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Research Article

Soil- and Seed-Borne Diseases of Tomato (*Solanum lycopersicum*): A Critical Review

Raj Kiran

Division of Plant Quarantine, ICAR-National Bureau of Plant Genetic Resources, New Delhi-110 012, India

*** Corresponding Author's E-mail: raj.kiran@icar.org.in**

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Abstract

Tomato production is severely affected by soil- and seed-borne pathogens, causing significant yield losses, with major soil-borne pathogens including *Fusarium oxysporum* f. sp. *lycopersici*, *Ralstonia solanacearum*, *Verticillium dahliae*, *Pythium* spp., *Rhizoctonia solani*, *Sclerotium rolfsii*, and *Macrophominaphaseolina*, while seed-borne pathogens such as *Clavibactermichiganensis* subsp. *michiganensis*, *Xanthomonas* spp., *Alternaria solani*, and *Septoria lycopersici* facilitate long-distance dissemination. These pathogens often produce overlapping and non-specific symptoms, including damping-off, wilting, root rot, vascular discoloration, stem cankers, and leaf spots, which complicates accurate field diagnosis. A reliable disease identification requires an integrated diagnostic approach combining field-based symptom observation with laboratory confirmation. Conventional methods such as isolation and morphological characterization remain important, but are increasingly complemented by sensitive and rapid molecular and serological techniques, including polymerase chain reaction (PCR), quantitative PCR (qPCR), loop-mediated isothermal amplification (LAMP), and enzyme-linked immunosorbent assay (ELISA). The integration of these advanced diagnostic tools enhances the accuracy and speed of pathogen detection, enabling early intervention and informed disease management strategies.

Key words: Tomato, Pathogen, Diseases, Soil & Air born.

Introduction:

Tomato (*Solanum lycopersicum* L.) is one of the most important vegetable crops globally, contributing significantly to food security, nutrition, and agricultural economies. Its adaptability to diverse agro-climatic conditions and its use in both fresh and processed forms have enabled widespread cultivation in smallholder and commercial systems (Sheneka *et al*., 2025). However, intensification of production systems, including protected cultivation, has increased vulnerability to plant diseases (Wang *et al*., 2024). Many of these diseases are soil- and seed-borne, causing yield losses of 30-40% and up to 80% under favorable conditions (Biswal *et al*., 2023). Soil and seeds act as reservoirs for pathogen survival, and practices such as monocropping and poor sanitation exacerbate disease incidence (Yuanyuan *et al*., 2013). Soil-borne pathogens persist through specialized survival structures such as chlamydospores, sclerotia, and microsclerotia, enabling long-term survival and continuous disease pressure (Rout, 2015; Ma *et al*., 2023). Seed-borne pathogens further contribute by acting as primary inoculum sources and facilitating long-distance dissemination. Diagnosis of these diseases can be challenging due to overlapping symptoms such as wilting, damping-off, and vascular discoloration, which may also resemble abiotic stresses. Although conventional methods such as morphological identification remain essential, the integration of molecular tools like PCR, qPCR, LAMP, and immunological assays such as ELISA enables more accurate and rapid detection of pathogens (Campos *et al*., 2023; Morcia*et al*., 2023). Emerging technologies such as metagenomics and biosensors are further enhancing diagnostic capabilities. In this review, we highlight the major soil- and seed-borne pathogens affecting tomato, focusing on distribution, symptoms, modes of transmission, favorable environmental conditions, and their impact on crop yield and also summarizes disease diagnosis and recent advances in sensitive and reliable pathogen detection methods.

1. Major Soil-Borne Diseases of Tomato

1.1 Damping-off

Damping-off is one of the most destructive diseases affecting tomato seedlings during nursery and early growth stages. It is caused by a complex of soil-borne pathogens, primarily *Pythium* spp., *Rhizoctonia solani*, and *Phytophthora* spp. (Rashad *et al*., 2022). Among these, *Pythium aphanidermatum* and *P. myriotylum* are particularly important (Elshahawy*et al*., 2018). The disease appears in two phases: pre-emergence damping-off, where seeds rot before emergence, and post-emergence damping-off, characterized by water-soaked lesions at the soil line leading to seedling collapse (Thakur *et al*., 2015). The infection process in *Pythium* involves motile zoospores that are attracted to root exudates, encyst, and germinate to infect host tissues. In contrast, *R. solani* forms infection cushions and causes reddish-brown lesions, while *Phytophthora spp.* induce dark lesions on stems and roots (Shalaby *et al*., 2022; Loliam*et al*., 2012)

1.2 Fusarium Wilt

Fusarium wilt, caused by *Fusarium oxysporum* f. sp. *lycopersici* (*Fol*), is among the most economically important soil-borne diseases of tomato worldwide. Yield losses typically range from 30-40%, but may reach up to 80% under favorable conditions. The disease is characterized by unilateral chlorosis of lower leaves, progressive wilting, vascular browning, and eventual plant death. The pathogen infects through roots, colonizes cortical tissues, and enters the xylem, where it produces conidia that spread systemically (García-Enciso *et al*., 2017; Li *et al*., 2023). Vascular blockage caused by fungal growth, tyloses, and gums leads to impaired water transport and wilting. A key feature of *Fol* is its ability to produce long-lived chlamydospores that persist in soil for up to 10-15 years. The pathogen exhibits significant pathogenic variability, with three physiological races (1, 2, and 3) identified based on host resistance interactions (Vignesh *et al*., 2020). Environmental conditions such as temperatures of 27-28°C, acidic soils, and high nitrogen levels enhance disease severity (Wang *et al*., 2024).

1.3 Verticillium Wilt

Verticillium wilt, caused by *Verticillium dahliae* and *V. albo-atrum*, is another vascular disease of tomato, generally less severe than Fusarium wilt but still of considerable importance. Symptoms include yellowing of lower leaves, V-shapedchlorosis, and vascular discoloration. This pathogen is the more prevalent species due to its wide host range and persistence. The pathogen survives in soil as microsclerotia for up to 10-15 years and infects roots in response to host exudates. Following root penetration, it colonizes the xylem and spreads systemically via conidia (Rout, 2015). Disease development is favoured by moderate temperatures (21-27°C), often making it more severe under relatively cooler conditions compared to Fusarium wilt.

1.4 Bacterial Wilt

Bacterial wilt, caused by *Ralstonia solanacearum*, is a highly destructive disease in tropical and subtropical tomato-growing regions (Murthy *et al*., 2014). The disease is characterized by rapid wilting without prior yellowing and the presence of milky bacterial ooze from cut stems (Singh *et al*., 2021). The pathogen enters through roots, colonizes the xylem, and proliferates rapidly, producing extracellular polysaccharides that block water transport (Murthy *et al*., 2014). Unlike fungal wilts, vascular browning is less pronounced, and wilting primarily results from physical blockage by bacterial cells. *R. solanacearum* exhibits extensive genetic diversity, classified into multiple phylotypes and sequevars, complicating disease management. The pathogen survives in soil, water, and alternative hosts and can persist in a viable but non-culturable (VBNC) state.

Disease development is favored by high temperatures (27-32°C), high moisture, and acidic soils.

1.5 Root Rot and Collar Rot

Root rot and collar rot caused by *Sclerotium rolfsii* and *Macrophominaphaseolina* are significant under warm and stress conditions (Ahmed *et al*., 2017). *S. rolfsii* causes collar rot with water-soaked lesions, abundant white mycelium, and characteristic mustard-like sclerotia. The pathogen survives as sclerotia and produces oxalic acid, facilitating host tissue colonization. In contrast, *M. phaseolina* causes charcoal rot, characterized by dry, brittle tissues and the formation of microsclerotia. It is particularly severe under high temperature and drought stress conditions. Both pathogens possess wide host ranges, limiting the effectiveness of crop rotation.

1.6 Emerging Soil-Borne Pathogens

In addition to major diseases, several emerging soil-borne pathogens are increasingly threatening tomato production (Hamed *et al*., 2026). Fusarium crown and root rot, caused by *F. oxysporum* f. sp. *radicis-lycopersici*, is favored by cooler temperatures (15-20°C) and is particularly problematic in greenhouse systems. Corky root rot caused by *Pyrenochaeta lycopersici* leads to reduced water and nutrient uptake, especially under intensive cultivation. Recent studies have also identified emerging root rot pathogens such as *Fusarium solani*, *M. phaseolina*, and *R. solani*, highlighting increasing pathogen diversity. *Phytophthora capsici* has expanded its host range to tomato, aided by motile zoospores and fungicide resistance. Additionally, nematode-fungal complexes involving *Meloidogyne* spp. exacerbate disease severity (Yuanyuan *et al*., 2013; Molinari *et al*., 2023).

1. **Major Seed-Borne Diseases of Tomato**

Seed transmission is a critical pathway for the introduction and spread of pathogens in tomato production, where even low infection levels can initiate epidemics. Pathogens associate with seeds through external contamination, internal infection, or systemic transmission from infected mother plants. External contamination involves adherence of spores or bacterial cells to seed coats, enabling infection during germination, while internal infection occurs through vascular connections, allowing pathogens to colonize seed tissues.

Internally seed-borne pathogens are particularly problematic as they evade surface disinfection and establish systemic infection in seedlings (Han *et al*., 2018). Seed transmission facilitates long-distance dissemination, introduction into disease-free areas, and establishment of primary inoculum (Peritore-Galve *et al*., 2021). Even very low infection levels (0.01-0.05%) can lead to outbreaks, especially for pathogens such as *Clavibactermichiganensis*subsp. *michiganensis* (Cmm) (Gleason *et al*., 1993; Chuis*et al*., 2023). Global seed trade increases phytosanitary risks, making seed health testing and certification essential, although detection limitations and VBNC states complicate management (Han *et* *al*., 2018). Understanding transmission mechanisms is fundamental for developing effective seed treatment strategies (Maeso*et al*., 2012).

2.1 Fungal Diseases

Seed-borne fungal pathogens such as *Alternaria solani* and *Septoria lycopersici* are important contributors to early disease establishment in tomato (Rasool *et al*., 2021). *A. solani*, the causal agent of early blight, can be present on or within seeds, leading to seedling blight and acting as a primary inoculum source for later foliar infection. The disease is characterized by concentric ring lesions, defoliation, and yield loss (Rasool *et al*., 2021). *Septoria lycopersici* is also seed-transmitted, though its role is less significant compared to survival on crop debris. Seed contamination occurs from infected fruits, and infected seedlings contribute to field-level disease spread. Other fungi such as *Fusarium* spp. and *Colletotrichum* spp. may also be seed associated.

2.2 Bacterial Diseases

Bacterial seed-borne diseases, particularly those caused by *Clavibactermichiganensis* subsp. *michiganensis* (*Cmm*) and *Xanthomonas* spp., are among the most challenging in tomato production (McFarquhar, 2015). *Cmm*, the causal agent of bacterial canker, can be both externally and internally seed-borne, leading to systemic infection and symptoms such as wilting, vascular discoloration, stem cankers, and "bird's eye" fruit lesions (Gonçalves, 2022). Low infection levels (0.01-0.05%) are sufficient to cause severe outbreaks, as infected seedlings act as primary inoculum sources (Gleason *et al*., 1993). The VBNC state further complicates detection and seed certification (Brochu *et al*., 2024). Management relies mainly on pathogen free seed and preventive treatments (Maeso*et al*., 2012). *Xanthomonas spp.* cause bacterial spot and are primarily externally seed-borne, leading to leaf spots, fruit lesions, and defoliation (McFarquhar, 2015).

2.3 Viral Pathogens

Seed transmission of viruses in tomato varies among species and remains partially controversial. Tobamoviruses such as Tomato mosaic virus (ToMV) and Tobacco mosaic virus (TMV) are known to be seed-transmitted, primarily through contaminated seed coats, with low transmission rates (<1%) (Gupta *et al*., 2023). However, these low levels are epidemiologically significant due to rapid secondary spread via mechanical transmission. Tomato brown rugose fruit virus (ToBRFV), an emerging tobamovirus, has raised concerns due to its resistance-breaking ability and potential seed transmission. Viral infections may also influence plant interactions with other pathogens, altering disease susceptibility.

2. Disease diagnosis and pathogen detection

Accurate diagnosis of soil- and seed-borne diseases in tomato requires an integrated approach combining field symptomatology with laboratory based morphological and molecular techniques, as symptoms often overlap among pathogens and may resemble abiotic stresses (Biswal *et al*., 2023). Field symptoms such as wilting, damping-off, vascular discoloration, root rot, and leaf lesions provide preliminary indications but are rarely definitive. For example, wilting may be caused by *Fusarium oxysporum* f. sp. *lycopersici*, *Verticillium* spp., *Ralstonia solanacearum*, nematodes, or drought stress, while vascular browning is commonly associated with wilt pathogens but requires confirmation (Murthy *et al*., 2014). Characteristic signs may aid preliminary diagnosis, such as bacterial streaming in *R. solanacearum* infections or collar lesions in damping-off caused by *Pythium* spp., *Rhizoctonia solani*, and *Phytophthora* spp. However, accurate identification necessitates laboratory confirmation, particularly for diseases like bacterial canker caused by *Clavibactermichiganensis* subsp. *michiganensis*, which exhibits symptoms similar to other bacterial infections (Peritore-Galve *et al*., 2021).

Morphological identification remains a foundational diagnostic method, based on pathogen structures observed in culture and infected tissues. Fungal pathogens are identified through mycelial and spore characteristics: *Fusarium oxysporum* produces sickle-shaped macroconidia and chlamydospores; *Rhizoctonia solani* exhibits right-angled hyphal branching and sclerotia; *Pythium* spp. show non-septate hyphae and oospores; and *Sclerotium rolfsii* forms abundant mycelium with mustard-like sclerotia (Rashad *et al*., 2022; Elshahawy*et al*., 2018; Ahmed *et al*., 2017). Bacterial pathogens are identified using colony morphology, Gram staining, and biochemical tests, with *R. solanacearum* producing fluidal colonies on TZC medium and *C. michiganensis* forming yellow, convex colonies (Murthy *et al*., 2014). Despite its utility, morphological identification is time-consuming and often insufficient for closely related taxa.

Molecular techniques have greatly improved pathogen detection by offering higher sensitivity, specificity, and speed (Campos *et al*., 2023). PCR-based methods enable rapid identification using pathogen-specific primers, while qPCR allows precise quantification with greater sensitivity. Advanced formats such as multiplex and TaqMan qPCR facilitate simultaneous detection of multiple pathogens and have been successfully applied to *Fusarium*spp. and *Clavibactermichiganensis* (Brochu *et al*., 2024). Digital PCR further enhances accuracy by enabling absolute quantification without standard curves, including detection of pathogens in VBNC states. LAMP provides a rapid, cost-effective alternative by amplifying DNA under isothermal conditions, producing results within 30-60 minutes and enabling field-level diagnostics (Adhikari *et al*., 2024). ELISA is also widely used for pathogen detection based on antigen-antibody interactions. It offers advantages such as high throughput, low cost, and suitability for large-scale screening, particularly for bacterial pathogens like *Clavibactermichiganensis* and *Xanthomonas* spp. Different formats, including DAS-ELISA, are commonly used in seed health testing. However, ELISA may show cross-reactivity, lower sensitivity than PCR, and inability to distinguish viable from non-viable cells, especially under VBNC conditions (Han *et al*., 2018). Therefore, it is often combined with molecular methods for confirmation.

There are some emerging tools such as metagenomics and biosensors are transforming disease diagnostics (Wang *et al*., 2024). Metagenomics enables comprehensive analysis of microbial communities without prior culturing, using sequencing of 16S rRNA and ITS regions to identify pathogens and beneficial microbes. These approaches reveal how practices like continuous cropping influence microbial balance

and disease development, and how biocontrol agents reshape rhizosphere communities (Antoniou *et al*., 2017). Shotgun metagenomics and related techniques further allow functional analysis of microbial genes and activity.Biosensors offer rapid, sensitive, and field-deployable detection by integrating biological recognition elements with signal transduction systems. Nanotechnology-based biosensors enhance detection efficiency and specificity (Elshahawy*et al*., 2018). Although still developing, these technologies hold strong potential for real-time monitoring and precision disease management.

Conclusion

Soil- and seed-borne diseases represent a major constraint to sustainable tomato production worldwide, causing significant yield losses and posing challenges due to their persistence, diverse modes of transmission, and complex symptomatology. The ability of pathogens to survive in soil through specialized structures and in seeds as primary inoculum sources underscores the need for effective monitoring and management strategies. While conventional diagnostic methods remain important, advances in molecular and serological techniques have significantly improved the accuracy, sensitivity, and speed of pathogen detection. Emerging tools such as metagenomics and biosensors further enhance our understanding of pathogen dynamics and offer promising avenues for real-time disease surveillance.Future research should focus on developing rapid, field-deployable diagnostic tools, understanding pathogen variability and climate interactions, and promoting sustainable management strategies to ensure resilient and productive tomato cultivation systems.

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