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REVIEW ARTICLE

Thrips-transmitted tobacco streak virus: A growing biotic challenge in sunflower (*Helianthus annuus*) cultivation and adaptive management strategies in India

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Abstract

Sunflower farming is under serious threat due to necrosis disease, predominantly caused by *Tobacco Streak Virus* (TSV) and transmitted by thrips. Among the vectors, *Thrips palmi* have been identified as a major carrier of this devastating disease. A critical component in the epidemiology of sunflower necrosis is the bioecology of thrips. Their complex behaviour such as specialized feeding, rapid reproduction and efficient dispersal-enable swift population build-up and facilitate virus transmission. These dynamics, coupled with environmental factors like temperature and humidity, contribute to seasonal disease outbreaks. Effective management of sunflower necrosis disease requires a comprehensive and integrated approach. Key strategies include adjusting the sowing time to avoid peak thrips activity, cultivating TSV-resistant sunflower varieties and minimizing weed hosts that serve as virus reservoirs. Biological control through the application of plant growth-promoting microbial consortia offers an eco-friendly and sustainable method to suppress vector populations. Additionally, the judicious use of insecticides in combination with biocontrol agents can enhance disease suppression while reducing chemical dependency. Although sunflower necrosis has been extensively studied in regions like India, its global distribution, impact and economic consequences remain underexplored. There is an urgent need for expanded region-specific research to evaluate its prevalence and severity across diverse agroclimatic zones. Multidisciplinary efforts are essential to develop resilient cropping systems, advance vector management strategies and safeguard sunflower production under changing environmental conditions.

Keywords: sunflower necrosis; transmission; serological and molecular detection; virus genome; management

Introduction

Oilseed crops play a major role in human and animal diets by providing essential nutrients such as unsaturated fatty acids (including omega-3 and omega-6), proteins, fat-soluble vitamins (particularly vitamin E), minerals like zinc and magnesium and dietary fiber. Around 3.85 % of the India's total oilseed production is generated by sunflowers. In 2022-2023 India harvested 2.79 lakh tonnes of sunflower from 2.69 lakh hectares, with an average productivity of 1037 kg ha^{-1} (1). In India, it is highly grown in Karnataka, Andhra Pradesh, Maharashtra and Tamil Nadu. Among the oilseed edible crops, sunflower (*Helianthus annuus*) is the third most important crop behind soybean and groundnut (2). Sunflower is indigenous to North America but cultivated globally because of its adaptability to withstand all climatic and soil conditions (3) and most of its products have been utilized as culinary or livestock feed (4) with the oil content of sunflower seed ranging from 35 to 43 %. Monounsaturated fatty acids, such as oleic and linoleic acids comprising around 90 % of total fatty acids help prevent heart diseases in humans. Sunflower oil contains polyunsaturated fatty acids such as omega-3s and omega-6s, which assist in reducing cholesterol and triglycerides. Processed sunflower seeds are rich in fatty acids, proteins and dietary fibres with low carbohydrates. Their seeds are good sources of vitamins, minerals and antioxidants (5). Chandhana (6) reported that India's sunflower production declined from 1.46 million tonnes (mt) in 2007-2008 to 0.3 (mt) in 2020-2021. The increase in human population creates a demand for edible sunflower seed, oil and its by-products. To meet this demand, efforts should be made to enhance sunflower production (7). Sunflower crop is highly affected by a range of diseases caused by viruses, fungi, bacteria and nematodes. Major examples include sunflower necrosis disease caused by TSV, alternaria leaf spot caused by *Alternaria helianthi*, downy mildew caused by *Plasmopara halstedii*, bacterial stalk rot caused by *Erwinia carotovora* and root-knot nematode infestations caused by *Meloidogyne* species. Viruses belonging to the Cucumovirus, Ilarvirus, Potyvirus, Tospovirus, Begomovirus and Umbravirus groups are causing higher yield loss to the crop (8) (Table 1).

Table 1. Viral diseases recorded in Sunflower crop

S.no	Virus	Genus	Disease	Transmission	Reference
1.	Tobacco streak virus	Illarvirus	Sunflower necrosis disease	*Thrips palmi*	(9)
2.	Sunflower mosaic virus	Potyvirus	Sunflower mosaic disease	*Myzus persicae* and *Capitphorus elaegni*	(10)
3.	Cucumber mosaic virus	Cucumovirus	Sunflower mosaic disease	Seed *and Aphis gossipi;* Myzus persicae	(11)
4.	Sunflower yellow blotch virus and sunflower crinkle virus	Umbravirus	Yellow blotch and leaf crinkle disease	*Aphis gossipi*	(12)
5.	Sunflower leaf curl virus	Begomovirus	Sunflower leaf curl disease	*Bemisia tabaci*	(13)
6.	Tobacco leaf curl virus	Begomovirus	Leaf curl disease	*Bemisia tabaci*	(14)
7.	Sunflower chlorotic mottle virus	Potyvirus	Sunflower chlorotic mottle virus disease	*Myzus persicae* and *Aphis gossypii*	(15)

Host range of TSV

TSV is reported to be infecting more than 200 plant species belongs to 30 dicotyledonous and monocotyledonous plant families (16). TSV occurrence was reported from over 26 countries worldwide (17). In Australia, TSV was first reported in 1971 in sunflower and has subsequently been reported from tobacco, strawberry, dahlia and various weed species, mostly from south-eastern Queensland (18). They recorded common occurrence of TSV in *Parthenium hysterophorus* as symptomless infection across larger area of central Queensland, which later served as a source of inoculum for pollen borne virus transmission by thrips. Globally so far five countries were reported with TSV infection in sunflower (Table 2, Fig. 1).

Table 2. Global occurrence of Tobacco streak virus in Sunflower: countries and timeline of reports

S.No	Country	Year of report	Reference
1.	India	2002	(19)
2.	Australia	2009	(20)
3.	Argentina	2019	(21)
4.	Iran	2008	(22)
5.	Netherland	1983	(23)
6.	United States	1982	(24)
7.	Brazil	2005	(25)

In India, TSV was first reported to infect sunflower causing necrosis disease (SND) and in peanut causing stem necrosis disease (PSND during 1999-2000 from Andhra Pradesh state (26). Since then, the virus has been responsible for causing serious damage to groundnut, sunflower and several other annual crops in Andhra Pradesh, Karnataka, Maharashtra and Tamil Nadu states (27). This disease may result in up to 100 % crop loss, depending on the cultivar or variety and the stage of infestation. It continues to be a significant constraint in sunflower crop production (28). Visible field symptom of this disease shows necrosis of leaves followed by necrosis on petioles, stems and floral calyx and complete death of seedlings. Necrosis occurrence during the bud formation stage causes the capitulum to flex and twist,

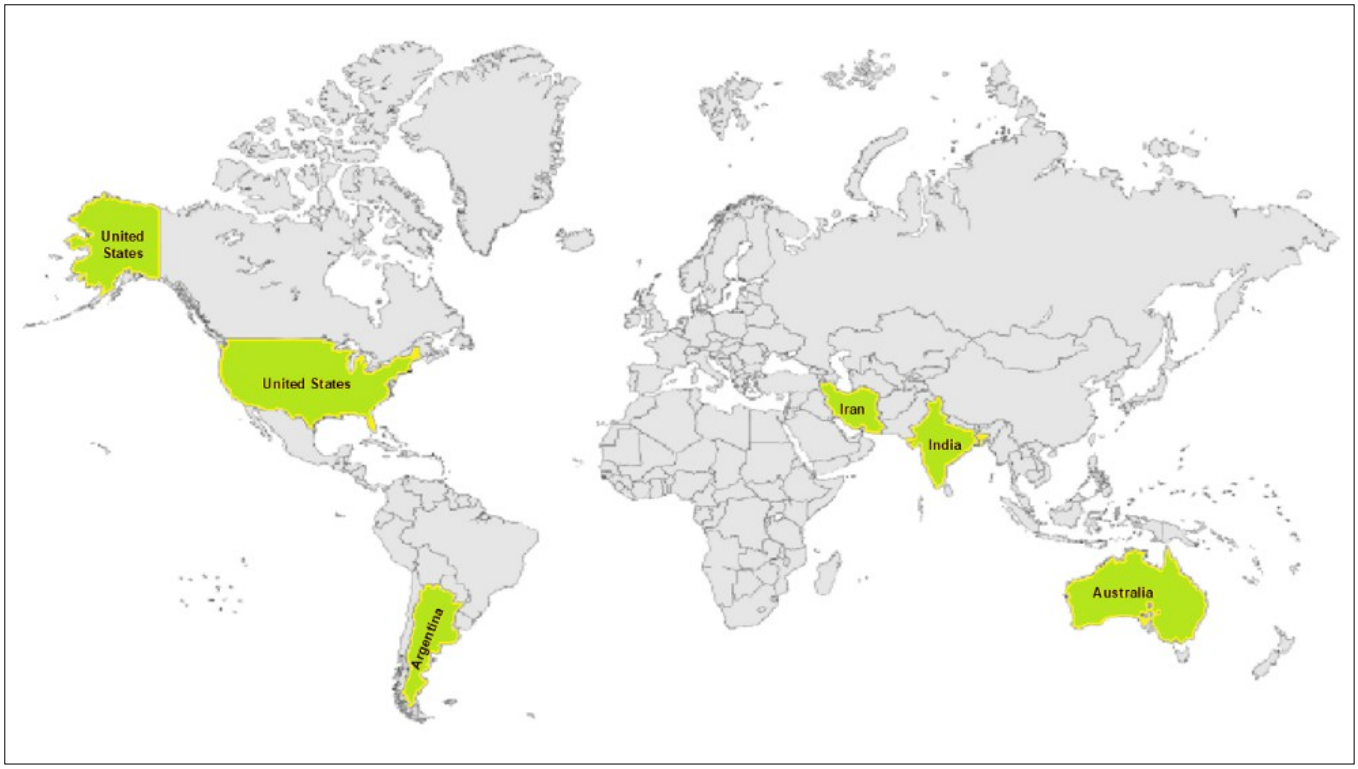

Fig 1. Countries with significant sunflower necrosis disease cases.

ultimately leading to the total failure of the seed setting (29). TSV belonging to genus *Illarvirus* was the causative agent of disease (28). The initial causative agent of sunflower necrosis was identified as tomato spotted wilt virus (TSWV) belonging to the tospovirus group. However, it was later determined to be TSV from the *Illarvirus* group (30). It equally affects widely cultivated sunflower species and weeds belonging to the families of Amaranthaceae, Chenopodiaceae and Fabaceae (31); Asteraceae, Leguminosae and Cucurbitaceae (28); Malvaceae, Cucurbitaceae and Solonaceae (32). A laboratory test was conducted to assess the host range of TSV in India by Prasada Rao et al. (33) showed that TSV infects a total of 24 species across nine different families. In addition to sunflower, four other major oilseed crops affected by Tobacco streak virus (TSV) include groundnut (Arachis hypogaea), soybean (Glycine max), sesame (Sesamum indicum) and safflower (Carthamus tinctorius). (Table 3). The virus also infects without symptoms in crops like *Amaranthus viridis*, *Commelina benghalensis*, *Parthenium hysterophorus* and *Trianthema portulacastrum*. In addition to sunflower, other economically significant crops that have been related to this virus are soybean, chickpea, tobacco and weeds like parthenium, black pigweed, blackberry nightshade, green amaranth and common thorn apple (34).

Table 3. Host range of TSV in oilseed crops

S.no	Crop	Scientific name	Reference
1.	Sunflower	*Helianthus annus*	(35)
2.	Castor	*Ricinus communis*	(36)
3.	Groundnut	*Arachis hypogaea*	(37)
4.	Niger	*Guizotia abyssinica*	(38)
5.	Safflower	*Carthamus tinctorious*	(39)

Symptoms of Sunflower necrosis disease

Symptoms include necrosis of leaves, petiole, stem and bracts, along with deformation of the head region. An early infection leads to complete plant death (Fig. 2) (40). In Australian sunflower production, TSV showed severe leaf necrosis and chlorosis as symptoms of infection in sunflowers, which greatly affected plant vigour and resulted in yield losses (41)**.** Previous studies recorded the incidence of TSV in sunflower ecosystem at Argentina. These symptoms were consistent with infections caused by viruses belonging to the *Bromoviridae* family, under which TSV is classified. In severely affected plants, reproductive structures were either malformed or completely absent, which drastically lowered seed output and oil content. As the disease progresses, secondary symptoms such as wilting and dieback may also be observed, particularly under conditions of high vector activity and favourable environmental conditions. The symptom expression can vary depending on the cultivar, growth stage at infection and climatic factors, making early diagnosis and timely intervention crucial for effective disease management.

Genomic organization of Tobacco streak virus

Ilarviruses, a genus within the *Bromoviridae* family, are characterized by non-enveloped, quasi-isometric virions, though some may exhibit a bacilliform shape, with diameters ranging from 26 to 36 nm (17). TSV, a member of this genus, possesses a tripartite positive-sense single-stranded RNA genome, each segment encoding proteins that are essential for viral replication, movement and pathogenicity. The first genomic segment, RNA 1, spans 3491 nucleotides and codes for a replicase-associated 1a protein. This protein includes two major domains: a methyltransferase domain, which assists in capping viral RNA and a helicase domain, which unwinds RNA strands during replication. Together, these functions are critical for regulating RNA synthesis and supporting viral replication. The second segment, RNA 2, is bicistronic and approximately 2700

Fig 2. Different types of symptoms in sunflower crop infected by TSV.

a: Plant with severe necrosis and dried head**; b**. Stem and petiole necrosis

nucleotides long, encoding two proteins (43). The RNA-dependent RNA polymerase (RdRp) is essential for synthesizing viral RNA, while the 2b protein serves as a post-transcriptional gene silencing (PTGS) suppressor, allowing the virus to bypass plant defence responses. The 2b protein is translated from a subgenomic RNA known as RNA 4a (44, 45). The third genomic segment, RNA 3, which ranges between 2100 and 2200 nucleotides, is also bicistronic and codes for two structural proteins. The 3a movement protein (289 amino acids) facilitates viral spread from cell to cell within the host plant. Meanwhile, the 3b protein (Coat Protein, 237 amino acids), which is expressed from subgenomic RNA 4, is responsible for virion assembly and systemic infection (46). Virions are comprise a single protein subunit of 26.2 kDa protein component and typically spherical, 26 to 35 nm in diameter (47). The genome is made up of about ⊠ 8000 nucleotides and they are tripartite RNA. Subgenomic ribonucleic acid may be present in the three RNA segments, which are found in distinct virions (Fig. 3).

Transmission dynamics of Sunflower necrosis disease

The transmission of TSV often occurs through sap, vector and seed transmission. Necrosis virus is transmitted through mechanical sap inoculation from an infected plant to a healthy plant (48). A quick and successful sap injection method for the TSV-Sunflower were found earlier (49). However, traditional sap inoculation by swabbing the leaf lamina with an abrasive was time-consuming and laborious. Several thrips' species including *Megalurothrips usitatus*, *Frankliniella schultzei*, *Scirtothrips dorsalis*, *Thrips palmi* and *Thrips tabaci* in field situations (49) can vector TSV and all are commonly found feeding in flowers (Fig. 4). In Australia, the prolific flowering of parthenium and crown beard (serving as source for TSV) make these ideal hosts for thrips, which can then easily move infected pollen into nearby crops (50). TSV transmission is highly favoured by climatic conditions that enable high thrips populations to develop and large amounts of infective pollen to be produced by weed hosts. These conditions generally occur during warmer months and are highly dependent on rainfall and weed growth patterns. In this transmission mode, thrips are not affected by the virus, but they carry contaminated pollen on their bodies to transmit the virus (33). *T. palmi* successfully transmit TSV to sunflower in an acquisition access period of 3-5 days leading to successful infection were confirmed (9). In three days of acquiring access period, *T. palmi* acquired the virus from sunflower plants with 13.33 % transmission and 16.67 percent of plants were successfully infected during the 6th day of inoculation access period (51). The percent of transmission increased with an increase in the acquisition feeding period. It requires just two thrips to spread the virus from an infected to a healthy sunflower plant. *Thrips tabaci* adults or nymphs could transmit TSV through infected pollen (Fig. 5) (52). In the previous study, thrips were mixed with virus-laden pollen from *Lycopersicon esculentum* (tomato) plants infected with TSV. When these thrips were placed on *Chenopodium amaranticolor* test seedlings, the virus was consistently transmitted. The virus was also regularly transmitted when virus-carrying pollen was placed along with the thrips then introduced. No transmission occurred when test seedlings were exposed to virus-carrying pollen in the absence of the thrips or to the thrips without pollen. Further, no transmission occurred when the thrips were fed on virus-infected leaves and then transferred to test seedlings in the absence of virus-carrying pollen. The transmission of TSV by *Thrips tabaci* depends on the presence of pollen-borne virus, which presumably infects via wounds made by the thrips. A detailed study on role of *Thrips palmi* and *Parthenium hysterophorus* pollen in active spread of TSV in cotton ecosystem were reported earlier (53). They confirmed that the adult *Thrips palmi* feeding on parthenium was carrying TSV infected parthenium pollen grains on their bodies upon moving to cotton plants. However, virus acquired thrips were unable to directly spread TSV when they were placed on cotton plants. Rather from performing as direct vectors, thrips mainly assist in transmitting virus-laden pollen grains incase of cotton. Symptoms appeared 22 days later when pollen from TSV-infected Parthenium plants was applied to cotton seedlings, either by itself or in the presence of thrips.

Seed transmission of TSV in sunflower

Virus transmission through seeds is an important route for the

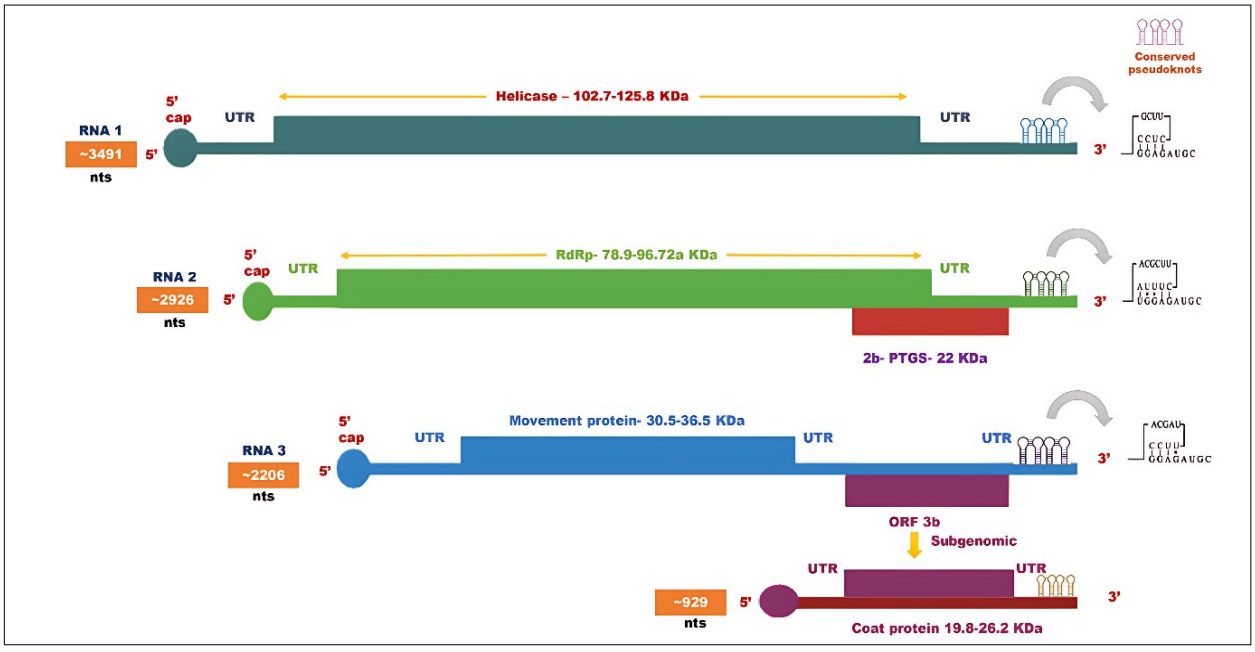

Fig 3. Genome organization of tobacco streak virus.

Fig 4. Thrips species feeding on sunflower crop.

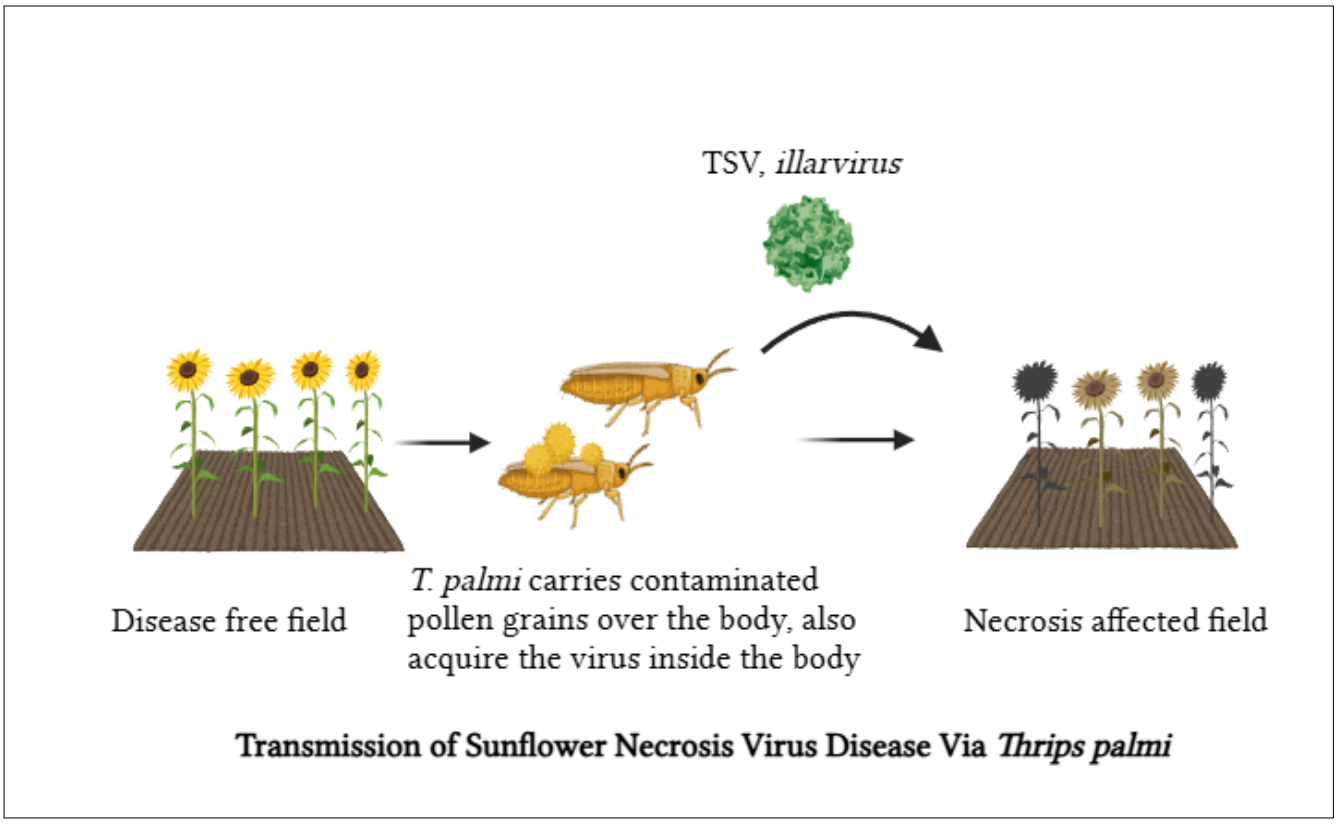

Fig 5. Transmission of necrosis disease via *T. palmi*.

transmission of viruses into new locations and exists in seeds until suitable vectors and hosts are available. TSV seed transmission was noted (24) in naturally infected hosts, specifically soybean, bean and asparagus. Also, seed transmission rates were reported up to 10 % (52) in tomatoes, 26.4 % (54) in beans and 6.8 % (18) in *Parthenium hysterophorus*. Seed transmission has been demonstrated in numerous TSV isolates from throughout the world in both naturally occurring and sap-inoculated plant seeds from various families. To date, no seed transmission of TSV has been reported in sunflower.

Thrips palmi (Order: Thysanoptera)

The economic destruction that thrips cause on cultivated crops makes them among the most significant insect pests in agriculture globally. *T. palmi* first appeared in 1925 on tobacco plants from Sumatra, Indonesia and rediscovered in 1980 (55). The Thripidae family includes about 1500 species spread across 250 genera. Most *Thrips* species are considered as pests causing damage to several crops. Depending on stages in the lifestyle, *T. palmi* can be found in several parts of plants viz. eggs in the tissue of leaves, flowers, larvae and adults on the same types of tissues, but prepupae and pupae can be formed in soil. Thrips damage symptom shows silvery feeding scars on the leaf surface, particularly next to the veins and midribs of the crop (55). The leaves of heavily diseased plants develop a silvered or broken look with stunted leaves and terminal shoots and damaged fruits look malformed (56). A diagnostic methodology for *T. palmi* identification was developed and published EPPO standard. National Plant Protection Organizations (NPPO), as the entities in the role of implementing phytosanitary measures, utilize EPPO (European and Mediterranean Plant Protection Organization) diagnostic protocols for regulated pests to locate and identify the European Union or EPPO-regulated pests lists (55).

Morphological characteristics and molecular identification of Thrips

A visual key by using several easy options and allowing the identification of 70 economically valuable species of Thysanoptera order in Central Europe were released (57). Important diagnostic traits with differentiate *Thrips palmi* from all other known species of the genus thrips known to exist (58). The full description of *T. palmi is* provided. Previous researcher have made it easier to study *T. palmi* morphologically among the mixed population (59). Former studies analyzed 264 thrips species by sequencing the mtCOI gene and found minor intra-species variation among 10 well-characterized species (60). However, there was an 18.6 percent recorded divergence between the species in the study carried out by him. A Computerized key for economically significant thrips species, along with colour slides displaying thrips photomicrographs and video recordings for nearly 180 thrips species was created (61). Molecular techniques, particularly mitochondrial cytochrome oxidase I (*mtCOI*) gene sequencing, are widely utilized for accurate thrips species identification. DNA extraction from thrips is typically carried out following established protocols (41). Amplification of a 5' region of the mtCOI gene is performed using the primer pair mtD7.2F (5' ATTAGGAGCHCCHGAYATAGCATT 3') and mtD9.2R (5' CAGGCAAGATTAAAATATAAACTTCTG 3') (62). The polymerase chain reaction (PCR) is conducted using a ready-to-use master mix in a thermocycler under optimized thermal cycling conditions, which include an initial denaturation at 94 °C for 3 minutes, followed by 35 cycles comprising denaturation at 94 °C for 30 seconds, annealing at 53 °C for 45 seconds and extension at 72 °C for 1 minute, concluding with a final extension at 72 °C for 20 minutes. The expected PCR product is approximately 480 base pairs in length and the amplified fragments are sequenced for species confirmation and phylogenetic analysis.

Identification key for *Thrips palmi*

Adult females are 0.9 mm long and vary in appearance from straw yellow to pale brown. Antennae are 7 segmented. Generally, 3-5 Segments in antennae are similarly bicolored. The posterior lateral margin of the pronotum has two pairs of setae, while the anterior lateral margin lacks any pair of setae. A pair of campaniform sensillae found on the mentanotum. Presence of disrupted rows of wing vein setae on the forewings. A long and lean abdomen is also an identification key for *Thrips palmi* (63).

Epidemiology of TSV causing necrosis disease

Studies on thrips vector interaction with the crop and environmental factors that contribute to disease spreading are essential for efficient control of tobacco streak virus. It may infect any developing stage of the sunflower crop to cause the disease. Late infected plants can produce flowers and generate pollen, which promotes virus spread and raises the possibility of outbreaks. Warm weather encourages the proliferation of thrips, weed growth and the production of pollen from affected plants (47). High temperatures were shown to have a strong and favourable association with the incidence of sunflowers. The first week of June to August during the kharif season was reported to have enhanced thrips population on sunflowers (64). Weed hosts pose a significant impact on viral disease epidemiology as well. The existence of weed hosts like parthenium, whose contaminated seeds may travel great distances and survive in the soil for extended periods, after seeds germinate and generate infected plants, which can serve as the source of inoculum for the spread of viruses (47).

Serological detection of TSV

TSV was serologically identified with only a particular antiserum. In the case of sunflower necrosis virus disease, the virus serologically using direct antigen coating-enzyme linked immune sorbet assay and reported, genotypes subjected to the experiment produced a positive reaction with TSV antisera and virus (51). The presence of the virus in 342 samples collected from Andhra Pradesh, Karnataka and Maharashtra (65). The samples include sunflower, groundnut, cotton, okra, soybean, marigold, cowpea, mungbean, safflower, niger, sesame and crossandra. TSV using DAC-ELISA in weed hosts including *Parthenium hysterophorus, Abutilon indicum, Ageratum conyzoides* and *Commenlina benghalensis* without showing any symptoms (39). Serodiagnosis of TSV in fields of Sreenivasapuram and Machupalli villages of Kadapa district, Andhra Pradesh and the collected leaf samples of sunflower plants having chlorotic and necrotic lesions (66). Using direct antigen coating DAC-ELISA, 61 samples were examined from which two were positive samples.

Molecular studies of TSV

Reverse transcription-polymerase chain reaction successfully amplified the TSV-CP gene from sunflower tissue using primers specific to the TSV coat protein area (67). All the necrosis disease-affected sunflower samples that were gathered from Maharashtra, Karnataka, Tamil Nadu and Andhra Pradesh showed a DNA band of the anticipated size (about 700 bp). For the RT-PCR study, a particular primer that could amplify the whole sub genomic RNA (~929 bp) encoding coat protein of ~717 bp (68). To find TSV in sunflower plants, a study utilized the double-antibody sandwich enzyme-linked immunosorbent assay (DAS-ELISA) and visual symptom assessment. RT-PCR was used to further confirm the virus's presence, demonstrating the value of molecular techniques in precise TSV detection (69). Assessments of sunflower hybrid's resistance to TSV were carried out in the fields of Australia. Same molecular detection technique RT-PCR, used to confirm TSV infections in the assessed hybrids, even though tolerance was the focus (50)**.** To investigate the pathogenicity and host range of TSV, Full-length infectious cDNA clones of the virus (70) . The identification and functional investigation of TSV in sunflower and other host plants were made easier by this molecular method. After reviewing the literature of research, it was revealed that there were very few publications on sunflower TSV molecular studies.

Management of sunflower necrosis disease

Generally, viral diseases in plants uncontrollably use curative methods due to their obligate intracellular nature. Therefore, risk -reducing and preventive measures must be included, considering the dynamics and pathogen evolution and plant-pathogen interactions. Designing management strategies for viral diseases in plants is done by considering the nature of host plants, such as annuals or perennials and their types of propagation, vector biology and ecology, transmission characteristics and infection cycle of plant viruses (71). For the management of necrosis disease, which is majorly transmitted by thrips (9), scientists have made experiments with different control techniques. Based on the observations made from the experiments, an effective management strategy against necrosis virus disease has been developed.

Cultural control

In cultural control, the most practical and affordable management of necrosis disease is to cultivate resistant varieties against the tobacco streak virus. During Kharif 2003, screening was carried out using 30 hybrids along with their parents against necrosis disease under field conditions in Hyderabad, Andhra Pradesh, India. "Modern" variety was used as control which showed a highly susceptible reaction to this disease. Among them, 14 hybrids (CMS 378A x RHA 265, CMS 378A x DSI 218, CMS 378A x RHA 344, CMS 234A x RHA 265, CMS 234A x RHA 271, CMS 234A x RHA 344, CMS 234A x RHA 345, CMS 234A x RHA 346, CMS 71A x RHA 345, DCMS 41 x RHA 274, DCMS 41 x SF 216, DCMS 42 x RHS 273, DCMS 42 x RHA 859 and DCMS 43 x DSI 218) and two parents (CMS 378A and CMS 234A) were identified as resistant. In a field screening of 106 genotypes of sunflowers, ten genotypes (GMU 685, 650, 664, 662, 661, 613, 676, KBSH 53, KBSH 53A and RHA 95C-1) were identified as highly resistant against disease incidence under field condition with the susceptible genotypes, these resistant varieties showed dense and longer trichomes which is negatively correlated with the disease incidence and thrips population (72). In Queensland, Australia, 23 distinct sunflower hybrids were examined in 470 plots during a five-year period (2008-2012). While certain hybrids, like Ausigold 61, were extremely sensitive to TSV, others, like NH2201, Hysun 304, Galah and Advantage, showed great resistance to the virus. The efficiency of these tolerant hybrids against the two main TSV strains present in Australia, TSV-parthenium and TSV-crownbeard, has been proven by glasshouse experiments. The best long-term control method for reducing disease outbreaks is the use of hybrids that are resistant to TSV. To mitigate the risk of TSV, farmers must avoid planting sunflower crops close to significant parthenium flowering areas. TSV incidence can be reduced by scheduling planting to avoid periods of high virus transmission and peak thrip activity. To control the spread of TSV, crop rotation and the removal of diseased plant trash are other advised methods. (50). In India, cultural practices like modifying the sowing period have been suggested as one of the disease management strategies. Additionally, it was discovered that planting sunflower seeds in post rainy season (September) helped to reduce the occurrence of necrosis (73). Usage of border crops like sorghum, has decreased necrosis incidence by 18-37 % (74).

Chemical control

Field experiments were carried out for three Kharif seasons of 2003-04, 2004-05 and 2006-07 at Mulegaon Farm, ZARS, Solapur, India. Based on the observations of thrips count and SNVD incidence, treatment includes seed treatment with imidacloprid 70 WS @ 5g kg^{-1} seed followed by two sprays of imidacloprid 17.8 SL @ 0.0045 percent at 20 and 30 days after sowing, has the lowest necrosis incidence over control (7.08 %) with the minimum number of thrips (6 thrips/leaf) and maximum seed yield (75).Previous researchers studied and examined several chemical treatments over three years (76). The most successful treatment included foliar sprayers of flonicamid 50 WG at 0.25 g/l at 30, 45 and 60 (DAS) in addition to seed treatment with imidacloprid 600 FS at 5 mL/kg. A reduced necrosis incidence of 4.21 % and a higher yield of 1630 kg/ha were the outcomes of this regimen. Additionally, former researchers evaluated the effectiveness of various chemical insecticides in suppressing *Thrips palmi*, the vector of necrosis disease (77). Following, foliar sprays of imidacloprid 17.8 SL at 0.5 mL/L at 30, 45 and 60 DAS and seed treatment with imidacloprid 600 FS at 5 mL/kg seed, the minimal disease incidence was 3.71 % at one month and 4.74 % at two months after germination. Additionally, a greater seed yield of 1165 kg/ha was obtained with this treatment.

Biological control

Biological control will be environmentally safe and the best alternative to chemical control. For, the first time, plant growth promoting microbial consortium (PGPMC)-mediated biological regulation of the disease under field circumstances was reported (78). PGPMC-2, which contains B two PGPMCs were tested in farmer's fields in conjunction with their farming practices (imidacloprid + mancozeb). Use of PGPMC 1 powder formulation, (PGPMC-1, which contains *Bacillus licheniformis* strain MML2501 + *Bacillus spp.* Strain MML2551 + *Pseudomonas aeruginosa* strain MML2212 + *Streptomyces fradiae* strain MML1042) resulted in significant improvement in disease control, seed germination, plant height and yield parameters. An additional seed yield of 840

kg ha^{-1}, an additional income of RS. 10920/ha and a benefit-cost ratio of 6.1 is obtained (78).

Use of antiviral compounds

The botanical antiviral principles tested for suppressing the disease were evaluated. It was discovered that the antiviral plant extracts from *Prosopis chilinesis* and *Bougainvillea spectabilis* were effective in lowering the viral infection in both sunflower and cowpea plants. The viral invasion was lessened more effectively by the combination of plant-based products and goat milk therapies than by either treatment alone. Additionally, when comparing AVP-treated sunflower plants to untreated control plants, the ELISA test revealed lower viral titers (number of infectious viral particles present in a sample) in the treated plants. Pathogenesis-related proteins and oxidative enzymes such as β-1,3 glucanase, peroxidase, polyphenol oxidase and phenylalanine ammonia-lyase were increased in sunflower plants treated with AVP. When compared to untreated control, the phenolic content of AVP-treated plants was higher. Thus, the triggering of various host defence-related enzymes and proteins by AVPs in response to disease infection has been focused on as the effective defensive strategy for the management of SNVD (79).

Integrated management of Sunflower necrosis disease

In the case of viral diseases, it was too difficult to manage via a single approach. Nowadays, sunflower varieties that are being used by farmers are focused only on obtaining higher seed yields rather than looking over different susceptible reactions to the disease. This has led to a huge outbreak of the disease.

To investigate the effectiveness of the Integrated disease management (IDM) approach, field trials were conducted during the Kharif seasons of 2002-2004 (3 years) at the main farm of Oilseeds Research Station, Latur (73) and 2016-17 at Zonal agricultural research station, AICRP (Sunflower), University of agricultural sciences, GKVK, Bengaluru (2). In both cases, a split-plot design was made consisting of two main treatments and eight sub-treatments. Which, main treatments were based on with or without the use of border crops (Maize or Sorghum) and sub-treatments were based on seed treatment with imidacloprid and spraying of chemicals or some defensive molecules. In the first case, the IDM approach was useful in managing the disease in which the lowest mean necrosis incidence of 10.2 % and maximum yield of 1222 kg/ha along with the highest benefit cost ratio of 3.4 was obtained for the main treatment i.e., utilizing sorghum as a border crop over non-border treatment. Among the sub-treatments, the lowest mean necrosis incidence of 4.9 percent, maximum yield of 1404 kg/ha and highest benefit cost ratio of 3.1 was observed in the case of seed treatment with imidacloprid and three sprays with Confidor (Imidacloprid) (73).

In the second case, the IDM technology was proven to be effective in managing vectors and disease by utilizing maize (Variant African tall) as a border crop and spraying pesticides such as fipronil 5 % SC and defence including molecules (Oligocarranegen). With a maximum yield of 12.22 q ha^{-1} over non-border treatment, the bordering maize crop had the lowest mean necrosis incidence of 11.69, 12.80 and 15.26 percent at 30, 60 and 90 DAS respectively The sub-treatments that produced the lowest incidence of necrosis disease were subjected to seed treatment with imidacloprid 600 FS at 5mL/kg + spray of defence including molecules (Oligocarranegon) and foliar application of fipronil 5 % SC at 15, 30 and 45 DAS respectively (2). Therefore, in both cases, the use of border crop and seed treatment with imidacloprid followed by spraying of chemicals reduced the disease incidence as well as increased the yield and recorded the highest B:C ratio. This approach would be used as a sustainable management strategy for controlling the disease.

Conclusion

Effective prevention and control require an understanding of the bioecology of thrips in addition to how they transmit the sunflower necrosis virus disease. Disease outbreaks are caused by thrips feeding behaviours, reproduction and virus-vector dynamics, requiring integrated control measures. Sustainable solutions can be achieved by combining biological controls, resistant cultivars, traditional practices and judicious pesticide usage. Among biological controls, the use of Plant Growth-Promoting Rhizobacteria (PGPR), endophytic fungi and entomopathogenic microbes has shown promise in suppressing thrips populations and enhancing plant defence responses, offering an eco-friendly alternative to chemical control. Early detection and specific methods are improved by developments in ecological research and molecular diagnostics. To effectively manage the disease and maintain the health of sunflower crops, an integrated approach that incorporates such measures is essential. Furthermore, enhancing disease mitigation efforts requires additional research into the effectiveness of removing TSV-infected weed hosts through chemical application or mechanical control before planting, as well as modifying agronomic practices to reduce thrips landings, which serve as a major virus transmission pathway. Ultimately, the development of a forecasting model and decision-support system would be invaluable for TSV and also thrips management in the sunflower ecosystem. Such a system could provide early warnings to farmers, enabling timely implementation of preventive and control measures both prior to sowing and throughout crop growth, thereby reducing economic losses and improving sunflower productivity.

Future perspectives

To find possible targets for preventing transmission, future studies focus on elucidating the molecular process underlying virus-vector interactions. It is crucial to create efficient diagnostic instruments for the early identification and tracking of thrips populations and global prevalence. Priority should be given to developing sunflower cultivars with improved resistance to the sunflower necrosis virus disease and thrips. Furthermore, investigating arising emerging biotechnology techniques and sustainable biological control agents, such as RNA interference and microbial symbiont manipulation, might open new possibilities for integrated pest and disease management. A key component of long-term control methods will be boosting farmer communication initiatives to encourage the adoption of ecologically friendly methods. Proposed disease control measures should include vector surveillance, field sanitation through removal of virus-infected weed hosts, optimal planting time adjustments, use of resistant cultivars and integration of

biological control with selective insecticides. Advancements in genome editing tools like CRISPR-Cas and RNAi-based gene silencing can play a pivotal role in engineering virus- or vector-resistant sunflower lines. Digital platforms, including mobile apps and remote sensing tools, can assist farmers in real-time thrips monitoring and early warning alerts. Additionally, the implications of climate change such as increased temperatures and altered humidity patterns must be considered, as they can significantly influence thrips population dynamics and TSV spread across new regions.

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Authors' contributions

RD wrote the draft of the manuscript. VB and PR reviewed and edited the manuscript. EP and RS read and approved the final manuscript SSP assisted in writing draft of the manuscript.

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