PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 11(sp4): 01–11
https://doi.org/10.14719/pst.4972

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REVIEW ARTICLE

Rising orthotospovirus incidence in India: Challenges and advances in management

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OPEN ACCESS

ARTICLE HISTORY
Received: 08 March 2024
Accepted: 13 September 2024
Available online
Version 1.0 : 08 November 2024

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
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CITE THIS ARTICLE
Swetha R, Rajinimala N, Yesuraja I, Jeberlin PB, Elanchezhyan K. Rising orthotospovirus incidence in India: Challenges and advances in management. Plant Science Today.2024;11(sp4):01-11. https://doi.org/10.14719/pst.4972

Abstract

Orthotospoviruses (OV) have emerged as a significant agricultural threat in India, posing a severe risk to critical crops, including tomato, chilli, watermelon and groundnut. This review explores the rising incidence of OV, including *Groundnut Bud Necrosis Orthotospovirus* (GBNV), *Watermelon Bud Necrosis Orthotospovirus* (WBNV), *Capsicum Chlorosis Orthotospovirus* (CaCV), *Peanut Yellow Spot Orthotospovirus* (PYSV), *Iris yellow spot Orthotospovirus* (IYSV) and *Tomato Spotted Wilt Orthotospovirus* (TSWV), along with the challenges in their management. These viruses have led to severe yield losses, sometimes causing complete crop failure due to their wide host range and the polyphagous nature of thrips. This further complicates control efforts by facilitating rapid spread across diverse crops and regions. The review highlights the multifaceted challenges in managing OV and thrips, including the lack of durable host resistance, limited diagnostic capabilities, and difficulties in controlling thrips populations. Current management strategies, including cultural practices, chemical control, biological control and resistant genotype development, have shown limited efficacy in providing long-term solutions. Recent advancements in biotechnological approaches, such as RNA interference, are discussed as promising pathways for improved virus management. The review underscores the need for genome editing techniques, such as CRISPR/Cas9, which offer the capacity to develop virus-resistant plants by targeting essential viral or vector genes to disrupt transmission cycles. Additionally, using nanoparticles for targeted delivery of antiviral compounds and novel detection tools presents another innovative solution to effectively mitigate the impact of OV on Indian agriculture.

Keywords

Groundnut Bud Necrosis Orthotospovirus; Watermelon Bud Necrosis Orthotospovirus; Capsicum Chlorosis Orthotospovirus; Peanut Yellow Spot Orthotospovirus; Iris yellow spot Orthotospovirus; Tomato Spotted Wilt Orthotospovirus

Introduction

OV belongs to the genus Orthotospovirus, the family *Tospoviridae*, order *Bunyavirales.* The Genome consists of a linear negative sense ssRNA (17.2 kb) made up of three RNA segments *viz.,* Large (L), Medium (M) and Small (S) RNA with five ORFs (1). OV is not seed-borne; instead, it is primarily transmitted through thrips from other crops or weeds and is secondarily transmitted by infected fields (2). Over 20 different OVs have been reported globally (3). In India, six *OV* have been identified, including *Watermelon Bud Necrosis Orthotospovirus* (WBNV), *Capsicum Chlorosis Orthotospovirus* (CaCV), *Iris yellow spot Orthotospovirus* (IYSV), *Peanut Yellow Spot Orthotospovirus* (PYSV), *Groundnut Bud Necrosis Orthotospovirus* (GBNV), and *Tomato Spotted Wilt Orthotospovirus* (TSWV). *OV* can potentially cause yield losses of up to 100% depending on the crop's developmental stage and the time of year (4). The incidence of the disease in host plants largely depends on thrips acquiring the virus from other infected crops or weed hosts, following a primarily monocyclic pattern (5). The emergence of tospoviruses as critical pathogens has posed significant challenges to cultivating field and horticultural crops. They are increasingly recognized as a major constraint on crop production in India (6). In the Indian subcontinent, these viruses have a significant economic impact and most of the research has been concentrated on them. They also pose a severe threat in neighbouring countries such as Bangladesh, Pakistan, and Sri Lanka (7). In India, tomato and chilli are the two most crucial vegetable crops severely impacted by tospoviruses. These viral infections can lead to complete crop failure, causing significant economic losses and social distress. While GBNV and WBNV are well-known threats, the emergence of CaCV presents a new challenge to the country's vegetable production (8).

Historical context and significance

The history of tospoviruses began in 1919 with the first documentation of tomato spotted wilt disease in Australia. By 1927, it was reported that thrips were responsible for transmitting the disease and in 1930, the causal agent was identified as TSWV (9). In India, from the 1960s onwards, symptoms resembling those caused by tospoviruses have been documented on various crops, including black gram, brinjal, chilli, cowpea, groundnut or peanut, mungbean, pea, potato, soybean and tomato (10-12). Before 1990, Tospovirus was considered a monotypic genus, with TSWV as its only species. Consequently, early reports of tospovirus -like diseases in India were assumed to be caused by TSWV. However, in 1992, serological studies suggested that the bud necrosis disease in groundnuts was caused by a different tospovirus, which was subsequently named GBNV (13). This virus was later confirmed as a distinct species through nucleocapsid protein (N) gene sequencing (14). Another unique tospovirus, PYSV, was identified, causing yellow spots on groundnuts (15).

During 1991 and 1992, a new and unusual disease on watermelon, characterized by leaf mottling and shoot dieback, was observed in parts of southern India. This disease was linked to a tospovirus, WBNV (16,17). Recently emerging OVs in India are IYSV has been reported on onion and garlic (18,19); CaCV has been identified in tomato and chilli (20, 21), GBNV infecting periwinkle (10), TSWV has been reported in Chrysanthemum, snapdragon, marigold, tomato (22-24). This widespread occurrence across various plant families underscores the potential significance of OV in Indian agriculture. These findings highlight OV's ongoing evolution and spread within the country, emphasizing the need for continued vigilance and research.

Taxonomic Classification and Evolution

The 2019 taxonomy report by the International Committee on Taxonomy of Viruses (ICTV) reclassified these viruses under the family *Tospoviridae* and the genus Orthotospovirus. Within the *Tospoviridae* family are five genera, with Orthotospovirus being the sole genus containing plant-infecting viruses. The genus Orthotospovirus is characterized by TSWV, which has a global distribution and a vast host range encompassing over 900 plant species across 90 families, including crop and ornamental plants (25). ICTV has reported and accepted approximately 30 different OVs as distinct species. They are divided into seven to nine serogroups based on serology (26).

Orthotospoviruses: A Growing Threat to Global Agriculture

OVs have emerged as significant threats to producing essential vegetables, legumes, and ornamental crops worldwide, causing substantial yield losses and diminishing crop quality (27). Several criteria are employed to distinguish between different species within the genus Orthotospovirus, including the amino acid identity of the N protein sequence, vector specificity and plant host range (28).

Major Orthotospovirus and Their Impact

Orthotospoviral diseases in India mainly involve diseases of vegetables, fruits, legumes and ornamental plants, including crops of Solanaceae, Cucurbitaceae, Asteraceae, and Fabaceae. PBNV have been reported on Leguminous and Solanaceous crops, while WBNV is predominant in cucurbitaceous crops, and CaCV is reported mainly on solanaceous crops (29). The host range of OV has expanded from crops and including weeds such as *Ageratum conyzoides,* which can serve as a reservoir for these viruses (30) and woody plants like mulberry and kiwi have also been reported as hosts in regions across Asia. However, this is more prominent in China (14).

The type species TSWV has an extensive host range, infecting over 1000 plant species from about 80 families of monocotyledons and dicotyledons, and it is ranked among the top 10 economically essential plant viruses globally (31). The significant economic yield losses are caused by TSWV, which infects groundnuts, pepper, and tomatoes globally and GBNV, which affects tomatoes and peanuts in Southeast Asia (32). It also exhibits a broad host range, affecting economically significant plants such as tomato, potato, tobacco, peanut, pepper, lettuce, papaya and ornamentals like Chrysanthemum, begonia, ageratum and impatiens (33).

Genomic Structure and Function

OV contains 5% nucleic acid, 5% carbohydrate, 20% lipid and 70% protein. It has a unique quasi-spherical particle of 80-120 nm diameter (34). The Genome consists of a linear negative sense ssRNA (17.2 kb) made up of three RNA segments *viz.,* Large (L), Medium (M) and Small (S) RNA with five ORFs. The S and M segments are ambisense, whereas the L is a negative sense RNA. This tripartite structure plays a crucial role in the replication and movement of viruses within host plants (35).

The L RNA (~8.9kb) segment encodes the RNA-dependent RNA polymerase (RdRp) (331k) in the viral complementary (vc) RNA strand (36). The M RNA (~4.8kb) segment encodes two proteins, *viz.,* movement protein (NSm) on the viral (v) RNA strand and glycoproteins (Gn and Gc) on the vcRNA strand, respectively. The movement protein (NSm), which was essential for the movement of the virus from cell to cell and the glycoproteins (Gn and Gc) present as spikes on the surface of the envelope membrane required for virus acquisition and transmission by thrips vectors (37). The S RNA (~2.9kb) segment encodes two proteins, *viz.,* nonstructural protein (NSs) on the vRNA strand and nucleocapsid protein (N) on the vcRNA strand, respectively. The nonstructural protein (NSs) functions as an RNA silencing suppressor and nucleocapsid protein (N) essential for the formation of ribonucleoprotein complexes (RNPs), which facilitate the replication and transcription of viral Genome (38). Coding regions of M and S segments were separated by an intergenic region (IR), which was rich in adenine and uracil and it was involved in the formation of a stable secondary stem-loop/ hairpin-like structure (39) (Fig. 1).

Epidemiology

The presence of thrips vector, virus inoculum, and host plants influences tospoviruses epidemiology. The ability of thrips vectors to multiply on weed hosts is essential, as infected weeds can serve as a "green bridge" for virus survival. Disease spread in annual crops typically occurs through primary transmission from external sources, with limited secondary spread within the crop. Weeds are crucial as infection reservoirs, with species varying across climatic zones (40). The study on temporal and spatial patterns of OV spread in lettuce and pepper plantings suggests predominantly monocyclic spread with limited polycyclic spread, which indicates factors such as wind direction, barriers, and proximity to virus sources influence the spread. In some areas of the southeastern United States, studies have explored the potential role of pine pollen in affecting the ovipositional behaviour of *Frankliniella occidentalis* and its subsequent impact on vector population growth and TSWV transmission (37). In Kenya, 29 weed species were identified as hosts of tospoviruses. They also reported *Amaranthus hybridus, Solanum nigrum, Tagetes minuta, and Datura stramonium* were highly susceptible to tospoviruses and supported the reproduction of *Frankliniella spp.* (41).

Tospoviruses and thrips vectors

Thrips exclusively transmit tospoviruses in a persistent circulative and propagative manner. A unique characteristic of the thrips-tospovirus interaction is that only adult thrips, which acquire the virus during their first larval stage, can transmit the virus (Fig. 2). The virus replicates in the insect's salivary glands, midgut epithelium and muscle cells allowing the thrips to transmit the virus throughout its lifespan (42).

Among the thrips diversity in the world, India recorded 12%. Out of 16 thrips species identified as vectors of tospoviruses globally, only six have been reported as vectors of tospoviruses in India, *viz., Ceratothripoides claratris, Frankliniella schultzei, F. occidentalis, Scirtothrips dorsalis, Thrips palm* and *Thrips tabaci* (Table 1). Due to its polyphagous nature, thrips is one of the most destructive pests in groundnut, tomato, chilli, onion, cucumber, watermelon, Chrysanthemum, brinjal, cotton and tobacco, causing considerable yield losses of 90% (11). This comprehensive understanding of thrips vectors and their relationships with tospoviruses is essential for developing effective management strategies in Indian agriculture.

Reassortment in Orthotospoviruses: Challenges in Detection and Identification

OV shows high genetic variability and frequent reassortment, exchanging genomic RNAs between isolates or species. This process can alter viral properties, including host range and vector transmissibility. The polyphagous nature of thrips vectors and continued virus proliferation suggest an increasing probability of mixed infections and reassortments. Accurate identification of reassortants is crucial for effective disease management, regulation and monitoring of Tospovirus spread (38, 43). The emergence of reassortant viruses like GRSV in Florida demonstrates the real-world impact of this phenomenon (44).

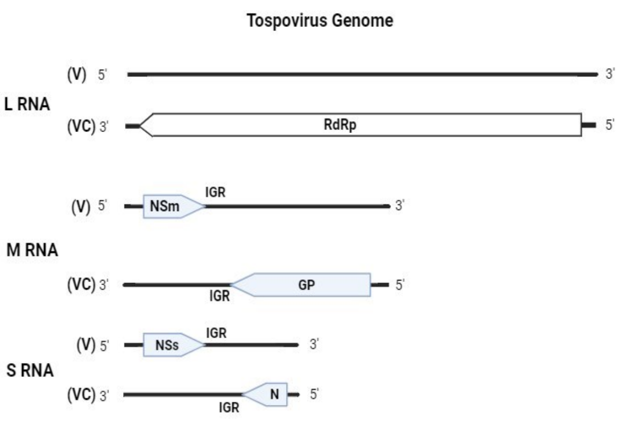

Fig. 1. Genome of Orthotospovirus

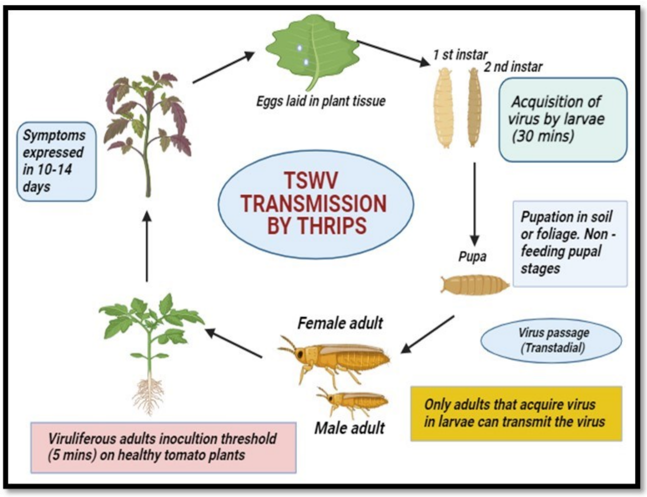

Fig. 2. Transmission cycle of Tospoviruses by Thrips

Table 1. Thrips species transmitting Orthotospoviruses in India

Thrips Species	Distribution	Transmission	Economic impact	Reference
T. palmi	Northern and Southern regions	GBNV, WBNV, CaCV, PYSV	90% yield loss in groundnut, watermelon	(2, 79-82)
S. dorsalis	Northern, central and southern regions	GBNV, PYSV	92% yield loss in chilli, tomato, gerbera	(79, 82-84)
T. tabaci	Southern regions	IYSV, GBNV	60% yield loss in onion	(83, 85)
F. schultzei	Widespread across all states of India	GBNV, TSWV	Severe yield loss in tomato, groundnut, chilli, chrysanthemum	(79, 82, 83, 86)
F. occidentalis	Southern regions	TSWV	70% yield loss in chrysanthemum	(11, 87, 88)
C. claratris	Delhi, Maharashtra, Orissa, Tamil Nadu	CaCV	Crop losses not estimated	(3, 11)

Detection methods relying solely on the N protein, located on S RNA, failed to identify reassortants, potentially leading to misdiagnosis and management issues (28). Genomic analysis of 67 sequences from 22 Orthotospovirus species revealed that reassortment and recombination events can significantly involve in genetic exchanges in S, M and L segments and may lead to improved virus movement, evasion of plant defences, and enhanced replication, posing challenges for accurate detection and identification (45).

Major Orthotospovirus Diseases Challenging Indian Agriculture

Capsicum chlorosis Orthotospovirus (CaCV)

CaCV was first reported on tomatoes in northern India and chilli in southern India (46). It is transmitted by several thrips species, including *C. claratris, F. schultzei, Microcephalothrips abdominalis and T. palmi* (47). The virus has been reported to infect various crops across different countries, including pepper, tomato, peanut, orchid, calla lily and wax flower (48). CaCV had expanded its host range, including amaranthus and peanut, producing symptoms similar to GBNV, making field differentiation challenging (49). CaCV significantly impacts crop production in India and affects chilli, tomato, groundnut and ornamentals with an incidence of 60% respectively (50).

CaCV causes various symptoms in chilli, such as leaf chlorosis, deformation and fruit distortion. In tomato *viz.,* leaf spots, ringspots and fruit discolouration. In groundnut *viz.,* leaf spots, stunting and necrosis (51). Advanced detection methods have been developed, such as duplex and multiplex RT-PCR assays for identifying CaCV in mixed infections and label-free immunosensors more sensitive than DAC-ELISA (46, 52).

Watermelon bud necrosis Orthotospovirus (WBNV)

WBNV belongs to serogroup-IV and was first observed causing bud necrosis disease on watermelon in India during 1991-1992. It has been characterized by necrosis of buds, petioles, leaves, necrotic streaks on vines, concentric rings on fruits and dieback. They caused significant yield losses of up to 100%, forcing farmers to withdraw watermelon cultivation in some parts of Southern India (53). *T. palmi* has been identified as a suspected vector for WBNV. Initially affecting watermelon and cucurbits, WBNV has spread to other crops across northern, southern and western states of India due to climate changes, diverse cropping patterns and thrips.

Recent studies have also identified WBNV in chilli, Chrysanthemum, tomato, bitter gourd, cucumber, pumpkin, ridge gourd and several weed species (45).

Peanut yellow spot Orthotospovirus (PYSV)

PYSV is a significant tospovirus in India, which causes yellow spots followed by necrosis on groundnut leaves. PYSV differs from other tospoviruses based on its transmission, host range, and serology. Its incidence exceeds 90% in southern India. Sequence analysis of PYSV confirms it as a unique species within the Tospovirus genus based on S RNA. Among the thrips species, *S. dorsalis* has been identified as a vector for PYSV (54).

Groundnut bud necrosis Orthotospovirus (GBNV)

Bud necrosis disease was first identified in India in 1964 and was initially attributed to TSWV but later reclassified as GBNV in 1992 based on serology and host range (3). Orthotospovirus infections are prevalent in Tamil Nadu, Karnataka, Maharashtra and Andhra Pradesh. GBNV affects various vegetables in India, including tomato, potato, chilli, groundnut and watermelon. It is efficiently transmitted by several thrips species, including *F. schultzei*, *S. dorsalis*, *T. palmi*, *T. tabaci* and *F. occidentalis,* which serve as vectors (55). GBNV poses a severe threat to tomato production, potentially causing up to 100% yield loss, with the plant being most susceptible during flowering and fruit production (56).

GBNV typically causes symptoms such as necrotic rings, chlorosis, mottling, bud drying, ringspot on fruits, stem necrosis and stunted growth across various hosts (10). In a recent study, researchers developed a novel spectral sensor-based device for real-time detection and severity estimation of GBNV in tomato plants. Their approach combined spectral analysis with machine learning, resulting in a handheld device capable of accurately predicting disease severity at various growth stages, even before visible symptoms appear (57).

Iris yellow spot Orthotospovirus (IYSV)

In India, IYSV was first reported on onion in Maharashtra, Madhya Pradesh, Uttar Pradesh, Karnataka and Gujarat (3). In 2018, Luminex xMAP-based microsphere immunoassays for specific detection of IYSV were developed due to their severity (58). Recent studies revealed that IYSV has been transmitted by *T. tabaci* and emerged as a significant threat to onion cultivation in Tamil Nadu. Surveys conducted from 2021 to 2023 revealed disease incidence of 53-73% across major onion-growing areas. Among the cultivars used in

Tamil Nadu, onion (cv. Co 5) is most susceptible to IYSV, with bulb yield losses reaching up to 60% due to thrip infestations. IYSV is characterized by symptoms *viz.,* straw yellow-coloured diamond-shaped chlorotic lesions on leaves and scapes, necrosis, spindle-shaped chlorotic concentric rings, yellow stripes and reduced bulb size. Apart from onions, IYSV affects Chrysanthemum and other allium crops, including garlic, chives, leeks and ornamental species. They can also persist in weed hosts like chenopodium, wild lettuce and amaranthus (49).

Tomato Spotted Wilt Orthotospovirus (TSWV)

In India, TSWV has emerged as a serious threat to various crops, it was first detected in Chrysanthemum, followed by snapdragon, marigold and tomato. Tomato crops had recorded the highest disease incidence (45%) of TSWV in Tamil Nadu (47). In India, TSWV caused economic yield loss of up to 90% in Chrysanthemum, tomato and other vegetable crops (59). TSWV transmitted particularly by *F. occidentalis* caused a yield loss of 90-100% in susceptible tomato cultivars when outbreaks occurred during critical growth stages (24). TSWV caused symptoms *viz.,* circular necrotic ring spots with green centre on leaf lamina, necrosis on stem and flower buds, chlorotic ringspot on fruits, necrosis and die back of terminal shoot (60). TSWV has a wide host range it infects thousands of plant species across 85 families, contributing to its devastating impact and widespread distribution. Due to their broad host range and the polyphagous nature of thrips present significant challenges for the management of TSWV (39).

Recently, a rapid detection method combining RT-RPA assay with lateral flow strips has been developed, offering quick and accurate diagnosis comparable to RT-PCR (61). Various serological detection techniques are used to diagnose TSWV prevalence, viz., DAS-ELISA and Dot-ELISA, which are widely used due to their efficiency and sensitivity (62).

Management of Orthotospoviruses and thrips

In India, management of OV includes understanding OV epidemiology and control strategies, which are essential in restraining the spread and impact of this virus (Fig. 2). However, controlling OV presents significant challenges due to several factors: wide host range, resistance to thrips and pesticides and scarcity of durable resistance in cultivated crops (7).

Integrated cultural management

Agricultural practices significantly impact thrips populations and tospovirus infections. Timely sowing of crops to avoid thrips activity effectively reduces virus incidence in various crops. In southern India, groundnut sown early with the onset of rains typically reduced GBNV infection. In northern India, maximum GBNV infection was observed in groundnut crops sown during May (63). In India, closer spacing in groundnut crops has been ineffective under field conditions. Higher plant density compensated for yield losses due to bud necrosis disease. Removing infected plants earlier than the spread of the virus has been shown to reduce virus incidence and crop loss. Intercropping also significantly reduced GBNV incidence in groundnuts by planting maize, pearl millet, pigeon pea, sorghum and mungbean. In watermelon cultivation, border cropping with maize significantly reduced WBNV incidence and delayed initial infection by 10 to 15 days (64).

Thrips are attracted to host plants through various cues, attraction can be disrupted using UV-reflective mulch. Additionally, combining reflective mulch with chemical treatments like Actigard has shown effectiveness in managing TSWV in tomato and pepper crops. Monitoring thrips populations often involves blue sticky traps, particularly effective for species like *F. occidentalis*. Using semiochemicals in conjunction with sticky traps effectively eradicates the thrips (65, 66). Recent studies have explored how black plastic mulch effectively reduced GBNV, TSWV incidence and the thrips population of tomatoes and peppers. In cucurbits, aluminum-surfaced plastic mulch is more effective in lowering WBNV incidence than black plastic mulch (67).

Biological control

Numerous studies have explored using natural enemies, predators, and entomopathogens to manage thrips populations transmitting tospoviruses. Parasitoids such as *Ceranisus* sp. and *Thripobius* sp., along with predatory bugs like *Orius tantillus*, showed varying efficacy against thrips. *Orius tantillus* consumed 166 thrips in its lifetime and was highly effective under field conditions against *S. dorsalis* (68). Entomopathogens, including nematodes and fungi, were also investigated as biocontrol agents. Nematode species from *Steinernema*, *Heterorhabditis* and *Thripinema* targeted soil-dwelling pupae. At the same time, fungal pathogens like *Beauveria bassiana*, *Metarhizium anisopliae* and *Lecanicillium lecanii* significantly reduced thrips populations, though their efficacy varied with environmental factors. Constraints in mass production and formulation limited their widespread use, but granular formulations of *B. bassiana* effectively controlled *F. occidentalis* in greenhouse conditions (69).

In managing tospoviruses using biological products, talc-based formulations of *Pseudomonas fluorescens*, combined with 3% neem oil, effectively managed TSWV by reducing thrips populations and viral incidence in tomato plants. Utilizing induced systemic resistance (ISR) and a natural biopesticide, this approach resulted in lower virus concentrations and better crop yields, offering a sustainable solution for managing the virus and its insect vector (70). Several studies showed the antiviral potential of plant extracts against plant viruses, extracts from *Mirabilis jalapa*, *Prosopis chilensis*, *Azadirachta indica*, and *Vitex negundo* significantly reduced TSWV, with *M. jalapa* achieving an 87.61% reduction (71). Additionally, *M. jalapa* exhibited the highest inhibitory activity against GBNV in cowpeas (72). In recent years, a study demonstrated that the culture filtrate of *Ganoderma lucidum* effectively managed GBNV in tomatoes and cowpeas by reducing virus multiplication and systemic movement, with squalene identified as a critical bioactive compound. However, further research was needed to understand its role in plant defence mechanisms (73).

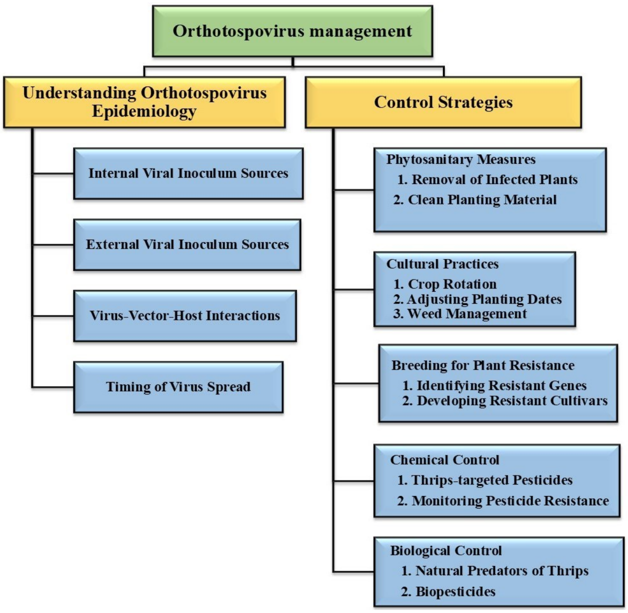

Fig. 3. Orthotospovirus control strategies in India

Chemical control

Management of thrips traditionally relied on various insecticides, including broad-spectrum insecticides *viz.,* pyrethroids, organophosphates, carbamates and neonicotinoids, which disrupted thrips control by harming native species and natural enemies. In managing *T. palmi* populations in mungbean, imidacloprid provided the most satisfactory control of both the vector and GBNV incidence (74).

Spinosad, a reduced-risk insecticide, was compatible with natural enemies and effectively controlled thrips populations, while newer narrow-spectrum insecticides such as pyridalyl and lufenuron were also used. However, the frequent use of these insecticides prompted the need for resistance management in thrips, requiring resistance monitoring and rotations among different chemical classes to address the issue effectively and combining insecticide rotation with other control methods, such as entomopathogenic organisms, successfully controlled thrips under greenhouse conditions. Acephate or Fipronil with neem oil at 10-day intervals from crop emergence to fruit formation effectively reduced thrips populations and WBNV-related losses (68, 75) (Fig. 4).

Host-Resistant Genotypes

Host resistance is a crucial strategy for managing viral diseases in agricultural systems, offering an environmentally friendly and economically viable

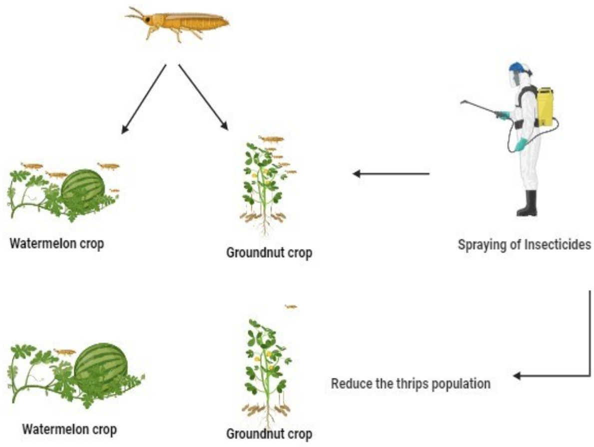

Fig. 4. Effect of Insecticide Spraying on Thrips Population Reduction

alternative to chemical control. This approach reduces the need for insecticides and helps maintain ecological balance. In India, significant approaches have been made to identify and develop resistant genotypes against GBNV, CaCV, WBNV and TSWV. Particular emphasis has been placed on developing GBNV-resistant groundnut genotypes (76). However, further work is required to develop resistant genotypes for OV in various economically essential crops (3).

Recent research has employed conventional and molecular breeding techniques to create resistant varieties with reduced GBNV incidence and improved adaptation to Indian agro-climatic conditions. Screening of tomato, chilli and watermelon accessions has identified promising resistant genotypes. Some examples of resistant genotypes developed in India are presented (Table 2).

RNA interference (RNAi)

RNA interference (RNAi) offers a promising strategy for managing OV and their thrips vectors through gene silencing. However, overcoming the limitations of transgenic plants requires novel approaches, such as topical or exogenous application of RNAi triggers. Recent studies have demonstrated its potential for controlling various thrips species and tospoviruses through different delivery approaches (77, 78).

Developing these innovative approaches could enhance ortho-tospovirus management while promoting sustainable agriculture in India. The recent study on RNAi for managing orthotospovirus and thrips is presented (Table 3).

Table 2. Host-resistant genotypes developed against Orthotospoviruses

Crop species	Orthotospovirus	Resistant/ tolerant genotypes	References
Groundnut	GBNV	ICGV 86699, ICGV 00351, TG -26	(89, 90)
Tomato	GBNV	IIHR-2988, IIHR-1940, IIHR-2901, PKM-1, PKM-2, PKM-3, VRG-17, VRG-95, IVRC-1	(91, 92)
Chilli	GBNV	EC631810, IIHR4360, IIHR4577, IIHR4578, IIHR4582, IIHR4585, IIHR4587, IIHR4588	(93)
Watermelon	WBNV	PI482334, PI219691, DWM 210, BIL-53 and IIHR-19	(4, 94, 95)

Table 3. RNAi approaches used in managing ortho tospoviruses and thrips

RNAi method	Targeted region	Target species	Impact	References
hpRNA	*NSs*	CaCV GBNV	Resistance against multiple viruses	(96)
Direct foliar application of	*NSs*	GBNV	reductions in viral RNA levels and disease	(97)
hpRNA	*RdRP*	GBNV	Reduced virus accumulation	(98)
syn-tasiRNAs	*NSm* and *RdRP*	TSWV	Highly effective and durable antiviral resistance	(99)
syn-tasiRNAs	*RdRP*	TSWV	Silenced the target gene	(100)
Microinjection method	*Vacuolar ATPase - B synthesis*	*F. occidentalis*	Reduction of target gene increases mortality, decreases fertility	(101)
Symbiont-mediated	Alpha-tubulin	*F. occidentalis*	Higher mortality in the first instar stage	(102)
Oral delivery	*SNF7* and *AQP*	*T. tabaci*	High mortality of adults	(103)
Oral delivery	*Vacuolar ATPase - B synthesis*	*T. palmi*	Reduction of target gene increases mortality, decreases fertility	(104)
Plasmid-mediated RNA interference (PM-RNAi).	*ACT, TUB, VATPase-B gene* and *SNF7*	*F. occidentalis*	Suppressed the target gene and high mortality rate	(105)

Conclusion and Future Perspectives

In conclusion, addressing the increasing incidence of OV in India demands a multidisciplinary approach. Key strategies include the development of virus-resistant crops, enhanced understanding of virus-vector-host interactions and the integration of advanced molecular tools for diagnostics and surveillance. A combination of improved cultural practices, judicious chemical use and biotechnological innovations such as gene editing and RNA interference holds promise. Collaboration between researchers and farmers is crucial for transforming these scientific advancements into effective field practices, ensuring sustainable agricultural productivity in light of this emerging threat.

The increasing prevalence of OV in India presents significant agricultural challenges. However, emerging technologies offer promising avenues for better control and management strategies. Future efforts should focus on high-throughput techniques such as RNA-Seq and advanced mass spectrometry to identify differentially expressed genes, proteins and metabolites in response to Orthotospovirus infection in host plants and thrips vectors.

Combining transcriptomics, proteomics and metabolomics can provide critical insights into Orthotospovirus-thrips interactions tailored to India's diverse crop varieties and thrips populations.

Future research should prioritize identifying Orthotospovirus-responsive genes in thrips, potentially facilitating the development of vector-resistant crop varieties adapted to Indian agriculture. Additionally, with climate variability in India, studying environmental impacts on Orthotospovirus epidemiology is crucial, allowing for adaptive management strategies across different regions. Investigating native Indian predators and parasitoids of thrips can promote biological control, reducing dependency on chemical pesticides. The scope of Nanoparticles for targeted delivery of antiviral compounds or as novel detection tools presents another innovative solution.

Moreover, the absence of CRISPR/Cas9 research for Orthotospovirus management in India highlights an opportunity. Genome editing techniques, such as CRISPR/Cas9, offer the potential for developing virus-resistant plants by targeting essential viral or vector genes to disrupt transmission cycles. These technologies can accelerate the development of virus-resistant crops suited to India's varied agro-climatic conditions. Integrating modern techniques with traditional agricultural practices can achieve sustainable long-term solutions to Orthotospovirus impacts.

Acknowledgements

The authors gratefully acknowledge Tamil Nadu Agricultural University, Coimbatore, for providing the platform to publish this article. Our heartful thanks to the Department of Plant Pathology, Agricultural College and Research Institute, Madurai, for facilitating the work.

Authors' contributions

SR and RN conceived the idea and wrote the manuscript. RN gave ideas, and SR designed the diagrams and tables. SR and RN revised the manuscript. YI, JPB and EK finalized the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None.

Declaration of generative AI and AI-assisted technologies in the writing process

While preparing this work, the authors used Grammarly and Claude to improve the language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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