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Insects as vectors and emerging trends in plant disease transmission

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Abstract

Insect vectors play a central role in the global spread of plant diseases across agronomic and horticultural crops. Hemipteran insects (e.g. aphids, whiteflies, leafhoppers, plant hoppers, psyllids, mealy bugs) dominate as vectors, transmitting most plant viruses, bacteria (phytopathogens) and phytoplasmas in diverse cropping systems. Insect transmission can be non-persistent (stylet-borne), semi-persistent (foregut-borne) or persistent circulative/propagative, depending on virus localization and retention in the vector. Viral diseases include geminiviruses (whitefly-begomoviruses), potyviruses (aphid-transmitted), luteoviruses, tospoviruses (thrips-transmitted) and others. Bacterial and phytoplasmal diseases (e.g. citrus greening by *Liberibacter*, yellows by phytoplasmas) are spread by xylem- and phloem-feeding hemipterans. Fungal pathogens (e.g. Dutch elm disease *Ophiostoma* by bark beetles) and nematodes (e.g. pinewood nematode by sawyer beetles) are also vectored by insects. Emerging trends include advances in genomics of vector-pathogen interactions, novel control technologies (RNAi, CRISPR, endosymbiont manipulation) and the impact of climate change on vector biology. Integrated disease management requires combining host resistance, cultural practices, biological control of vectors and precise monitoring and forecasting. Global case examples (e.g. begomovirus epidemics, citrus huanglongbing, *Xylella* outbreaks) and Indian scenarios (e.g. rice tungro, cotton leaf curl virus) illustrate the complexity of vector-mediated epidemics. This review synthesizes current knowledge on insect vectors, transmission mechanisms and management of vector-borne plant diseases, with an emphasis on recent research advances and global/Indian case studies.

Keywords: Insect vector, plant pathogen, virus transmission, hemipterans, phytoplasma, integrated management, climate change, genomics, biocontrol

Introduction

Insect vectors are living arthropods—most commonly insects—that acquire pathogens from an infected host (plant, animal or human) and transfer them to a susceptible host, thereby facilitating disease spread. In public health, vectors such as mosquitoes, ticks and sandflies ingest or carry viruses, bacteria or parasites during feeding on an infected host and subsequently inject them into a new host via bites; this role is often biological, as pathogens replicate or develop within the vector before transmission. In agriculture, insect vectors (e.g., aphids, leafhoppers, whiteflies and thrips) acquire plant pathogens—viruses, bacteria, phytoplasmas or fungi—by feeding on diseased tissues or through body contact and inoculate healthy plants during subsequent feeding probes; many plant pathogens are transmitted in non-persistent, semi-persistent or persistent manners, depending on whether they circulate within the insect or adhere to its mouthparts. The efficiency of insects as vectors is determined by vector competence (the ability to acquire, support and transmit a pathogen), vector capacity (including population density and feeding behavior) and environmental factors (temperature, humidity and host availability). Controlling vector-borne diseases relies on interrupting these transmission processes—through chemical, biological or cultural methods—targeting both the vector population and its interaction with hosts.

Insect vectors are vital agents in the epidemiology of plant diseases. An estimated 70-80% of known plant viruses depend on insects for transmission. In particular, piercing-sucking hemipterans (e.g. aphids, whiteflies, leafhoppers, plant hoppers, psyllids, mealy bugs) serve as vectors of viruses, bacteria and phytoplasmas across crop systems. These insects pierce plant tissues to feed, acquiring pathogens and later inoculating healthy plants. The insect's ability to acquire and transmit pathogens is determined by feeding behaviour and specialized virus-vector interactions. Plant viruses have evolved diverse transmission modes (non-persistent, semi-persistent, persistent-circulative, persistent-propagative) governed by where the virus resides in the vector and whether it replicates there. Similarly, bacteria and phytoplasmas are often circulative in phloem-feeding insects, establishing persistent infections in the insect host. Together, these vector-pathogen systems create complex disease cycles that threaten yield and quality in both agronomic and horticultural crops worldwide.

Overview of Insect Vectors and Mechanisms of Disease Transmission

Insect vectors of plant pathogens span several orders, with Hemiptera being most prominent. Major vectors include:

- **Aphids (Aphididae):** Among the most important vectors, transmitting ~30% of plant viruses. They commonly mediate non-persistent (stylet-borne) and circulative virus transmission. Aphids also carry some phytoplasmas.
- **Whiteflies (Aleyrodidae):** Effective global vectors (e.g. *Bemisia tabaci*) that transmit persistent circulative viruses (geminiviruses such as Begomovirus). Whitefly-transmitted viruses have devastated many crops (e.g. cotton, vegetables).
- **Thrips (Thysanoptera):** Tiny vectors of tospoviruses (e.g. Tomato spotted wilt virus) in a persistent-propagative mode. Only thrips can transmit these orthotospoviruses.
- **Leafhoppers and Planthoppers (Cicadellidae/Fulgoroidea):** Phloem-feeders that transmit persistent circulative viruses (e.g. luteoviruses, Fiji viruses) and phytoplasmas. For instance, rice tungro viruses are leafhopper-transmitted and Fiji viruses by planthoppers replicate inside the insect.
- **Psyllids (Psyllidae):** Vectors of phloem-limited bacteria such as *Candidatus Liberibacter* (causing citrus greening) and phytoplasmas (e.g. potato purple top disease). Psyllid vectors like *Diuraphis citri* are highly efficient.
- **Mealybugs (Pseudococcidae):** Sap-sucking insects that spread viruses (e.g. some plant-infecting closteroviruses) in semi-persistent modes.
- **Beetles (Coleoptera):** Although not as ubiquitous as hemipterans, many beetles vector diverse pathogens. Beetle-vectored diseases include viruses (cowpea mosaic virus by bean leaf beetle), bacteria, fungi (see below) and nematodes.

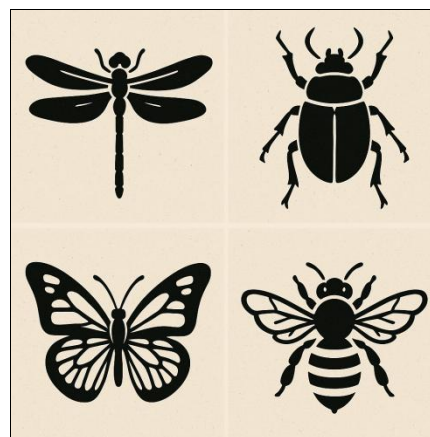
These vectors use specialized mouthparts to pierce plants. Transmission modes are classified as:

- **Non-Persistent (stylet-borne):** Virus adheres briefly to insect mouthparts; rapid acquisition/transmission (seconds to minutes). E.g. potyviruses and cucumoviruses by aphids.
- **Semi-Persistent (foregut-borne):** Virus retained in foregut or mouthparts for hours/days. Acquisition takes longer.
- **Persistent Circulative:** Virus passes through gut into hemolymph and salivary glands but does not replicate in insect. Insect remains viruliferous for life. E.g. many

luteoviruses and begomoviruses.

- **Persistent Propagative:** Virus circulates and also replicates within the vector. Pathogen multiplies inside insect (e.g. phytoplasmas, some reoviruses).

Each mode requires different acquisition/inoculation feeding times and vector physiology. For example, *Fijiviruses* acquired by planthoppers replicate in the vector's gut and salivary glands (propagative transmission). In contrast, geminiviruses in whiteflies are circulative but non-propagative, requiring a latent period within the vector. Viral ligands (coat proteins, helper proteins) and insect receptors govern specificity. Collectively, these mechanisms underlie the efficiency and dynamics of disease spread in crops.



Insect-Transmitted Plant Viruses

Insect vectors are responsible for most economically important plant viruses. Different viruses exploit different vector groups and transmission modes. Notable examples include:

- **Begomoviruses (Geminiviridae):** Circular ssDNA viruses, largest plant virus genus. Transmitted by whiteflies (e.g. *Bemisia tabaci*) in a persistent circulative manner. Begomoviruses cause cotton leaf curl, tomato leaf curl, cassava mosaic, etc. Their bipartite genomes (DNA-A/B) and associated satellites encode proteins for replication and movement. Whiteflies' global distribution has led to begomovirus pandemics.
- **Potviruses (Potyviridae):** The largest RNA virus genus (~176 species). These flexuous filamentous viruses infect many crops (e.g. potato virus Y). Nearly all potyviruses are transmitted by aphids in a non-persistent, stylet-borne mode. Acquisition is rapid; transmission depends on coat protein-aphid receptor interactions (capsid or helper strategy). Potyvirus diversity is worldwide, with >40 species reported in India alone.
- **Luteoviruses (Luteoviridae):** Phloem-limited RNA viruses transmitted persistently by aphids. Examples include cereal yellow dwarf viruses and potato leafroll virus. Transmission is circulative; the virus circulates in aphid hemolymph to salivary glands but does not replicate in the vector.
- **Tospo viruses (Bunyavirales, e.g. Tomato spotted wilt virus):** Negative-strand RNA viruses vectored exclusively by thrips in a persistent-propagative mode. Thrips larvae acquire virus from infected plants and adults transmit it to healthy plants. Tospoviruses cause severe diseases in tomato, pepper and ornamentals.
- **Other Virus Groups:** Geminivirus genera Mastrevirus (maize streak virus by leafhoppers), Capulavirus, etc.;

Closteroviruses (BYDV by aphids, Beet yellows virus by aphids); Nepoviruses/picornavirus-like by beetles or flies; Tobamoviruses largely mechanical (rarely vectored by insects). Many viruses rely on insects to reach new hosts.

Viruses often manipulate vectors and host plants to enhance transmission. For example, infected plants may become more

attractive to vectors or vectors may exhibit altered feeding behaviours when viruliferous. Circulative viruses may alter vector physiology or survival to facilitate spread. Studying the molecular virus-vector interface (e.g. aphid receptors for viral coat proteins) has revealed targets for disrupting transmission.

Insects as Vectors

S. No.	Insect Vector (Scientific Name)	Type of Insect	Disease Transmitted	Causal Agent	Host Plant Examples
1	<i>Bemisia tabaci</i>	Whitefly	Tomato Yellow Leaf Curl	Tomato Yellow Leaf Curl Virus (TYLCV)	Tomato, Chilli, Tobacco
2	<i>Myzus persicae</i>	Aphid	Potato Virus Y	Potyvirus	Potato, Tobacco
3	<i>Nephotettix virescens</i>	Leafhopper	Rice Tungro Disease	Rice Tungro Virus + Bacilliform Virus	Rice
4	<i>Nilaparvata lugens</i>	Planthopper	Rice Grassy Stunt, Ragged Stunt	Reovirus	Rice
5	<i>Frankliniella occidentalis</i>	Thrips	Tomato Spotted Wilt	Tospovirus	Tomato, Groundnut, Chilli
6	<i>Phenacoccus solenopsis</i>	Mealybug	Cotton Leaf Curl	Cotton Leaf Curl Virus	Cotton, Okra
7	<i>Diaphorina citri</i>	Psyllid	Citrus Greening (HLB)	<i>Candidatus liberibacter</i> spp.	Citrus (Orange, Lemon)
8	<i>Circulifer tenellus</i>	Leafhopper	Curly Top Disease	Curtovirus	Sugar beet, Tomato, Pepper
9	<i>Rhopalosiphum maidis</i>	Aphid	Maize Dwarf Mosaic	Potyvirus	Maize, Sorghum
10	<i>Schizaphis graminum</i>	Aphid	Barley Yellow Dwarf	Luteovirus	Wheat, Barley, Oats
11	<i>Aeneolamia</i> spp.	Spittlebug	Sugarcane White Leaf Disease	Phytoplasma	Sugarcane
12	<i>Empoasca fabae</i>	Leafhopper	Aster Yellows	Phytoplasma	Lettuce, Carrot, Onion
13	<i>Brevicoryne brassicae</i>	Aphid	Turnip Mosaic Virus	Potyvirus	Cabbage, Mustard
14	<i>Trialeurodes vaporariorum</i>	Whitefly	Lettuce Infectious Yellows	Crinivirus	Lettuce, Tomato
15	<i>Peregrinus maidis</i>	Planthopper	Maize Mosaic Disease	Nucleorhabdovirus	Maize
16	<i>Hyalesthes obsoletus</i>	Planthopper	Bois Noir (Grapevine yellows)	Phytoplasma (<i>Candidatus Phytoplasma solani</i>)	Grapevine
17	<i>Scaphoideus titanus</i>	Leafhopper	Flavescence dorée	Phytoplasma (<i>Candidatus Phytoplasma vitis</i>)	Grapevine
18	<i>Bemisia argentifolii</i>	Whitefly	Bean Golden Mosaic Virus	Begomovirus	Bean, Tomato
19	<i>Laodelphax striatellus</i>	Planthopper	Rice Stripe Disease	Tenuivirus	Rice
20	<i>Maconellicoccus hirsutus</i>	Mealybug	Hibiscus Mealybug-associated Virus Complex	Virus Complex	Hibiscus, Cotton, Guava

Bacterial and Phytoplasmal Diseases Spread by Insects

Several important bacterial pathogens are transmitted by insects, especially hemipterans:

- ***Xylella fastidiosa*:** A xylem-limited Gram-negative bacterium causing diseases like Pierce's disease in grape, citrus variegated chlorosis and olive quick decline. It is transmitted in a semi-persistent, non-circulative manner by xylem-feeding leafhoppers and spittlebugs. The bacterium attaches to insect foregut surfaces and is inoculated to new plants when the insect feeds. *Xylella*'s broad host range and many vector species have led to epidemics in Europe (olive trees) and Americas.
- ***Candidatus liberibacter* spp. (Huanglongbing - HLB):** Phloem-restricted alpha-proteobacteria causing citrus greening. *Liberibacter asiaticus* is transmitted by the Asian citrus psyllid (*Diaphorina citri*) in a persistent circulative manner. Once acquired, the bacterium circulates within the psyllid for life. HLB has devastated citrus industries; one review notes >\$4 billion annual losses in North America alone.
- **Phytoplasmas:** Wall-less Mollicutes (formerly mycoplasma-like) that infect phloem. Phytoplasmas (e.g. aster yellows, apple proliferation) are transmitted persistently by phloem-feeding leafhoppers, planthoppers and psyllids. They replicate in both plant and insect hosts, causing symptoms like witches'-broom, virescence and phyllody. Phytoplasmas can manipulate vector biology (e.g. increasing fecundity or altering host preference) to promote transmission. Management of these diseases relies on vector

control and removal of infected plants.

- **Spiroplasmas and Rickettsia-like Organisms:** Also transmitted by leafhoppers, causing diseases like corn stunt (Spiroplasma) and phloem necrosis. These obligate, phloem-colonizing bacteria require insects for spread.
- **Other Bacteria:** Some bacteria (e.g. *Erwinia*, *Clavibacter*) are occasionally vectored by sucking insects, but many are spread by soil, tools or contact rather than insects.

Notably, the transmission of phloem specialists (*Liberibacter*, phytoplasmas) tends to be persistent and circulative, whereas the xylem specialist *Xylella* is semi-persistent/non-circulative. Control strategies focus heavily on insecticide applications and removal of symptomatic trees, since resistant cultivars are scarce.

Fungal and Nematode Pathogens Facilitated by Insect Activity

Insects also act as vectors or facilitators for fungal and nematode diseases:

- **Fungal Pathogens:** Many wood- and bark-infecting fungi hitchhike on beetles. Dutch elm disease (caused by *Ophiostoma ulmi* and *O. novo-ulmi*) is spread by elm bark beetles (Scolytinae). Similarly, laurel wilt (caused by *Raffaelealauricola*) is transmitted by ambrosia beetles. Bark beetles commonly carry *Ophiostomatoid* fungi that cause blue-stain and cankers in conifers and hardwoods. In agriculture, nitidulid beetles vector fruit tree fungal diseases (e.g. the bitter rot pathogen *Glomerella* in apples). In many

cases, beetle feeding or breeding galleries create infection courts for fungi.

- **Nematodes:** Certain plant-parasitic nematodes are vectored by insects. The pinewood nematode (*Bursaphelenchus xylophilus*), which causes pine wilt, is carried by cerambycid pine sawyer beetles (*Monochamus* spp.). Dispersal-stage nematodes survive in the tracheae of adult beetles and exit into pine trees during beetle feeding or oviposition. Pine wilt has killed millions of pine trees in Asia and Europe. Another example is the red ring nematode (*B. cocophilus*), which invades coconut palm and is spread by the red palm weevil (*Rhynchophorus palmarum*). These beetles carry nematodes in their bodies or feces, infecting palms during feeding.
- **Others:** Some nematodes (e.g. hop stunt viroid vectors) are indirectly influenced by insect wounds or activities. In summary, insect feeding can create wounds or introduce fungal/nematode inoculum, significantly affecting disease incidence.

Overall, beetle-fungus and beetle-nematode symbioses are critical in forestry and some cropping systems. The broad role of insects in disseminating diverse pathogens underscores the importance of understanding vector biology beyond just viruses and bacteria.

Emerging Trends in Vector Biology and Epidemiology

Recent advances are reshaping our understanding of vector-borne diseases.

- **Molecular and Omics Insights:** High-throughput sequencing and transcriptomics are uncovering the genetic bases of vector competence. Studies of vector transcriptomes (e.g. *Bemisia*, *Myzus*) during infection reveal immune and metabolic pathways involved in pathogen acquisition. Host-vector co-evolution has become a focus, recognizing that symbiotic bacteria (e.g. *Wolbachia*, *Rickettsia*) in vectors can influence pathogen transmission efficiency. The role of vector microbiomes is an active research area (reviewed in Pathogens 2016).
- **Vector-Pathogen Interaction Mechanisms:** Detailed studies identify insect receptors and virus proteins required for transmission. For example, aphid stylet proteins binding potyvirus coat protein have been characterized and blocking these interactions (via RNAi) can reduce virus spread. Similarly, plant and insect factors that facilitate or inhibit pathogen passage (e.g. endosymbiont-derived peptides) are under investigation.
- **Genomic Tools and Gene Editing:** CRISPR/Cas and RNA interference (RNAi) are being developed to target vectors. Proof-of-concept studies have created transgenic plants expressing dsRNA that silence essential genes in feeding insects, reducing vector fitness or blocking pathogen replication. Paratransgenesis - genetically modifying symbionts in the vector - is explored as a means to deliver anti-pathogen effectors (originally used in mosquito vectors). Although in early stages for plant systems, these approaches represent a novel frontier in vector management.
- **Remote Sensing and Modelling:** Advances in remote sensing, GIS and predictive modelling improve monitoring of vector populations and disease risk. Real-time weather data, coupled with vector ecology models, allow forecasting of outbreak conditions. For example, degree-day models predict aphid flight periods, aiding timely interventions. Climate-driven distribution models project potential

expansion of vectors into new regions (see next section).

- **Behavioural and Ecological Studies:** Improved methodologies like Electrical Penetration Graph (EPG) analyses elucidate detailed feeding behaviours tied to transmission events. Landscape-level studies reveal how habitat fragmentation or cropping systems affect vector movement and inter-crop spread. Network analyses are being applied to vector-plant-pathogen interactions to predict emergent epidemics.

In sum, emerging technologies - from molecular biology to informatics - are enhancing our ability to dissect vector-pathogen systems and devise targeted control strategies. Continued integration of these disciplines is critical as new vector species and pathogens emerge.

Impact of Climate Change on Vector-Pathogen Dynamics

Climate change is increasingly recognized as a driver of vector-borne plant diseases. Rising temperatures, altered precipitation and increased CO₂ levels affect insect biology and disease epidemiology. Key impacts include:

- **Range Expansion:** Warmer climates allow insect vectors to expand poleward or to higher elevations. For instance, whitefly *Bemisia tabaci* biotypes have spread into regions that were previously unsuitable, carrying geminiviruses with them. Note that global warming can expand pest geographic range and increase invasive species risk. In India and globally, there is concern that vector ranges will broaden, exposing new crops to insect-transmitted pathogens.
- **Overwinter Survival and Generations:** Milder winters increase overwinter survival of temperate vectors (e.g. aphids, plant hoppers). Higher temperatures can also increase the number of generations per year, leading to more vector population build-up and virus spread. For example, elevated temperatures have been linked to earlier onset of rice plant hopper populations in Asia, exacerbating rice tungro outbreaks.
- **Vector-Pathogen Synchronicity:** Climate change can disrupt or enhance the synchronization between vector life cycles and plant susceptibility. Changes in precipitation and humidity influence vector breeding sites (e.g. mosquitos, but also plant hoppers in rice paddies). emphasize that climate-induced phenological shifts may increase insect-transmitted disease incidence.
- **Indirect Effects on Hosts:** Increased CO₂ and drought stress can alter plant physiology (e.g. phloem composition), which in turn may affect vector feeding behaviour and pathogen multiplication. Nutrient-poor phloem under drought may concentrate viruses, potentially changing transmission efficiency.
- **Extreme Events:** Climate extremes (storms, heatwaves) can lead to sudden vector dispersal or crop vulnerability. For example, storm-driven long-distance dispersal of aphids carrying new virus strains has been documented.

Overall, climate change is projected to increase the incidence and unpredictability of insect-vectored diseases. Adaptive management (see next) and continual monitoring of vector populations will be essential under changing conditions.

Integrated Management Approaches

Preventing and controlling vector-borne diseases requires integrated strategies that combine multiple tactics:

- **Cultural Practices:** Crop rotation, removal of alternate host plants and weeds and sanitation reduce sources of both vectors and pathogens. For example, destroying volunteer plants or uncultivated hosts of whiteflies can slow begomovirus spread. Adjusting planting dates to avoid peak vector flights or using reflective mulches to deter aphids have proven useful.
- **Host Resistance:** Breeding and deploying resistant or tolerant cultivars is an effective long-term strategy. Resistance genes (e.g. Ty genes in tomato for begomovirus tolerance) can dramatically reduce disease incidence. However, for many virus and phytoplasma diseases, genetic resistance is limited. Transgenic virus-resistant plants (expressing viral coat proteins or RNAi constructs) have been developed for some crops (e.g. papaya ring spot). Similarly, tolerant rootstocks are used to manage citrus greening.
- **Chemical Control:** Judicious use of insecticides can reduce vector populations and break transmission cycles. Systemic neonicotinoids or pyrethroids are often used against aphids, whiteflies and psyllids. However, reliance on chemicals risks resistance development and non-target impacts. For persistent pathogens (e.g. phytoplasmas), insecticide-treated border rows or barrier sprays can slow disease ingress.
- **Biological Control:** Natural enemies (predators, parasitoids, entomopathogenic fungi) can suppress vectors. For example, *Encarsia* and *Eretmocerus* wasps are effective biocontrol agents of whiteflies. Lady beetles and lacewings feed on aphids and whiteflies. Deployment of entomopathogenic fungi (e.g. *Beauveria bassiana*) against plant hoppers or thrips is being explored. Conservation biocontrol (e.g. intercropping to attract predators) helps maintain these beneficial.
- **Physical and Mechanical Controls:** In protected environments (greenhouses), insect-proof screening, UV-absorbing films or sticky traps limit vector entry. Row covers on field crops can exclude aphids during early growth stages.
- **Monitoring and Forecasting:** Integrated pest management (IPM) emphasizes regular scouting and use of thresholds. Yellow sticky traps and pheromone traps help monitor vector abundance. Incorporating climate and pest models improves forecasting outbreaks, enabling timely interventions.
- **Emerging Biotechnologies:** RNAi sprays (spray-induced gene silencing) are being developed to target critical genes in vectors or pathogens. For instance, dsRNA applied to plants can be ingested by sap-feeders, silencing vector genes and reducing viability. Paratransgenesis (see above) remains experimental but holds promise for the future.

Each approach has trade-offs, so a combination is recommended. For example, managing citrus greening involves psyllid control (insecticides, parasitoids), removal of infected trees and use of disease-free planting material. In rice tungro, resistant varieties, leafhopper control and planting timing are combined. Continual innovation (e.g. exploiting endosymbionts to block transmission) is required to stay ahead of evolving vector-pathogen systems.

Case Studies from Global and Indian Contexts

Global Examples: Vector-borne diseases have caused major international crop crises. *Cotton leaf curl virus* (a begomovirus

complex) transmitted by *Bemisia tabaci* has periodically devastated cotton in South Asia, the Middle East and Africa. *Rice tungro disease* (two viruses by green leafhoppers) repeatedly causes up to 100% yield loss in South and Southeast Asia. Citrus *huanglongbing* (HLB) is now the most damaging citrus disease worldwide; spread by *Diaphorinacitri*, it has forced drastic measures in Florida, Brazil and China. In Europe, *Xylella fastidiosa* spread by spittlebugs and sharpshooters has decimated olives in Italy and vine infections in France. Phytoplasma outbreaks (e.g. grapevine yellows, elm phloem necrosis) illustrate vector impact in horticulture.

Indian Examples: India's diverse agriculture sees numerous vector-borne diseases. Rice tungro (vector: *Nephotettix* leafhoppers) remains a chronic problem in paddy fields. *Cotton leaf curl disease* (a complex of begomoviruses) transmitted by whiteflies causes severe cotton losses in India and Pakistan. Many vegetable and fruit viruses (e.g. cucumber mosaic, tomato yellow leaf curl, banana bunchy top) are transmitted by aphids or whiteflies. In horticulture, the spread of *Ca. Liberibacter asiaticus* (HLB) into India's citrus belts poses an emerging threat. Notably, surveys find a high diversity of potyviruses in India (43 species recorded), reflecting rich viral diversity vectored by aphids. Integrated management in India often combines traditional practices (e.g. planting Marigolds to deter whiteflies) with modern tools (biopesticides, resistant cultivars).

These case studies underscore the ubiquity and severity of vector-transmitted diseases. Worldwide, climatic and trade changes allow invasive vectors (e.g. exotic psyllids, planthoppers) to move into new regions, potentially introducing novel pathogens. Thus, national and global surveillance, quarantine and collaborative research (e.g. International Plant Protection Convention efforts) are key to managing emerging vector-borne plant diseases.

Conclusion

Insect vectors remain central to the epidemiology of plant diseases. A broad array of insects - from aphids to beetles - transmit viruses, bacteria, phytoplasmas, fungi and nematodes, affecting both staple and specialty crops. Understanding the mechanisms of transmission (behavioural, molecular, ecological) is critical for developing effective controls. Emerging research in genomics, microbiomes and climate modelling provides new insights into vector biology. However, climate change and globalization continue to challenge existing management approaches by expanding vector ranges and introducing new diseases. An integrated management strategy, combining cultural, biological and novel biotechnological tools, is essential to mitigate vector-borne plant diseases. Continued surveillance, interdisciplinary research and adoption of innovative technologies will be vital for safeguarding crop health in a changing world.

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