to Spain. The term "love apple" was recorded during the Elizabethan era, and scholars have put forth two distinct hypotheses to account for the etymology of this designation. The botanical specimens cultivated in Seville during the year 1501 displayed fruit with a yellow hue. Following this, the plants mentioned above were subsequently transported to Morocco and then to Italy by the year 1544 (Table 2).

Table 1. *Fusarium* wilt severity in Tomatoes under different environmental conditions.

Environment Type	Temp.	Humidity	Soil Type	Severity Level	Description
Hot and Dry	> 30°C	Low	Sandy	High	High temperatures and low humidity stress plants, making them more susceptible to infection.
Hot and Humid	> 30°C	High	Clayey	Moderate to High	High humidity promotes fungal growth, leading to moderate to high infection levels.
Mild and Humid	20-30°C	High	Loamy	Moderate	Moderate temperatures and high humidity create favorable conditions for fungus, but less stress on plants.
Cool and Humid	< 20°C	High	Loamy	Low	Cooler temperatures slow down fungal growth, reducing infection severity.
Cool and dry	< 20°C	Low	Sandy or Loamy	Low	Low temperatures and low humidity limit fungal growth and infection spread.
Controlled	20-25°C	Controlled	Sterilized Loamy	Very Low	Controlled environments with managed temperature, humidity, and soil conditions significantly reduce disease incidence.

Table 2. *Fusarium* wilt severity in Tomatoes in different countries.

Country	Average Temperature	Humidity	Soil Type	Severity Level	Description
USA	20-30°C	Moderate	Loamy	High	Common in warmer regions with high humidity.
India	25-35°C	High	Sandy Loam	Very High	Hot and humid conditions favor disease spread.
Netherlands	10-20°C	High	Clayey	Low	Cooler climate reduces disease incidence.
Brazil	25-30°C	High	Sandy Loam	High	Favorable conditions for fungal growth.
China	15-25°C	Moderate	Loamy	Moderate	Varied climate; moderate severity overall.
Egypt	20-35°C	Low	Sandy	High	Hot and dry conditions stress plants, increasing susceptibility.

S. lycopersicum

The tomato was initially classified as *Lycopersicon esculentum* by Peralta et al. (2006). However, subsequent studies conducted by Peralta et al. (2006) led to the reclassification of the plant above as *S. lycopersicum*. The tomato plant is categorized as a diploid organism, exhibiting 24 chromosomes, represented as 2n = 2x. The tomato genome encompasses a substantial amount of genetic material, estimated to be around 950 megabases (Mb). Notably, over three-quarters of this genome comprises heterochromatin, a genomic region characterized by its scarcity of genes. The geographical area known as the Andean region, which includes Colombia, Ecuador, Peru, Bolivia, and Chile, is recognized as the primary location where the genus *Solanum* section *Lycopersicum* (formerly referred to as the genus *Lycopersicon*) originated. Lycopersicon has two species, where Eulycopersicon species displays a range of color variations, encompassing hues such as red, yellow, and brown. While, Eriopersicon species displays a primarily green pigmentation, frequently accompanied by discernible purple stripes. The geographic region in which the native distribution of all wild relatives of tomatoes is limited has been documented by Rick (1973). In Italy, the botanical specimen was designated as 'porno dei Mori' or 'Moor's apple' owing to its inherent geographical provenance. The Parisians would readily modify the designation of the fruit to 'pomme d'amour' and ascribe aphrodisiac properties to it. An alternative elucidation regarding the term "love apple" etymology can be attributed to the year 1554. During this period, the yellow fruit was commonly known as "pomi d'oro," "mala aurea," or "poma amoris," which were interchangeable terms that continued to be utilized until the 19th century. In the context of this nation, the expressions mentioned above were rendered as "amour apple." Although there has been a notable rise in the worldwide population, which has corresponded with an increase in the consumption of tomatoes, a definitive causal link between these two variables has not been firmly established. The tomato belongs to the Solanaceae family, and previous attempts to classify the various species have predominantly centered on the coloration of the fully ripened fruit (Davies et al., 1981).

Fusarium oxysporum

One of the significant causes of crop quality and production losses worldwide is phytopathogenic microorganisms. These phytopathogens provide a consequential barrier for the sectors that produce tomato products. Between 30 and 40% of the world's annual economic output is lost to diseases brought on by microbes before and after harvest, amounting to nearly 40 billion dollars. Notwithstanding, this crop's immense dissemination and lucrative influence, tomatoes are endangered by several diseases, particularly those caused by viruses, bacteria, nematodes and fungi (Lahlali et al., 2022). Fungal pathogens are responsible for approximately 80% of plant diseases. The most predominant water and soil-borne diseases of tomatoes are caused by *Fusarium* species (Cheng et al., 2021). In addition, it is widely recognized that the spread of diseases brought on by soil-borne pathogens, i.e., *Fusarium* spp., is one of the primary reasons for restricting agricultural output if not controlled. *Fusarium* had been giving rise to severe losses to tomato crops before its revelation in absolute scientific terms (Tang et al., 2021).

Table 3. How *Fusarium* attack tomato plants.

Stage	Description	Impact on Plant
Inoculation	The fungus *Fusarium oxysporum* f. sp. *lycopersici* infects through the roots.	Root infection starts.
Colonization	Fungal spores germinate and mycelium grows through root cortex into vascular tissue.	Disruption of water and nutrient flow.
Symptom's development	Vascular tissue becomes clogged, leading to wilting and yellowing of leaves.	Wilting, yellowing, and stunted growth.
Spread	Fungus spreads to other parts of the plant through the xylem.	Systemic infection, leading to plant death.
Survival	Fungal spores (chlamydospores) survive in soil or plant debris.	Long-term soil contamination.

Fusarium wilt is a fungal pathogen primarily disseminated via the soil medium; obstructing xylem vessels responsible for water transportation in plants (Table 3). The obstruction results in the withering of plants and, in numerous instances, the death of the vegetation. The fungus is soil borne and enters the plant through the roots (Figure 1). It clogs and blocks the xylem vessel and prevents water translocation to upper parts of the plant. Symptoms of *Fusarium* wilt can be very similar to Verticillium wilt. *Fusarium* wilt starts to show on a single leaf or shoot, near the top of the plant. The plant can recover at night when temperatures are cooler. However, as the disease progresses, the entire plant will wilt and will not recover at night. The lower leaves turn yellow, often just on one side. The yellowing will gradually move up the plant. The wilted leaves will dry out and fall off. Dark brown streaks are noticed when affected stems are cut length-wise. The occurrence of *Fusarium* wilts can be attributed to the presence of pathogenic strains from various *Fusarium* species, including *F. eumartii, F. oxysporum, F. avenaceum, F. solani, F. sulphureum,* and *F. tabacinum*. These strains commonly demonstrate a notable specificity towards the plants they infect. However, *F. oxysporum* is the perpetrator that is most commonly encountered. *Fusarium* species encompass a collection of filamentous fungi classified within the genus *Fusarium*. *Fusarium oxysporum* Schlechtendahl is a genus of filamentous fungi that belongs to the family Nectriaceae. Filamentous fungi, or molds, are a diverse group of microorganisms characterized by their elongated, thread-like structures called hyphae. Several species of *Fusarium* display a restricted geographic range in tropical regions, whereas others are more commonly found in temperate zones. Moreover, specific species have been observed to inhabit desert, alpine, and arctic regions, thereby subjecting themselves to adverse climatic circumstances (Francis & Burgess, 1975). Jeschke et al. (1990) reported a significant discrepancy in the geographic spread of *Fusarium* species, wherein a greater occurrence was observed in agriculturally productive cultivated and rangeland soils compared to forest soils. *Fusarium* species are commonly recognized as fungi that predominantly inhabit soil, frequently in conjunction with plant roots, and exhibit parasitic or saprophytic lifestyles (Nelson et al., 1994). The organism's diverse range of species has received substantial recognition for its notable involvement as a pathogen in plant diseases. Various species can produce mycotoxins, including fumonisins, zearalenones, and trichothecenes. This phenomenon leads to vegetation contamination and subsequent integration into the ecological food web. Mycotoxins pose significant health and safety hazards to various ecological components, including wildlife, livestock, agricultural commodities, and human populations (Arif et al., 2011; Balali & Iranpoor, 2006; Wang et al., 2011). According to the research conducted by Nelson et al. (1994), the widespread distribution of *Fusarium* species can be attributed to their exceptional ability to thrive on a diverse array of substrates, combined with their highly effective mechanisms for dispersing spores. The *Fusarium* species possess significant economic significance due to their capacity to act as plant pathogens, giving rise to various diseases, including crown rot, head blight, and scab. These diseases particularly impact cereal crops, affecting the agricultural sector and the overall economy. Moreover, it is worth noting that these particular species play a significant role in the induction of vascular wilts in a wide array of horticultural crops, including but not limited to tomatoes, cucurbits, and bananas. The *Fusarium* genus has garnered significant scientific interest owing to its notable influence on the prevalence of root rots, cankers, as well as diverse diseases, such as pokkah-boeng in sugarcane as well as bakanae disease in rice (Booth, 1977).

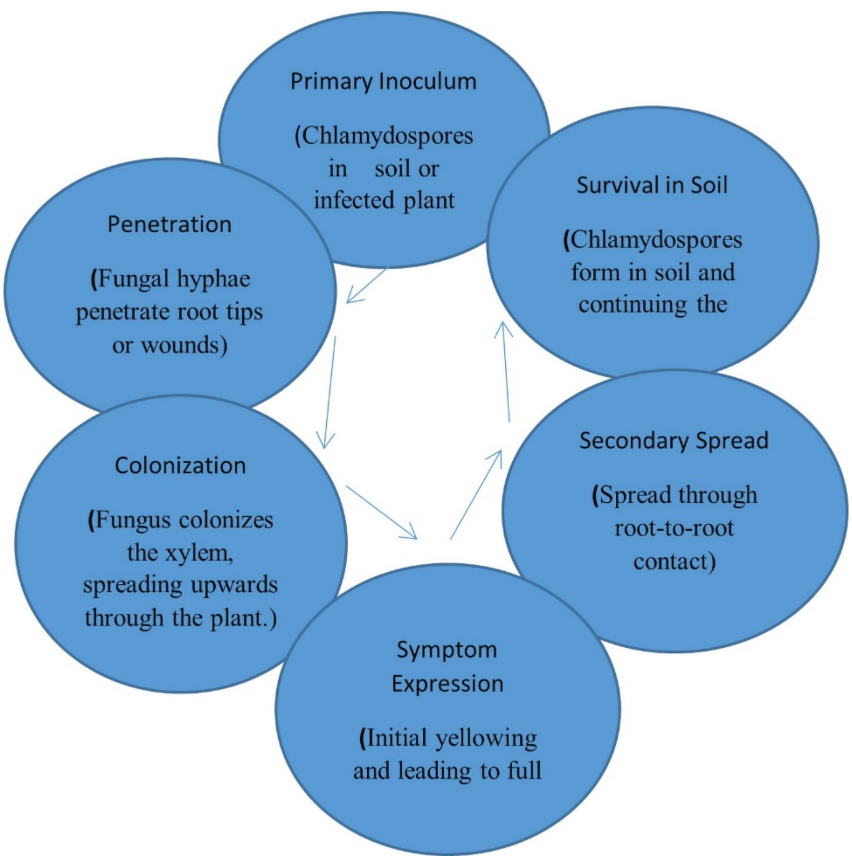

Figure 1. Disease cycle of *Fusarium* wilt of tomato.

Morphological and Molecular Characterization

Based on the seminal research conducted by Mueller & Beckman (1988), as well as the subsequent investigation carried out by Wang et al. (2011), it has been established that the taxonomic classification of the genus *Fusarium* comprises a comprehensive assemblage of no less than 20 discrete species. The empirical evidence put forth by sheds light on the presence of a teleomorphic state within specific *Fusarium* species. The species documented in the particular context under consideration are *Fusarium solani, F. oxysporum, F. equisetti, and F. chlamydosporum* (Chimbekujwo, 2000; Summerell et al., 2001). The classification system employed for *Fusarium* species is predicated upon essential characteristics encompassing a comprehensive range of discernible and microscopic attributes. The characteristics mentioned above encompass the colony's pigmentation, the macroconidia's dimensions and morphology, the quantity, shape, and arrangement of microconidia, and the presence or absence of chlamydospores (De Hoog et al., 2000). *Fusarium* wilts refer to a group of plant diseases resulting from various species' actions within the fungal genus. A diverse assemblage of 85 distinct cultures of *Fusarium* species was cultivated on Sabouraud Dextrose Agar, a growth medium, under meticulously controlled conditions at a consistent temperature of 25°C. Various colony morphologies were observed in these cultures, as documented by Yogalakshmi et al. (2021). The observed morphologies displayed a variety of growth patterns, such as woolly, cottony, flat, or spreading. When observed from a higher vantage point, the colony's coloration displays a diverse array of hues, including white, cream, tan, salmon, cinnamon, yellow, red, violet, pink, and purple. Based on the study conducted by Nelson et al. (1994), the underside of the object displays a varied assortment of hues, encompassing tan, red, dark purple, brown, and potentially even a lack of pigmentation. In unfavorable conditions, the fungus can produce sclerotia, an individual entity known as sclerotium. Yogalakshmi et al. (2021) defines the term "sclerotium" as a conglomeration of hyphae that undergoes a dormant phase in response to adverse environmental conditions. Following the restoration of favorable conditions, the sclerotium commences the germination process, thereby serving as a potential reservoir of infection. (Nelson et al., 1994) reported that *Fusarium* species commonly develop both macroconidia and microconidia via slender phialides. The macroconidia display transparent properties and are comprised of two to several cells. The organisms exhibit a variety of morphologies, ranging from fusiform to sickle-shaped. The existence of an elongated apical cell and a pedicellate basal cell distinguishes the morphological features under consideration. The aforementioned structural configuration is commonly observed among the majority of individuals. The microconidia demonstrate a range of attributes, including consisting of one to two cells, exhibiting a transparent morphology, and displaying a pyriform, fusiform, or ovoid structure. Furthermore, the morphology of microconidia may manifest as either straight or curved.

Management

The tomato crop is reducing productivity due to various biotic factors, encompassing nematodes, fungi, bacteria, and viruses. Nevertheless, it is crucial to acknowledge that soil-borne pathogens exert a substantial influence on diminishing overall crop productivity (Agrios, 2005). Tomato is a vegetable crop of significant economic value. However, it is at the bank of destruction due to different diseases, pests, high prices of agriculture inputs (fertilizer, pesticides), and the absence of modern technologies. Less perception and water shortage are the leading cause of the low yield of tomatoes. Mostly soil-borne fungal species, including *Fusarium, Verticillium, Pythium,* and *Rhizoctonia,* attack tomatoes and affect tomato quality and yield. Among all diseases, tomato wilt is the most devastating disease, creating severe production loss.

Use of Pesticides

In a country like Pakistan, chemicals are often used to manage diseases but can adversely affect health and climate. Pesticides are used on a large scale to produce tomatoes; they badly affect the non-target soil, water channel, and beneficial bacteria and fungi and adversely affect climate.

Previous studies have indicated that excessive pesticide use poses significant threats to groundwater quality (Arias-Estévez et al., 2008), harms to ecosystems, and causes severe diseases in humans (Athukorala et al., 2012; Okello & Swinton, 2010). Additionally, it affects marine life and destroys beneficial organisms essential for plant growth (Brethour & Weersink, 2001; Cuyno et al., 2001; Skevas et al., 2013). Almost 75% of total imported pesticide applications on tomatoes lead to massive disturbances in the ecosystem and badly affect rural people's health. Based on the findings of Khooharo et al. (2008), the data indicates a significant increase in the utilization of pesticides, as demonstrated by the substantial rise in quantities from 906 metric tonnes in 1980 to 5519 metric tonnes in 1992. Khan et al. (2020) present data on market share distribution among pesticide manufacturers across different provinces. Punjab constituted the majority with a significant share of 90%, followed by Sindh with a proportion of 8%. In contrast, Baluchistan and KPK collectively contributed a relatively small portion of 2%. Cotton cultivation occupies 2.4% of the total arable land available worldwide. Significantly, cotton cultivation plays a noteworthy role in satisfying a considerable proportion of the worldwide need for insecticides, accounting for 24%, and contributes to 11% of the global demand for pesticides. The contamination of groundwater occurs due to the introduction of pesticides, as stated by the World Wildlife Fund (WWF, 2003). Pesticides are expensive, dangerous for our environment and human health, challenging to process and register, and cost almost $ 30,000,000 (Chet, 1990). Therefore, researchers in academic institutions and all private companies aim to introduce non-chemical methods of disease management in the world. To date, the efficacy of fungicides in providing sufficient protection against *Fusarium* wilts has yet to be established. Moreover, a growing inclination has been toward adopting and promoting sustainable agricultural practices (Lemanceau & Alabouvette, 1993). Undoubtedly, introducing chemical substances, particularly pesticides, can harm the overall quality of food products and the surrounding environment. Alternative ways to suppress *Fusarium* wilts, such as biological control, must be developed urgently.

Use of Biocontrol agents

Soil-borne pathogens can be controlled through cultural practices, enhancing the resistance of the host, introducing the other organism into the soil, using fumigants, and acting as native microflora without influencing the environment (Deacon, 1988). Therefore, this research aims to develop new management practices against destructive diseases, which are easy to adopt and should be environmentally friendly. Biocontrol agents are the natural ways to manage the disease and reduction of inoculum through another organism without the entire destruction of crops (Cook & Baker, 1983; Ali et al., 2024a; Ali et al., 2024b). They have been reported to be used in the control of *Fusarium* wilts for many crops including tomato, cucumber, melon, strawberry, banana and carnation (Horinouchi et al. 2008). Bio-control agents such as non-pathogenic *F. oxysporum* (Katsube and Akasaka, 1997; Momol and Pernezny, 2003), hypovirulent binucleate *Rhizoctonia* (Muslim et al. 2003), *Gliocladium virens*, *Trichoderma hamatum*, *Burkholderia cepaci*, *Pseudomonas fluorescens* (Larkin et al. 1996), *Bacillus subtilis*, *Streptomyces pulcher* (Monda, 2002), *Baccillus polymayxa* (Hamed et al. 2009) and *Enterobacter cloacae* (Tsuda et al. 2001) have been reported to control *Fusarium* wilt disease. Use of Mycoparasites such as *T. harzianum*, *T. viride* and *T. harmatum* as bio-control agents in tomato field significantly controlled tomato wilt caused by *F. oxysporum* f. sp. *lycopersici* (Ojha and Chatterjee, 2012). The biocontrol applied in the soil to suppress wilt fungus first needs to multiply in the rhizosphere and then colonize the root to become systemic. Most of the Trichoderma species generally grow in their natural habitat and colonize root surfaces or become endophytes (Ruano-Rosa et al. 2016). The first recorded documentation of the biocontrol effectiveness of *Trichoderma* was presented by Pandya et al. (2011). The efficacy of *Trichoderma* species as biocontrol agents against fungal phytopathogens has been extensively acknowledged. The indirect effects of microorganisms can be discerned through various mechanisms, including engaging in competition for essential resources and physical space, altering environmental conditions, facilitating plant growth, eliciting plant defense responses, and initiating antibiosis. In addition, microorganisms can exert direct influences via mechanisms such as mycoparasitism (Papavizas, 1985; Howell, 2003). *Trichoderma* species are characterized by their rapid growth, persistent conidia, and wide range of substrate utilization. According to Hjeljord et al. (2000), these organisms exhibit high efficiency in competing for nutrition and living space. According to Benítez et al. (2004), *Trichoderma spp*. exhibit a notable capacity for synthesizing siderophores, which effectively sequester iron and inhibit the proliferation of other fungal species. Hence, the attributes of soil exert an influence on the efficacy of *Trichoderma* as a biocontrol agent. Several mechanisms have been proposed to explain the phenomenon of biocontrol, with the main contributing factor believed to be the enhanced competitive ability of antagonistic microorganisms in nutrient competition compared to pathogens (Lemanceau, 1989; Couteaudier & Alabouvette, 1990; Schuster & Schmoll, 2010). The putative mechanism of action against *Fusarium oxysporum* may entail the production of lytic enzymes by antagonistic microorganisms. Mitchell & Alexander (1961) documented the utilization of bacterial strains that demonstrate lytic enzyme production to control *Fusarium* wilt. The idea of employing nonpathogenic Fusaria to manage *Fusarium* wilts emerged from the study of soils that exhibit inherent suppressive characteristics against *Fusarium* wilts. *Fusarium*Research is ongoing to develop effective management strategies, including exploring eco-friendly methods and understanding the genetic makeup of the pathogen (Inami et al. 2014; SG, 2024). Suppression of *Fusarium* wilt using biocontrol agents has been achieved through interactions among the plant, the pathogen, the biocontrol agents, the microbial community around the plant and the physical environment (Barea et al. 2004). Hydrolytic enzymes of antagonistic microorganisms have been considered to play an important role in the biological control of plant pathogens. Many enzymes have been isolated from various strains of Trichoderma species (Harman et al. 1996), *Gliocladium vixens* (Di-pietro et al. 2003), *Paenibacillus* and *Streptomyces* species (Singh et al. 1999), and their activities were assayed and found effective in controlling *Fusarium* wilts. This is accomplished through competition; secretions of antibiotics, parasitism and induced resistance (Shishido et al. 2005).

CONCLUSIONS AND FUTURE ASPECTS

*Fusarium*FOL poses a significant threat to tomato production, causing growth and biomass reductions ranging from 9 to 24%. While chemical fungicides have traditionally been used for control, their efficacy against FOL and other soilborne diseases is often limited. Additionally, growing concerns regarding their detrimental environmental and human health impacts necessitate the exploration of safer, eco-friendly alternatives. This review highlights non-chemical management strategies with the potential to effectively control FOL. The emergence of new virulent strains, fungicide-induced elimination of beneficial soil microorganisms, and the impracticality of long-term crop rotation further complicate FOL management. Considering the drawbacks of chemical control, the development of novel alternatives is crucial for sustainable tomato production. Our research demonstrates the promise of *Trichoderma harzianum* as a biocontrol agent. Application of this fungus significantly reduced wilt severity (9-28%) and improved plant growth parameters (9-28%) and biomass (15-21%). It is important to acknowledge that implementing these eco-friendly methods might not completely eradicate all soilborne pathogens. Integrated Disease Management (IDM) strategies, which combine these methods with judicious fungicide use, when necessary, offer a more comprehensive solution. This multifaceted approach is highly recommended to ensure the long-term sustainability of tomato production. The findings presented here provide a valuable foundation for developing effective IDM practices to safeguard tomatoes against FOL. However, field trials are necessary to validate the efficacy of the identified Trichoderma isolates before their widespread adoption by farmers.

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All authors contributed equally to this research.

AUTHOR CONTRIBUTIONS

Iqra Kanwal: Writing– review & editing, Figure preparations. Atika Iffat: Writing original draft, Writing– review & editing. Muhammad Bilal Shaukat: Project administration, writing– review & editing. Talha Shafique: Finalization, Writing– review & editing. Yasir Majeed: Writing– review & editing, Validation. Muhammad Irfan Zafar: Visualization, Writing– review & editing. Hassan Moatasam Awan: Software, Writing– review & editing. Irum Tabbasum: Collecting literature, Writing– review & editing. Adeeba Iqbal: Collecting literature, Writing– review & editing. Muhammed Tatar, Parnaz Mortazavi**,** Amjad Ali and Rahma Bejaoui: Conceptualization, Writing– review & editing. Humera Aslam and Farwa Seemab: Collecting literature, Writing– review & editing.

COMPETING OF INTEREST

The authors declare that the research was carried without any commercial or financial relationships that could be construed as a potential conflict of interest.

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