



Whiteflies as Vectors of Plant Viruses: Biology, Molecular Interactions and Management Strategies

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Whiteflies are among the most important sucking insect pests of agricultural and horticultural crops. Their importance extends far beyond the direct injury caused by sap feeding. Heavy infestation can weaken plants, promote honeydew accumulation and encourage the development of sooty mould, but the most serious consequence of whitefly infestation is often the transmission of plant viruses. Among whiteflies, the *Bemisia tabaci* species complex has received particular attention because of its exceptionally broad host range, extensive geographical distribution and ability to transmit a large number of economically important viruses. Molecular studies have established that *B. tabaci* is not a single homogeneous biological entity but a complex of morphologically similar species that can differ in distribution, host association, insecticide susceptibility and ability to transmit viruses (De Barro et al., 2011). Globally invasive members such as Middle East-Asia Minor 1 (MEAM1) and Mediterranean (MED) have contributed substantially to the spread and emergence of whitefly-associated crop diseases. More than 400 plant virus species have been reported to be transmitted by members of the *B. tabaci* complex, with begomoviruses representing the largest group (Ferreira et al., 2024). As a result, understanding the biology of the vector, its interactions with viruses and host plants, and the factors influencing transmission is essential for designing effective crop-protection strategies.

Major plant viruses transmitted by whiteflies

Whiteflies transmit viruses belonging to several taxonomic groups, and their relationships with the vector differ considerably.

1. Begomoviruses

Begomoviruses belonging to the family Geminiviridae constitute the largest and economically most important group of whitefly-transmitted plant viruses. They possess circular single-stranded DNA genomes and are associated with several devastating crop diseases. Important examples include Tomato yellow leaf curl virus and related tomato leaf curl viruses, cassava mosaic begomoviruses, cotton leaf curl-associated begomoviruses and numerous yellow mosaic and leaf curl viruses affecting legumes, chilli, okra and other crops. Begomoviruses are generally transmitted by *B. tabaci* in a persistent circulative manner (Navas-Castillo et al., 2011; Ghosh and Ghanim, 2021).

2. Other whitefly-transmitted viruses

Whiteflies also transmit several RNA viruses. Criniviruses of the family Closteroviridae include economically important pathogens such as Tomato chlorosis virus and Cucurbit yellow stunting disorder virus. Whitefly-transmitted viruses also occur within the genera *Ipomovirus*, *Torradovirus* and *Carlavirus* (Navas-Castillo et al., 2011; Polston and Capobianco, 2013). Unlike begomoviruses, many of these viruses are transmitted semi-persistently or through other non-circulative relationships. Their acquisition, retention and inoculation characteristics therefore differ from those of persistent circulative viruses.

Table 1: Major groups of whitefly-transmitted plant viruses

Virus group	Family	Representative examples	Important vector	General transmission pattern
Begomovirus	Geminiviridae	Tomato yellow leaf curl virus, cassava mosaic begomoviruses, cotton leaf curl-associated viruses	<i>Bemisia tabaci</i> complex	Persistent, circulative
Crinivirus	Closteroviridae	Tomato chlorosis virus, Cucurbit yellow stunting disorder virus	<i>B. tabaci</i> and other competent whiteflies	Semi-persistent
Ipomovirus	Potyviridae	Cucumber vein yellowing virus	<i>B. tabaci</i>	Semi-persistent
Torradovirus	Secoviridae	Tomato torrado virus	<i>B. tabaci</i> and/or <i>Trialeurodes vaporariorum</i> , depending on virus	Semi-persistent
Carlavirus	Betaflexiviridae	Selected whitefly-transmitted species	Primarily <i>Bemisia</i> spp.	Non-circulative relationships reported

How does a whitefly transmit a Begomovirus?

Whiteflies possess piercing-sucking mouthparts specially adapted for feeding on plant vascular tissues. During feeding, the stylets penetrate plant tissues until they reach the phloem. If the plant is infected, virus particles present in the phloem sap may be acquired by the feeding adult. The pathway followed by a begomovirus can be represented simply as:

Infected plant → phloem feeding → whitefly gut → haemolymph → salivary glands → healthy plant

After ingestion, virus particles pass through the alimentary canal and reach the midgut. To become transmissible, they must cross the gut epithelial barrier and enter the haemolymph. Virions then circulate within the insect and ultimately reach the primary salivary glands. During later feeding on a healthy plant, the virus is released with the saliva and introduced into plant tissue (Ghanim, 2014; Ghosh and Ghanim, 2021). Because the virus must pass through several internal barriers, transmission is not simply a matter of the insect carrying contaminated plant sap. Successful transmission depends on specific biological and molecular interactions between the virus and its vector.

Interactions between whiteflies and viruses

Research during the last two decades has greatly improved our understanding of how viruses move through whitefly tissues.

1. Viral coat protein and vector recognition

The begomovirus coat protein is important not only for protecting the viral genome but also for interactions with vector tissues. Differences in the ability of viral particles to interact with whitefly proteins can influence whether a particular virus is efficiently transmitted. An important breakthrough was the discovery of the cubilin-amnionless, or Cubam, receptor complex in the *B. tabaci* midgut. Cubilin (CUBN) and amnionless (AMN) form a receptor complex that can interact with begomovirus capsid proteins. Zhao et al. (2020) demonstrated that this interaction facilitates virus entry into midgut epithelial cells through an endocytic pathway. Reducing the expression of receptor components decreased virus acquisition and

transmission, providing direct evidence that specific whitefly receptors participate in vector competence.

2. Heat-shock proteins

Heat-shock protein 70 (HSP70) has also been implicated in begomovirus–whitefly interactions. Götz et al. (2012) demonstrated an association between HSP70 and begomoviruses within the whitefly and showed that alteration of this interaction can influence virus transmission. These findings illustrate that virus movement through a whitefly is an active biological process involving several insect proteins rather than simple passive circulation.

3. Role of bacterial endosymbionts

Whiteflies live in close association with bacterial endosymbionts. The obligate symbiont *Portiera aleyrodidarum* provides nutrients that are scarce in phloem sap, while facultative symbionts may differ among whitefly populations. One historically important observation involved a GroEL-like chaperonin produced by whitefly-associated bacteria. Morin et al. (1999) demonstrated that the protein could interact with Tomato yellow leaf curl virus and proposed that this association helped protect virus particles during passage through the haemolymph. The involvement of symbiont-associated proteins, however, should not be assumed to be identical in every whitefly-virus combination. Symbiont composition varies among whitefly populations, and different viruses may interact differently with their vectors.

4. The plant-virus-whitefly relationship

Transmission involves three partners rather than two: the plant, the virus and the whitefly. Virus infection can change the physiology of a host plant by modifying nutrient composition, volatile production, defence signalling and other metabolic processes. These changes may subsequently affect whitefly attraction, settling behaviour, feeding and reproduction. Interesting behavioural patterns have been documented in several virus–whitefly systems. Non-viruliferous whiteflies may show increased attraction towards virus-infected plants, which can increase the chance of acquiring the virus. After virus acquisition, changes in preference may encourage movement towards uninfected plants, thereby favouring further transmission (Zhao et al., 2022). However, this should not be treated as a universal rule. The response depends on the particular virus, whitefly species, plant genotype and environmental conditions. Whitefly feeding itself also induces plant defence responses. Salicylic acid, jasmonic acid and other signalling pathways can participate in these responses, while whitefly salivary effectors may modify plant immunity (Morin et al., 2024). Virus epidemics in the field are therefore influenced by a complex network of interactions rather than by whitefly numbers alone.

Why are whitefly-transmitted viral diseases difficult to control?

One of the greatest challenges in managing these diseases is that relatively few viruliferous adults may be sufficient to initiate infection. An insecticide may eventually kill a feeding whitefly, but the insect may have already inoculated the virus before mortality occurs. Consequently, successful suppression of the vector population does not always produce an equivalent reduction in virus incidence. Another major concern is the evolution of insecticide resistance. *Bemisia tabaci* populations have developed resistance to several insecticide groups used repeatedly against them (Horowitz et al., 2020). Heavy dependence on chemical control can therefore become progressively less effective and may also interfere with beneficial insects. Management should consequently focus on preventing or delaying infection, not simply killing whiteflies after they have established in the crop.

Integrated management strategies

1. Start with healthy planting material

Virus-free seedlings and propagating material are the first line of defence. Seedlings should preferably be raised in protected nurseries where whitefly entry is minimized. Early infection often has a greater effect on crop growth and yield than infection occurring later.

2. Grow resistant or tolerant varieties

Where available, resistant cultivars offer one of the most sustainable approaches to reducing viral disease. Resistance may restrict virus infection, reduce symptom severity or minimize

yield loss. Combining virus resistance with traits that reduce whitefly colonization can provide additional protection.

3. Reduce sources of virus inoculum

Infected crop plants, volunteer plants and suitable weed hosts may maintain viruses and whiteflies between cropping periods. Removal of important sources of inoculum, together with good field sanitation, can reduce opportunities for disease spread. Roguing infected plants can be useful under appropriate circumstances, particularly when disease incidence is low and infected plants can be removed before they become major sources of virus.

4. Use physical and cultural methods

Insect-proof netting can reduce whitefly entry into nurseries and protected cultivation. Reflective or UV-modifying materials may interfere with host location by flying adults in some cropping systems. Appropriate planting periods, crop-free intervals where locally suitable, removal of crop residues and synchronized cultivation may also reduce vector and virus carry-over. Yellow sticky traps can be useful for monitoring adult whiteflies, although traps alone should not be expected to control high populations.

5. Protect natural enemies

Whiteflies are attacked by several predators and parasitoids. Species belonging to the parasitoid genera *Encarsia* and *Eretmocerus* are particularly important and have been used successfully in biological-control programmes. Predatory insects and mites can also contribute to population suppression (Gerling et al., 2001). Entomopathogenic fungi can provide additional suppression when temperature and humidity favour infection. Conservation of naturally occurring beneficial organisms is therefore an important component of integrated pest management.

6. Use insecticides carefully

Chemical control may still be necessary when whitefly pressure is high, but insecticides should be used as one component of an integrated programme rather than as the sole management measure. Repeated application of products with the same mode of action increases selection pressure for resistance. Rotation among appropriate mode-of-action groups, avoidance of unnecessary sprays, monitoring of local susceptibility and conservation of natural enemies can help maintain the usefulness of available insecticides (Horowitz et al., 2020).

7. Surveillance and early Detection

Early detection is particularly important for invasive whiteflies and emerging virus diseases. Regular crop inspection, yellow sticky-trap monitoring, recognition of suspicious symptoms and timely identification of the vector and virus can help prevent wider establishment. Morphological identification remains important, but closely related whitefly species may be difficult to distinguish reliably. Molecular approaches, including PCR, quantitative PCR, DNA barcoding and increasingly rapid isothermal or field-deployable assays, can complement conventional identification and strengthen surveillance programmes. Rapid and accurate diagnosis allows management measures to be implemented before an infestation or disease outbreak becomes widespread (Brahma et al., 2026).

Future prospects

Advances in molecular entomology are creating new opportunities to interfere directly with virus transmission. Identification of receptors such as the Cubam complex demonstrates that specific whitefly molecules are essential for particular stages of the transmission pathway. Future research may identify additional targets associated with the gut, salivary glands, immune system, salivary effectors and symbiotic microorganisms. RNA interference, host-induced gene silencing and related molecular approaches may eventually complement existing IPM programmes. At the same time, molecular diagnostics are becoming faster, more sensitive and increasingly suitable for use outside sophisticated laboratories. Integration of rapid diagnostics with field surveillance could substantially improve early warning, quarantine and pest-management decisions.

Conclusion

Whiteflies, particularly members of the *Bemisia tabaci* complex, are among the most important vectors of plant viruses affecting agricultural crops. Their importance arises from a combination of wide host range, adaptability, invasive potential and the ability to transmit hundreds of plant viruses. Virus transmission depends on intricate interactions among the whitefly, virus and host plant. Begomoviruses must successfully cross the gut, haemolymph and salivary gland barriers, with specific vector proteins participating at different stages. At the same time, viral infection can alter plant characteristics and vector behaviour in ways that influence disease spread. These complex relationships explain why whitefly-transmitted viral diseases cannot be managed effectively through insecticide use alone. A sustainable programme should integrate healthy planting material, resistant varieties, sanitation, exclusion, cultural practices, conservation of natural enemies, vector monitoring, rapid diagnosis and judicious insecticide use. Improved understanding of the molecular mechanisms underlying virus transmission will further strengthen our ability to develop precise and environmentally sustainable strategies for protecting crops from whitefly-borne viral diseases.

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