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Tomato Spotted Wilt Virus (TSWV) in India: Epidemiology, Thrips-Mediated Transmission, Molecular Interactions and Integrated Disease Management

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Abstract:
Tomato spotted wilt virus (TSWV), a member of the genus Orthotospovirus (family Tospoviridae), is one of the most destructive viral pathogens affecting vegetables, legumes, and ornamentals in India. The virus has a wide host range, including tomato, chilli, groundnut, and several weed species, which act as reservoirs and play a critical role in disease epidemiology. TSWV is transmitted in a persistent propagative manner by thrips, mainly *Thrips palmi*, *Frankliniella schultzei*, and *Scirtothrips dorsalis*, which are widely distributed across Indian agro-climatic zones. Virus acquisition occurs during the larval stages, followed by replication and transmission by adults. Molecular interactions between TSWV proteins and thrips midgut and salivary gland tissues govern virus replication, movement, and vector competence. In host plants, TSWV suppresses RNA silencing pathways and alters defense signaling, resulting in severe symptoms and significant yield losses. Integrated disease management of TSWV in India relies on a holistic approach involving early diagnosis, vector population management, use of resistant cultivars, and removal of alternate hosts, reflective mulches, and judicious insecticide application. Understanding virus–vector–host molecular interactions, combined with sustainable management practices, is crucial for long-term control of TSWV under Indian conditions.

Keywords: Tomato spotted wilt virus (TSWV), Orthotospovirus, Thrips vectors, Epidemiology, RNA silencing, Integrated disease management, India.

INTRODUCTION

Tomato spotted wilt virus (TSWV) is one of the most destructive plant viruses worldwide, causing severe economic losses in agricultural and horticultural crops. The virus belongs to the genus *Orthotospovirus* (family *Tospoviridae*) and possesses a tripartite, single-stranded RNA genome of negative and ambisense polarity, enclosed within quasi-spherical enveloped virions (Adkins, 2000; Kormelink et al., 2011). TSWV is characterized by an exceptionally wide host range, infecting more than 1,000 plant species across monocotyledonous and dicotyledonous families, making it a persistent and difficult-to-manage pathogen (Pappu et al., 2009; Dietzgen & Whitfield, 2018). Its adaptability to diverse agro-climatic conditions and efficient transmission by thrips vectors have contributed to its global emergence as a major threat to crop production.

In India, TSWV has gained increasing importance over the last two decades and is now recognized as a serious constraint in the cultivation of economically important crops such as tomato, chilli, capsicum, groundnut, and ornamentals. The virus has been reported from several states including Karnataka, Andhra Pradesh, Maharashtra, Tamil Nadu, and Telangana, with both incidence and severity increasing steadily (Jain & Mandal, 2018). Yield losses ranging from 20% to as high as 90% have been reported, depending on crop stage, cultivar susceptibility, and vector pressure. The diversity of cultivated hosts, continuous cropping practices, and the presence of susceptible weed reservoirs contribute significantly to virus survival and year-round disease pressure under Indian farming systems.

The epidemiology of TSWV is closely associated with thrips vectors, which are the sole agents of virus transmission. In India, *Thrips palmi*, *Frankliniella schultzei*, and *Scirtothrips dorsalis* are the major vector species involved in disease spread. TSWV is transmitted in a persistent-propagative manner, where virus acquisition occurs only during larval stages, followed by replication within the vector and lifelong transmission by adults (Whitfield et al., 2005; Funderburk et al., 2010). This unique transmission mechanism complicates management, as targeting adult thrips alone does not effectively disrupt the disease cycle. Environmental factors such as temperature, humidity, cropping patterns, and weed flora strongly influence thrips population dynamics and virus dissemination. Continuous cultivation of susceptible crops, overlapping growing seasons, and indiscriminate insecticide use have exacerbated TSWV outbreaks by promoting vector multiplication and insecticide resistance (Pappu et al., 2009). At the molecular level, viral proteins such as the non-structural protein NSs play a critical role in suppressing host RNA silencing and facilitating systemic infection (Takeda et al., 2002; Chen & Zhou, 2019). Despite progress in understanding virus–vector–host interactions, gaps remain in knowledge of molecular diversity of Indian isolates, vector competence, and host resistance mechanisms. Integrated, region-specific management strategies are therefore essential for sustainable control of TSWV in India.

2. TAXONOMY AND GENOME ORGANIZATION

2.1 Taxonomy and Classification of Tomato Spotted Wilt Virus

Tomato spotted wilt virus (TSWV) holds a unique and historically significant position in plant virology. It was among the earliest plant viruses shown to be transmitted by insect vectors and represents the first plant-infecting virus recognized within the order *Bunyavirales*. Since its initial discovery, advances in molecular biology, genome sequencing, and phylogenetic analysis have greatly refined the taxonomic understanding of TSWV, leading to its current classification within the genus *Orthotospovirus*.

According to the latest classification by the International Committee on Taxonomy of Viruses (ICTV), TSWV is placed in the genus *Orthotospovirus*, family *Tospoviridae*, order *Bunyavirales* (ICTV, 2023). Previously, TSWV and related viruses were grouped under the genus *Tospovirus* within the family *Bunyaviridae*. However, comparative genomic and phylogenetic studies revealed that plant-infecting tospoviruses differ markedly from animal-infecting bunyaviruses in genome expression strategies, host specificity, vector relationships, and evolutionary history (Adkins, 2000; Pappu et al., 2009). These findings prompted a major taxonomic revision, resulting in the creation of the family *Tospoviridae* and the renaming of the genus as *Orthotospovirus*, better reflecting evolutionary divergence and plant–thrips adaptation.

Viruses belonging to the genus *Orthotospovirus* are characterized by enveloped, quasi-spherical virions containing a tripartite single-stranded RNA genome of negative or ambisense polarity. The genome is divided into Large (L), Medium (M), and Small (S) RNA segments, which encode the RNA-dependent RNA polymerase (RdRp), envelope glycoproteins and movement protein, and the nucleocapsid protein along with a silencing suppressor, respectively (Whitfield et al., 2005; Jain et al., 2010). These molecular features clearly distinguish orthotospoviruses from other members of the order *Bunyavirales*. The genus includes several economically important plant viruses transmitted exclusively by thrips in a persistent propagative manner, such as Tomato spotted wilt virus (TSWV), Groundnut bud necrosis virus (GBNV), Capsicum chlorosis virus (CaCV), Watermelon silver mottle virus (WSMoV), Iris yellow spot virus (IYSV), Peanut chlorotic fan-spot virus (PCFSV), and Melon yellow spot virus (MYSV) (Pappu et al., 2009; Mandal et al., 2012). Among these, TSWV is the most widely distributed and extensively studied species and serves as the type species of the genus *Orthotospovirus*.

2.2 Genome Organization and Structure of TSWV

Tomato spotted wilt virus possesses a tripartite, single-stranded RNA genome encapsidated within quasi-spherical, membrane-bound virions measuring approximately 80–120 nm in diameter. The virions are enveloped and contain surface glycoprotein spikes embedded in a lipid bilayer derived from host cell membranes. Each genomic RNA segment is encapsidated by the viral nucleocapsid (N) protein and is associated with the viral RNA-dependent RNA polymerase, forming ribonucleoprotein (RNP) complexes essential for replication and transcription (Adkins, 2000; Whitfield et al., 2005). The L segment is of negative-sense polarity, whereas the M and S segments exhibit ambisense coding strategies, a defining feature of orthotospoviruses (Pappu et al., 2009; Tatineni et al., 2014).

Large (L) RNA Segment

The L RNA segment is approximately 8.9 kb in length and contains a single open reading frame encoding the RNA-dependent RNA polymerase (RdRp). This multifunctional enzyme catalyzes viral genome replication and transcription using a cap-snatching mechanism, in which capped leader sequences are cleaved from host mRNAs and utilized as primers for viral mRNA synthesis (Adkins, 2000). The RdRp contains conserved motifs characteristic of bunyaviral polymerases, including domains involved in RNA binding and catalytic activity. Due to its functional importance and relative sequence conservation, the RdRp gene is frequently used in phylogenetic and molecular epidemiological analyses of TSWV isolates from different geographical regions, including India (Mandal et al., 2012; Jain & Mandal, 2018).

Medium (M) RNA Segment

The M RNA segment is approximately 4.8 kb in length and follows an ambisense coding strategy, encoding two proteins in opposite orientations separated by an intergenic region. One open reading frame encodes a glycoprotein precursor that is post-translationally cleaved into two envelope glycoproteins, Gn and Gc, within the endoplasmic reticulum and Golgi apparatus. These glycoproteins are embedded in the viral envelope and are essential for virion assembly, budding, and virus–vector interactions. In thrips vectors, Gn and Gc mediate virus attachment to midgut epithelial cells and subsequent dissemination to the salivary glands, thereby determining vector competence and transmission efficiency (Whitfield et al., 2005). The second open reading frame encodes the non-structural movement protein (NSm), which is required for cell-to-cell movement of the virus in infected plant tissues. NSm interacts with host cytoskeletal components and modifies plasmodesmata, enabling the transport of viral RNP complexes. A characteristic feature of NSm is its ability to form tubule-like structures that facilitate intercellular movement (Storms et al., 1995; Pappu et al., 2009).

Small (S) RNA Segment

The S RNA segment, approximately 2.9 kb in length, also exhibits an ambisense coding strategy. One open reading frame encodes the nucleocapsid (N) protein, which encapsidates viral RNA segments to form stable RNP complexes and plays a crucial role in replication, transcription, and virion assembly. Due to its high conservation and immunogenicity, the N protein is widely used in serological diagnostic assays such as ELISA (Adkins, 2000). The second open reading frame encodes the non-structural protein NSs, a major virulence determinant and potent suppressor of RNA silencing. By inhibiting the RNA interference pathway, NSs facilitates viral accumulation and systemic infection. Genetic variability in the NSs gene has been associated with differences in virulence, host range, and adaptation among TSWV isolates, including those reported from India (Takeda et al., 2002; Mandal et al., 2012).

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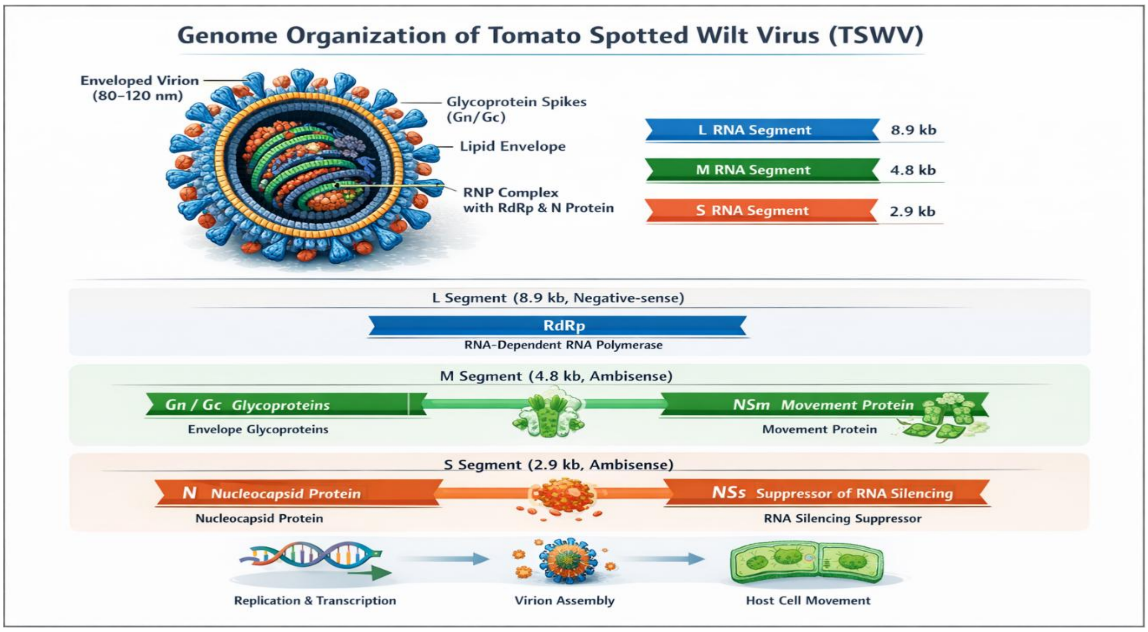

Fig. 1. Genome Organization of Tomato spotted wilt virus (TSWV)

3. TOMATO SPOTTED WILT VIRUS (TSWV) MAJOR VECTORS IN INDIA

3.1 Vectors of Tomato spotted wilt virus (TSWV)

Table 1. Major thrips vectors of Tomato spotted wilt virus (TSWV) in India and their crop associations

Thrips species	Vector status for TSWV	Major host crops	Agro-climatic distribution in India	Remarks
Thrips palmi Karny	Primary vector	Chilli, tomato, brinjal, cucurbits, groundnut, legumes	Widely distributed in tropical and subtropical regions (South, Central, Eastern India)	Highly polyphagous; high transmission efficiency; rapid population buildup; insecticide resistance common
Frankliniella schultzei (Trybom)	Primary vector	Tomato, groundnut, chilli, ornamentals	Southern, Central and Western India	Dark morph predominant in warm regions; aggressive feeding behavior
Scirtothrips dorsalis Hood	Secondary vector	Chilli, cotton, mango, ornamentals	Pan-India, especially warm and semi-arid regions	Important in mixed cropping systems; lower transmission efficiency
Frankliniella occidentalis (Pergande)	Primary (global) / emerging in India	Tomato, capsicum, ornamentals	Restricted but expanding; mainly polyhouses and greenhouses	Highly efficient vector; multiple insecticide resistance

3.2 Mode of Transmission

Tomato spotted wilt virus (TSWV) is transmitted by thrips in a **persistent, propagative** manner, a transmission mode that clearly distinguishes orthotospoviruses from many other plant viruses that are transmitted in non-persistent or semi-persistent fashions. This specialized virus–vector relationship involves virus acquisition during specific developmental stages of the insect, replication within vector tissues, and lifelong infectivity of viruliferous adults, thereby playing a central role in TSWV epidemiology.

Acquisition Phase

Acquisition of TSWV occurs **exclusively during the larval stages** of thrips, particularly the first and second instars, while feeding on infected plant tissues. Numerous experimental studies have demonstrated that adult thrips are incapable of acquiring the virus, even after prolonged feeding on infected hosts. However, thrips that acquire TSWV during the larval stage retain the virus through subsequent molts and remain infective throughout their adult lifespan. This phenomenon, known as **transracial persistence**, has profound epidemiological significance, as it highlights the importance of early larval feeding sites in disease initiation and spread (Ullman et al., 1997; German et al., 1992; Oliver, & Whitfield, 2016). The restriction of virus acquisition to larval stages is attributed to physiological and cellular differences between larval and adult thrips, particularly in the midgut epithelium. As a result, populations with high larval density feeding on infected plants act as primary drivers of TSWV epidemics in the field.

Latent Period and Replication

Following acquisition, TSWV undergoes a **latent period** within the thrips vector during which active viral replication occurs. Initial replication is localized in the **midgut epithelial cells** of the larva, after which the virus disseminates to other tissues, including the visceral muscles and salivary glands. The ability of TSWV to replicate within vector tissues confirms its **propagative nature**, a characteristic feature of orthotospoviruses (Ullman et al., 1993; Whitfield et al., 2005; Jones, 2005). Replication within the salivary glands is essential for successful transmission to plants. Once the virus reaches and multiplies

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in these tissues, the thrips becomes permanently viruliferous. Importantly, there is no evidence of transovarial transmission of TSWV, meaning that each generation of thrips must acquire the virus anew from infected plants (Kritzman et al., 2002).

Inoculation Phase

Transmission of TSWV to healthy plants occurs when **viruliferous adult thrips** feed on susceptible host tissues. During feeding, virus-containing saliva is injected into epidermal and mesophyll cells, initiating infection. Even brief feeding probes are sufficient for successful virus inoculation, making chemical control of vectors particularly challenging once adults become viruliferous (Ullman et al., 2002). The efficiency of inoculation is influenced by several factors, including thrips species, virus isolate, host plant susceptibility, and environmental conditions. High vector competence combined with rapid thrips population growth often results in explosive disease outbreaks, especially in warm climates and intensive cropping systems such as those prevalent in India. Overall, the persistent–propagative transmission mechanism of TSWV underpins its epidemiological success and presents significant challenges for disease management, emphasizing the need for integrated strategies targeting both vector populations and virus sources.

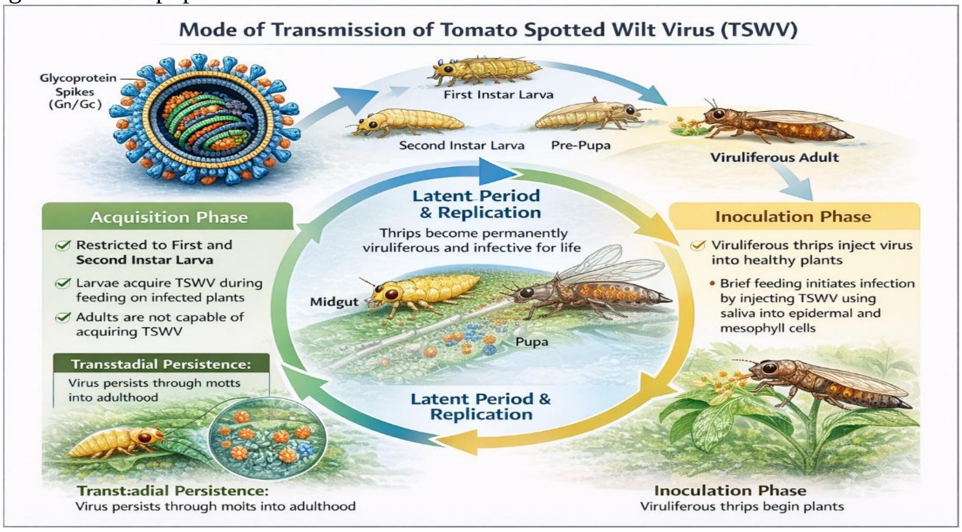

Fig. 2. Mode of Transmission of Tomato spotted wilt virus (TSWV)

3.3 Epidemiological Role of Thrips

Thrips play a central epidemiological role in the transmission and spread of Tomato spotted wilt virus (TSWV), acting as its only known vectors. The virus is acquired exclusively during larval stages and is transmitted in a persistent–propagative manner throughout the adult life of the insect (Whitfield et al., 2005). In India, *Thrips palmi*, *Frankliniella schultzei*, and *Scirtothrips dorsalis* are major vectors, differing in transmission efficiency depending on species, developmental stage, and environmental conditions (Mandal et al., 2012; Cortês et al. 1998). Their polyphagous nature, high reproductive rate, and continuous presence on crops and weeds facilitate virus persistence and drive severe TSWV epidemics (Pappu et al., 2009).

Table 2. Epidemiological role of thrips vectors in TSWV transmission in India

Parameter	*T. palmi*	*F. schultzei*	*S. dorsalis*	*F. occidentalis*
Mode of transmission	Persistent, propagative	Persistent, propagative	Persistent, propagative	Persistent, propagative
Virus acquisition stage	Larval instars (I & II)	Larval instars	Larval instars	Larval instars
Adult transmission	Yes	Yes	Yes	Yes
Transmission efficiency	High	High	Moderate	Very high
Importance under Indian conditions	Very high	High	Moderate	Increasing (protected cultivation)

Table 3. Crop–vector–region relationships influencing TSWV epidemics in India

Crop	Dominant vector(s)	Major affected regions	Epidemiological significance
Tomato	T. palmi, F. schultzei, F. occidentalis	Karnataka, Maharashtra, Andhra Pradesh, Tamil Nadu	Severe yield losses; rapid secondary spread
Chilli	T. palmi, S. dorsalis	Telangana, Andhra Pradesh, Maharashtra	Mixed infections common; year-round disease pressure
Groundnut	F. schultzei, T. palmi	Andhra Pradesh, Gujarat, Tamil Nadu	Often associated with Groundnut bud necrosis virus
Ornamentals	F. occidentalis, F. schultzei	Protected cultivation across India	Acts as virus reservoir

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4. EPIDEMIOLOGICAL CYCLE OF TOMATO SPOTTED WILT VIRUS IN INDIA

4.1 Epidemiological Cycle

The epidemiology of Tomato spotted wilt virus (TSWV) in India is governed by a complex and dynamic interaction among the virus, thrips vectors, host plant diversity, cropping systems, and environmental conditions. The ability of TSWV to infect a wide range of cultivated crops and wild plant species enables its continuous survival and dissemination across diverse agro-ecological zones of the country. Multiple vegetable crops such as tomato, chilli, brinjal, groundnut, and ornamentals, along with numerous weed species, serve as reservoirs for both the virus and its thrips vectors, ensuring year-round virus persistence (Pappu et al., 2009; Mandal et al., 2012, Bhaskara et. al. 2014).

Weed hosts and volunteer crop plants play a particularly critical role during off-seasons by acting as "green bridges" that facilitate survival of viruliferous thrips populations. Species such as *Parthenium hysterophorus*, *Ageratum conyzoides*, *Solanum nigrum*, and *Datura stramonium* have been reported to harbor TSWV and support vector populations, thereby initiating primary infection foci at the onset of cropping seasons (Ghotbi et al., 2005; Jain & Mandal, 2018). Seasonal fluctuations in thrips populations strongly influence TSWV epidemics in India. In most regions, thrips populations peak during warm and dry periods, particularly from February to April and from October to December. These periods coincide with optimal temperatures for thrips development and reproduction and often overlap with critical growth stages of tomato and chilli crops, resulting in high disease incidence and rapid secondary spread (Jones, 2005; Riley et al., 2011). Conversely, heavy rainfall during monsoon seasons tends to suppress thrips populations, temporarily reducing disease pressure.

Cropping practices prevalent in Indian agriculture significantly contribute to the epidemiological cycle of TSWV. Staggered planting schedules, overlapping crop cycles, and mixed cropping systems maintain a continuous availability of susceptible hosts, facilitating uninterrupted virus transmission. The widespread cultivation of susceptible hybrids lacking durable resistance further exacerbates disease spread (Prins & Goldbach, 1998; Srinivasan et al., 2012). In recent years, the rapid expansion of protected cultivation systems such as polyhouses and greenhouses has added a new dimension to TSWV epidemiology in India. These environments provide stable temperatures, reduced rainfall, and abundant host plants, creating ideal conditions for thrips survival, reproduction, and virus transmission. The introduction and establishment of highly efficient vectors such as *Frankliniella occidentalis* in protected cultivation systems pose a serious threat to intensive vegetable production (Morse & Hoddle, 2006; Rotenberg et al., 2015).

Overall, the epidemiological cycle of TSWV in India is sustained by continuous host availability, efficient vector transmission, favorable climatic conditions, and intensive cropping practices. Understanding these interconnected factors is essential for developing region-specific, sustainable disease management strategies.

4.2 Factors Influencing Disease Spread of Tomato Spotted Wilt Virus in India

The spread and severity of Tomato spotted wilt virus (TSWV) in India are governed by a complex interplay of **biotic and abiotic factors** that affect both the virus and its thrips vectors. Understanding these factors is essential for designing effective disease management strategies.

Temperature

Temperature is a critical determinant of both vector and virus dynamics. Higher temperatures accelerate the development and reproductive rate of thrips, particularly *Thrips palmi* and *Frankliniella schultzei*, which in turn increases the rate of TSWV transmission (Jones, 2005; Riley et al., 2011). Moreover, virus replication within the vector is temperature-dependent, with higher temperatures shortening the latent period and enhancing viral titers in salivary glands, leading to increased inoculation efficiency (Ullman et al., 2002; Whitfield et al., 2005).

Relative Humidity

Moderate relative humidity (50–70%) favors thrips survival, feeding activity, and reproduction, thereby enhancing virus spread (Morse & Hoddle, 2006; Reitz, 2009). Conversely, extreme humidity, either very low (<30%) or very high (>85%), negatively impacts thrips populations and mobility, indirectly reducing TSWV transmission (Funderburk et al., 2016; Mound, 2005).

Host Plant Diversity

The presence of multiple cultivated and wild host plants significantly contributes to TSWV epidemiology in India. Wild weeds, volunteer crops, and mixed cropping systems act as reservoirs for both the virus and viruliferous thrips during off-season periods, facilitating early-season outbreaks and continuous epidemic cycles (Pappu et al., 2009; Mandal et al., 2012; Jain & Mandal, 2018). Key reservoir species reported include *Parthenium hysterophorus*, *Ageratum conyzoides*, *Solanum nigrum*, and *Datura stramonium* (Ghotbi et al., 2005; Srinivasan et al., 2012).

Insecticide Resistance

The indiscriminate and repeated application of insecticides has resulted in the development of resistance in major thrips vectors. Resistant populations of *T. palmi*, *F. schultzei*, and *F. occidentalis* reduce the efficacy of chemical control strategies, thereby facilitating ongoing virus transmission and disease outbreaks (Reitz, 2009; Seal et al., 2010; Rotenberg et al., 2015; Srinivasan, et al., 2015). Resistance management strategies, including rotation of insecticides with different modes of action and integration with biological control, are crucial for reducing disease spread.

Climate Change

Changing climatic conditions, including higher mean temperatures and altered precipitation patterns, are expanding the geographic range of thrips vectors in India. This shift results in extended cropping periods, higher vector population densities, and increased frequency and intensity of TSWV epidemics (Dietzgen et al., 2016; Kormelink et al., 2011; Pappu et al., 2009). Modeling studies suggest that climate variability may favor early establishment of thrips in northern and central India, which historically had lower disease pressure.

Other Contributing Factors

Additional factors influencing the spread of Tomato spotted wilt virus (TSWV) include overlapping and staggered cropping patterns that ensure continuous availability of susceptible hosts, thereby sustaining virus and vector populations throughout the year, as well as the rapid expansion of protected cultivation systems such as polyhouses and greenhouses, which create stable microclimates favorable for thrips survival and efficient virus transmission. The high mobility of thrips further accelerates secondary spread through frequent dispersal between crops, particularly under warm and dry conditions, while genetic diversity among TSWV isolates contributes to variability in virulence, host range, and transmission efficiency. Collectively, these interacting environmental, biological, and anthropogenic factors drive TSWV epidemics in India and underscore the need for integrated management strategies that incorporate vector ecology, climatic influences, host diversity, and insecticide resistance dynamics.

5. HOST RANGE AND ECONOMIC LOSSES

The **persistent–propagative transmission** of Tomato spotted wilt virus (TSWV) by thrips, combined with the extensive host range of both the virus and its vectors, presents a significant challenge for disease management in India. TSWV infects a wide variety of **solanaceous, cucurbitaceous, and leguminous crops,** as well as ornamental plants and weed species, allowing continuous virus survival and efficient spread throughout the cropping season (Pappu et al., 2009; Mandal et al., 2012).

5.1. Host Range

In India, the host range of Tomato spotted wilt virus (TSWV) is extensive and includes several economically important plant species. Among vegetable crops, tomato (*Solanum lycopersicum*), chilli (*Capsicum annuum*), brinjal (*Solanum melongena*), cucumber (*Cucumis sativus*), okra (*Abelmoschus esculentus*), and beans (*Phaseolus vulgaris*) are commonly affected (Jain & Mandal, 2018; Srinivasan et al., 2012). Groundnut and other oilseeds are also significant hosts, with groundnut (*Arachis hypogaea*) being severely impacted by Groundnut bud necrosis virus (GBNV), a virus closely related to TSWV that shares similar thrips vectors and epidemiological characteristics (Pappu et al., 2009). In the case of ornamental crops, marigold (*Tagetes* spp.), sunflower (*Helianthus annuus*), chrysanthemum (*Chrysanthemum* spp.), and gerbera (*Gerbera jamesonii*) have been reported as important hosts, particularly under protected cultivation conditions (Morse & Hoddle, 2006). Additionally, several weeds and wild hosts, including *Parthenium hysterophorus*, *Ageratum conyzoides*, *Datura stramonium*, and *Solanum nigrum*, serve as reservoirs for both TSWV and its thrips vectors, enabling virus survival during off-season periods and facilitating disease carryover (Ghotbi et al., 2005; Rotenberg et al., 2015). This wide host range allows TSWV to persist even in the absence of main crops, thereby promoting primary inoculum buildup and contributing to early-season epidemics.

5.2. Economic Losses

TSWV causes substantial economic losses in India through yield reduction, deterioration of marketable quality, and outright crop rejection under both field and protected cultivation systems. In **tomato and chilli**, infection is characterized by necrotic spots, leaf chlorosis, stunted plant growth, and fruit malformation, often resulting in yield losses ranging from 30–60% during severe outbreaks (Mandal et al., 2012; Jain & Mandal, 2018). In **groundnut**, although the crop is predominantly affected by Groundnut bud necrosis virus (GBNV), TSWV also contributes to poor pod filling and reduced seed quality, leading to yield losses of approximately 20–50% (Pappu et al., 2009). The impact is particularly severe in **ornamental crops**, where symptoms such as flower deformation, concentric ring spots, and stunting drastically reduce aesthetic value and marketability, with losses exceeding 40–70% in high-density greenhouse and protected cultivation systems (Morse & Hoddle, 2006). In **mixed cropping systems,** especially in regions with overlapping susceptible hosts, TSWV epidemics can result in compounded economic losses due to continuous secondary spread between different crop species (Srinivasan et al., 2012). These losses are further exacerbated by the high costs associated with repeated chemical control measures targeting thrips vectors and the frequent need to replant severely affected crops, a burden that is particularly heavy for smallholder farming systems.

Table 4. Host Range, Symptoms, and Economic Impact of Tomato Spotted Wilt Virus (TSWV) in India

Host Category	Host Species (India)	Symptoms	Estimated Yield Loss (%)	References
Vegetable Crops	Tomato (Solanum lycopersicum), Chilli (Capsicum annuum), Brinjal (Solanum melongena), Cucumber (Cucumis sativus), Okra (Abelmoschus esculentus), Beans (Phaseolus vulgaris)	Necrotic spots, leaf chlorosis, stunted growth, fruit malformation	30–60%	Mandal et al., 2012; Jain & Mandal, 2018
Groundnut & Oilseeds	Groundnut (Arachis hypogaea)	Reduced pod fill, poor seed quality	20–50%	Pappu et al., 2009
Ornamentals	Marigold (Tagetes spp.), Sunflower (Helianthus annuus), Chrysanthemum (Chrysanthemum spp.), Gerbera (Gerbera jamesonii)	Flower deformation, ring spots, stunting	40–70%	Morse & Hoddle, 2006
Weeds & Wild Hosts	Parthenium hysterophorus, Ageratum conyzoides, Datura stramonium, Solanum nigrum	Act as virus reservoirs, asymptomatic or mild symptoms	N/A	Ghotbi et al., 2005; Rotenberg et al., 2015
Mixed Cropping Systems	Multiple overlapping crops	Compounded secondary spread, reduced yield	Variable	Srinivasan et al., 2012

6. SYMPTOMATOLOGY

The symptoms of Tomato spotted wilt virus (TSWV) infection are highly variable and depend on host species, cultivar, plant age at the time of infection, virus isolate, vector pressure, and environmental conditions. Across susceptible hosts, typical symptoms include chlorosis, necrosis, bronzing, mosaic patterns, concentric ring spots, stunting, and various growth

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abnormalities (Adkins, 2000; Pappu et al., 2009).

6.1. Foliar Symptoms

Early symptoms usually appear on young leaves as chlorotic or bronze discoloration, which later progresses to necrotic spots, streaks, and patches. Concentric ring spots and line patterns, considered diagnostic for TSWV infection, are commonly observed on the leaves of tomato, chilli, capsicum, and several ornamental crops. In severe infections, extensive leaf necrosis and deformation may occur, often leading to premature leaf drop (German et al., 1992; Mumford et al., 2003).

6.2. Stem and Bud Symptoms

Necrosis of terminal buds is a characteristic symptom in crops such as groundnut and chilli, resulting in the arrest of apical growth and the proliferation of lateral shoots, giving plants a bushy appearance. Stem necrosis, brown streaking, and collapse of growing points are frequently observed under high virus pressure or early infection, significantly reducing plant vigor and yield potential (Jain & Mandal, 2018; Mandal et al., 2012).

6.3. Fruit Symptoms

In tomato and capsicum, fruits often exhibit concentric ring spots, chlorotic or necrotic blotches, surface deformities, and uneven ripening. Infected fruits are generally smaller, malformed, and unsuitable for fresh consumption or processing, resulting in substantial economic losses. Fruit symptoms are particularly important from a marketability perspective, as even mild visual defects can render produce unmarketable (Adkins, 2000; Pappu et al., 2009).

7. VIRUS–HOST INTERACTIONS

The interaction between Tomato spotted wilt virus (TSWV) and its plant hosts is complex and involves multiple molecular and physiological processes that determine the outcome of infection. Successful infection depends on the ability of the virus to overcome host defense mechanisms, replicate efficiently, and move systemically within the plant. The severity of disease symptoms is influenced by host genotype, virus strain, plant developmental stage, and environmental conditions (Adkins, 2000; Pappu et al., 2009).

7.1. Host Defense Responses

Plants have evolved sophisticated defense mechanisms to restrict viral infection, including basal immunity, RNA silencing, and hypersensitive responses mediated by resistance (R) genes. Among these, RNA silencing represents the primary antiviral defense in plants. During TSWV infection, double-stranded RNA intermediates generated during viral replication are recognized by the host silencing machinery, leading to the production of small interfering RNAs (siRNAs) that guide the sequence-specific degradation of viral RNA (Ding & Voinnet, 2007; Latham, & Jones, 2019; Prins, et al., 2021) In response, TSWV has evolved counter-defense strategies to suppress host RNA silencing. The non-structural protein NSs, encoded by the S RNA segment, functions as a potent suppressor of RNA silencing. NSs binds siRNAs and interferes with their incorporation into the RNA-induced silencing complex (RISC), thereby inhibiting effective antiviral defense and promoting viral accumulation (Takeda et al., 2002; Bucher et al., 2003). Studies on Indian TSWV isolates have revealed considerable variability in NSs sequences, which may contribute to differences in virulence, host range, and adaptation under diverse agro-climatic conditions (Mandal et al., 2012; Jain & Mandal, 2018).

7.2 Role of Viral Proteins

Several TSWV-encoded proteins play critical roles in pathogenicity and symptom expression. The nucleocapsid protein (N) is essential for viral RNA encapsidation, replication, and virion assembly, and also interacts with host proteins involved in intracellular trafficking and virus accumulation (Adkins, 2000). The non-structural movement protein NSm facilitates both cell-to-cell and systemic movement of the virus by modifying plasmodesmata and forming tubule-like structures that transport viral ribonucleoprotein complexes between adjacent cells (Storms et al., 1995; Pappu et al., 2009). The envelope glycoproteins Gn and Gc are primarily involved in virus assembly and thrips-mediated transmission; however, emerging evidence suggests that these proteins may also indirectly influence host cellular responses and symptom development by affecting virus localization and accumulation (Whitfield et al., 2005).

7.3 Host Resistance and Resistance Breakdown

Host resistance to TSWV is governed by both qualitative and quantitative genetic factors. In tomato, resistance genes such as *Sw-5* have been widely deployed in breeding programmes. The *Sw-5* gene confers resistance by recognizing the NSm protein and triggering a hypersensitive response that restricts virus replication and movement (Spassova et al., 2001; Chaisuekul et al., 2003; Peiró et al., 2014). In India, the deployment of *Sw-5*-based resistance in tomato hybrids has provided partial and region-specific control of TSWV; however, resistance-breaking isolates have been reported from several tomato-growing regions, raising concerns about the durability of single-gene resistance (Mandal et al., 2012; Jain & Mandal, 2018). In crops such as chilli and groundnut, strong and stable sources of resistance are limited, and most commercially cultivated varieties remain highly susceptible. Elucidating the molecular basis of host resistance, virus evolution, and resistance breakdown under Indian conditions remains a major research priority.

8. DIAGNOSIS OF TSWV

8.1. Importance of Accurate Diagnosis

Accurate and early diagnosis of Tomato spotted wilt virus (TSWV) is a critical component of effective disease management and epidemiological surveillance. The wide host range of the virus, coupled with highly variable symptom expression, often leads to misdiagnosis in the field. Symptoms of TSWV infection may resemble those caused by nutrient deficiencies, herbicide injury, or other viral and fungal diseases. Therefore, reliable diagnostic tools are essential for confirming infection, assessing disease incidence, and implementing timely management strategies (Mumford et al., 2003; Pappu et al., 2009; Mandal et al., 2020). In India, the increasing economic importance of TSWV has driven the adoption of both conventional and advanced diagnostic techniques. These methods differ in sensitivity, specificity, cost, and suitability for field or laboratory application (Mandal et al., 2012).

8.2. Symptom-Based and Biological Diagnosis

Visual assessment of symptoms is often the first step in diagnosing TSWV in the field. Characteristic symptoms such as chlorotic and necrotic ring spots, bronzing of leaves, bud necrosis, and fruit deformation can provide preliminary indications of infection. However, symptom expression is strongly influenced by host genotype, plant age, environmental conditions, and virus isolate, making visual diagnosis unreliable as a standalone method (Adkins, 2000; German et al., 1992). Biological indexing using indicator plants such as *Nicotiana benthamiana*, *N. tabacum*, and *Petunia hybrida* has historically been used to confirm TSWV infection. Inoculated indicator

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plants typically develop systemic necrosis, chlorosis, or local lesions. Although biological assays are valuable for research and virus characterization, they are time-consuming and impractical for large-scale field diagnosis (Mumford et al., 2003).

8.3. Serological Diagnostic Methods

Enzyme-Linked Immunosorbent Assay (ELISA)

Double antibody sandwich enzyme-linked immunosorbent assay (DAS-ELISA) is one of the most widely used serological methods for TSWV detection in India. The technique is based on the specific interaction between viral antigens, mainly the nucleocapsid (N) protein, and virus-specific antibodies. DAS-ELISA is relatively simple, cost-effective, and suitable for large-scale screening of plant samples (Clark & Adams, 1977; Adkins, 2000). Commercial ELISA kits for TSWV are routinely used by research institutions, seed companies, and diagnostic laboratories in India. While the method is effective for detecting virus in symptomatic plants, it may fail to detect low virus titers during early or latent stages of infection (Mandal et al., 2012; Jain & Mandal, 2018).

Dot Immunobinding Assay (DIBA)

Dot immunobinding assay (DIBA) is a rapid and inexpensive serological technique used for preliminary screening of TSWV. Plant extracts are spotted onto nitrocellulose membranes and probed with virus-specific antibodies. Although less sensitive than ELISA, DIBA is useful for rapid surveys and diagnosis under resource-limited conditions (Hampton et al., 1990; Mandal et al., 2012).

8.4. Molecular Diagnostic Techniques

Reverse Transcription Polymerase Chain Reaction (RT-PCR)

RT-PCR is a highly sensitive and specific method for detecting TSWV and has become a standard diagnostic tool in Indian laboratories. Primers targeting conserved regions of the N, NSs, or NSm genes are commonly used. RT-PCR enables detection of TSWV in asymptomatic plants and is frequently employed to confirm serological results (Mumford et al., 1996; Pappu et al., 2009). Several studies in India have used RT-PCR to detect and characterize TSWV isolates from tomato, chilli, groundnut, and ornamental crops, contributing to a better understanding of virus diversity and distribution (Mandal et al., 2012; Jain & Mandal, 2018; Batuman, et. al., 2014).

Quantitative Real-Time RT-PCR (qRT-PCR)

Quantitative real-time RT-PCR (qRT-PCR) provides enhanced sensitivity and allows precise quantification of viral RNA in infected tissues. This technique is particularly useful for epidemiological studies, resistance screening, and analysis of virus–host interactions. In India, qRT-PCR has been applied to study virus accumulation in resistant and susceptible cultivars and to monitor virus load in thrips vectors (Whitfield et al., 2005; Mandal et al., 2012; Zhou, et al., 2017). Despite its advantages, the requirement for specialized equipment and technical expertise restricts its routine use to well-equipped laboratories.

8.5. Isothermal Amplification Techniques

Loop-Mediated Isothermal Amplification (LAMP)

Loop-mediated isothermal amplification (LAMP) is a rapid, sensitive, and field-deployable molecular diagnostic technique that has gained attention in recent years. LAMP assays for TSWV detection have been developed using primers targeting conserved genomic regions and can be completed within a short time under isothermal conditions (Notomi et al., 2000). In India, LAMP-based detection of TSWV has shown promise for rapid screening of nursery seedlings and field samples, facilitating early disease detection and timely management interventions (Mandal et al., 2012; Jain & Mandal, 2018).

Table 5. Diagnostic methods for detection of Tomato spotted wilt virus (TSWV) and their applicability under Indian conditions

Diagnostic Category	Method	Principle	Sensitivity / Specificity	Advantages	Limitations	References
Symptom-based diagnosis	Visual field diagnosis	Identification based on characteristic symptoms such as chlorotic and necrotic ring spots, bronzing, bud necrosis, and fruit deformation	Low / Low	Rapid, no equipment required, useful for preliminary assessment	Symptoms highly variable; easily confused with nutrient deficiencies, herbicide injury, or other diseases	Adkins (2000); German et al. (1992)
Biological diagnosis	Indicator plants (*Nicotiana benthamiana*, *N. tabacum*, *Petunia hybrida*)	Mechanical inoculation and observation of characteristic symptoms	Moderate / Moderate	Useful for virus characterization and research studies	Time-consuming, labor-intensive, unsuitable for large-scale diagnosis	Mumford et al. (2003)
Serological methods	DAS-ELISA	Antigen–antibody reaction targeting nucleocapsid (N) protein	Moderate / High	Cost-effective, suitable for large-scale screening, widely used in India	Low sensitivity in early or latent infections	Clark & Adams (1977); Adkins (2000); Mandal et al. (2012)
	DIBA	Dot blot immunoassay using virus-specific antibodies	Low–Moderate / Moderate	Rapid, inexpensive, minimal equipment required	Less sensitive than ELISA; qualitative results	Hampton et al. (1990); Mandal et al. (2012)
Molecular methods	RT-PCR	Amplification of viral RNA targeting N, NSs, or NSm genes	High / Very high	Detects low virus titers; suitable for asymptomatic plants; confirmatory test	Requires laboratory facilities and skilled personnel	Mumford et al. (1996); Pappu et al. (2009)
	qRT-PCR	Quantitative amplification of viral RNA	Very high / Very high	Highly sensitive; allows virus quantification; useful for epidemiological and resistance studies	Expensive equipment; limited to advanced laboratories	Whitfield et al. (2005); Mandal et al. (2012)
Isothermal amplification	LAMP	Isothermal amplification using multiple primers	High / High	Rapid, field-deployable, no thermal cycler required	Primer design complex; limited standardization	Notomi et al. (2000); Mandal et al. (2012); Jain & Mandal (2018)

Detection of TSWV in Thrips Vectors

Detection of TSWV in thrips vectors is essential for understanding disease epidemiology and assessing vector competence. Both ELISA and RT-PCR have been successfully used to detect viral antigens or RNA in individual thrips or pooled samples. Molecular detection in vectors provides insights into virus acquisition efficiency, latent periods, and transmission dynamics under field conditions (Ullman et al., 1993; Whitfield et al., 2005).Such vector-based diagnostics are particularly valuable in predicting disease outbreaks and developing integrated management strategies targeting both virus and vector populations.

9. INTEGRATED DISEASE MANAGEMENT OF TSWV

9.1 Need for IDM

Management of Tomato spotted wilt virus (TSWV) is particularly challenging due to the absence of curative treatments, wide host range, and efficient thrips-mediated transmission. Reliance on any single control strategy, especially chemical control of vectors, has consistently proven inadequate and unsustainable under Indian agro-climatic conditions. Therefore, Integrated Disease Management (IDM) approaches that combine multiple compatible strategies are essential for effective and long-term suppression of TSWV (Pappu et al., 2009; Mandal et al., 2012; Whitfield et al., 2005).

9.2 Cultural Management Practices

Virus-Free Planting Material

The use of virus-free seedlings is one of the most critical components of TSWV management. Infection at the nursery stage often leads to severe disease outbreaks in the field. Raising seedlings in insect-proof net houses, using sterile growing media, and regular monitoring for thrips infestation significantly reduce primary infection sources (Jain & Mandal, 2018; Pappu et al., 2009). Nursery certification programmes and strict phytosanitary measures are particularly important for tomato, chilli, and ornamental crops.

Planting Time

Altering planting dates to avoid peak thrips population periods can significantly reduce disease incidence. In many parts of India, early or delayed planting has been shown to escape severe TSWV epidemics by avoiding periods of high vector activity (Mandal et al., 2012; Riley et al., 2011).

Weed and Alternate Host Management

Weed hosts play a crucial role in maintaining TSWV and thrips populations during off-seasons. Removal of weed species such as *Parthenium hysterophorus*, *Datura stramonium*, and *Solanum nigrum* from field borders and nearby areas helps reduce virus reservoirs (Groves et al., 2001; Pappu et al., 2009).

Reflective Mulches

Reflective plastic mulches repel thrips by disrupting their host-finding behavior. Several studies in India and elsewhere have demonstrated reduced thrips landing rates and lower TSWV incidence in crops grown on silver or aluminum-coated mulches (Summers et al., 2004; Mandal et al., 2012).

9.3. Chemical Control

Insecticides Used in India

Chemical control remains an important component of IDM, particularly during early crop growth stages when plants are most vulnerable to infection. Commonly used insecticides against thrips in India include neonicotinoids, spinosyns, avermectins, and pyridine azomethines. Rotation of insecticides with different modes of action is essential to delay resistance development (IRAC, 2023; Jain & Mandal, 2018 & Ananthakrishnan, T. N., 1993).

Limitations & resistance

Chemical control alone cannot prevent virus transmission because thrips can transmit TSWV within minutes of feeding. Moreover, excessive insecticide use promotes resistance development and adversely affects natural enemies and pollinators, emphasizing the need for judicious use within an IDM framework (Riley et al., 2011; Mandal et al., 2012).

9.4. Biological Control

Biological control offers an environmentally sustainable approach to thrips management. Natural enemies such as predatory mites (*Amblyseius* spp.), minute pirate bugs (*Orius* spp.), and entomopathogenic fungi including *Beauveria bassiana*, *Metarhizium anisopliae*, and *Verticillium lecanii* have shown promising results under Indian conditions (Vijayalakshmi et al., 2014; Mandal et al., 2012). Integration of biopesticides with reduced chemical inputs supports sustainable thrips management.

9.5. Host Plant Resistance

Resistant Varieties

Host resistance is the most effective and economically sustainable strategy for managing TSWV. In tomato, resistance genes such as *Sw-5* have been incorporated into several commercial hybrids cultivated in India, providing protection against many TSWV strains (Stevens et al., 1992; Margaria et al., 2015; Jain & Mandal, 2018). However, resistance-breaking isolates have been reported, necessitating continuous monitoring.

Breeding Challenges

In crops such as chilli and groundnut, strong and durable resistance sources are limited. Breeding programmes focusing on germplasm screening, marker-assisted selection, and pyramiding of resistance genes are ongoing in India (Mandal et al., 2012; Pappu et al., 2009).

9.6. Protected Cultivation and Physical Barriers

In protected cultivation systems, insect-proof nets, double-door entry systems, and strict sanitation practices significantly reduce thrips entry and virus spread. Yellow and blue sticky traps are widely used for monitoring and partial suppression of thrips populations (Cloyd & Sadof, 2000; Jain & Mandal, 2018).

9.7. Regulatory and Quarantine Measures

Strict quarantine regulations are essential to prevent the introduction and spread of virulent TSWV strains and efficient thrips vectors. Certification of planting material, regulation of seedling movement, and continuous surveillance of nurseries are critical components of national disease management strategies (Mumford et al., 2003; Pappu et al., 2009).

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10. FUTURE PERSPECTIVES

Future management of Tomato spotted wilt virus (TSWV) requires a paradigm shift from reactive control measures to predictive, molecularly informed, and climate-resilient strategies. Advances in genomics and bioinformatics offer strong opportunities for **genomics-assisted resistance breeding**, particularly through the identification of novel resistance genes, quantitative trait loci (QTLs), and resistance-breaking variants of TSWV. High-throughput sequencing of Indian TSWV isolates and wild germplasm can accelerate the development of durable, multi-gene resistance and reduce reliance on single resistance sources such as *Sw-5*. Emerging evidence suggests that the **thrips microbiome** plays a significant role in shaping vector fitness, immune responses, and virus transmission efficiency. Understanding interactions between TSWV, thrips-associated symbionts, and host plants could open new avenues for disrupting virus transmission. Manipulation of the thrips microbiome using microbial antagonists or symbiont-based approaches represents a promising but largely unexplored strategy under Indian conditions.Climate change is expected to profoundly influence TSWV epidemiology by altering thrips population dynamics, host distribution, and virus survival. Therefore, **climate-smart Integrated Disease Management (IDM)** strategies that integrate weather-based forecasting, vector surveillance, resistant cultivars, and ecologically sound interventions will be essential. Region-specific models linking climate variables with thrips activity can improve early warning systems and decision-making. Finally, **RNA-based antiviral technologies**, particularly spray-induced gene silencing (SIGS), offer innovative, non-transgenic alternatives for TSWV control. Targeting viral genes or key thrips transmission factors using double-stranded RNA could provide highly specific and environmentally safe disease suppression. Although still in early stages, adapting RNA-based approaches for field-scale application in India represents a promising frontier for sustainable TSWV management.

CONCLUSION

Tomato spotted wilt virus (TSWV) is among the most destructive plant viruses affecting agricultural and horticultural crops in India. Its wide host range, high adaptability, and efficient thrips-mediated persistent–propagative transmission have enabled its spread across diverse agro-ecological regions. The rising incidence in economically important crops such as tomato, chilli, groundnut, and ornamentals highlights TSWV as a major and growing phytopathological threat. The epidemiological success of TSWV in India is driven by multiple interacting factors, including the abundance of competent thrips vectors, continuous host availability due to overlapping cropping seasons, weed reservoirs, favorable climatic conditions, and the expansion of protected cultivation. Dominant vectors such as Thrips palmi and Frankliniella schultzei in open fields, along with the emergence of F. occidentalis in polyhouse systems, have intensified disease pressure. Insecticide resistance in thrips populations further reduces the effectiveness of chemical control and necessitates alternative management approaches.

Advances in molecular biology have enhanced understanding of TSWV genome organization, protein functions, and virus–host–vector interactions. However, important gaps remain regarding the molecular diversity of Indian TSWV isolates, variability in vector competence, climate-driven epidemiological shifts, and the durability of resistance genes such as Sw-5. Strengthening molecular surveillance and genomics-based epidemiological studies is therefore critical. Early and accurate diagnosis remains central to TSWV management. Although ELISA, RT-PCR, qRT-PCR, and LAMP are available, wider adoption of rapid, field-deployable diagnostics is needed for nursery certification and vector monitoring. In the absence of curative measures, sustainable management must rely on integrated disease management strategies combining resistant cultivars, cultural practices, biological control, rational insecticide use, and quarantine measures.

Overall, effective mitigation of TSWV in India requires coordinated, interdisciplinary efforts integrating molecular research, epidemiology, breeding, diagnostics, and farmer-oriented practices to ensure long-term crop productivity and sustainability

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