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Aphid-Transmitted Plant Viruses: Epidemiology and Integrated Vector Management

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Abstract

Plant-aphid-virus interactions pose a significant threat to global crop production and food security. Aphids transmit plant viruses through persistent, semi-persistent and non-persistent modes, affecting the epidemiology of viral diseases in diverse host plants. Spatial patterns, vector behaviour, migration, and environmental factors such as temperature, humidity, rainfall, and landscape features influence Transmission dynamics. Advances in epidemiological modelling, geographic information systems (GIS), remote sensing, and molecular diagnostics have improved monitoring and detection of aphids and viruses. Integrated vector management strategies, including cultural, biological, chemical, host plant resistance, and physical control, are limiting factors that reduce aphid populations and virus spread. However, management is challenged by the rapid reproduction of aphids, complex virus-vector-host interactions, and the adaptability of viral strains. Key knowledge gaps persist, particularly regarding interactions under field conditions in tropical and subtropical systems. Future directions emphasize biotechnological and digital innovations, including nanotechnology, CRISPR/Cas-based resistance, artificial intelligence, and decision support systems to enhance disease forecasting and crop resilience. Sustainable management of aphid-transmitted plant viruses requires strengthening international collaboration and coordinated surveillance. This review synthesizes current knowledge on epidemiology, biology, and integrated management of aphid-transmitted viruses, while highlighting challenges, research gaps, and emerging innovations to support sustainable agriculture.

Keywords: Aphid-transmitted viruses, Plant virus epidemiology, Integrated vector management, Virus-vector interactions, Virus transmission mechanisms, Aphid life cycle, Virus host range

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Introduction

Background and Significance

Plant viruses are a threat to global crop production, causing enormous yield losses and threatening food security. A wide range of plants are affected by plant viruses, causing significant crop losses; even in the United States, losses are estimated to be approximately US$60 billion (Abdelkhalek and Hafez, 2019). This danger is intensified by the fact that new viral strains are being produced that can adapt to transformations in agriculture, climatic conditions and plant transport worldwide. The transmission and control of viral diseases represent further complexities (Jangra *et al*., 2024). The synergistic effects of virus mixtures are ranked as their harm to crops (Ghosh *et al*., 2021), and also qualify as synergism by virus-vectors. Conventional control interventions are environmental hazards and stimulate the evolution of resistant strains, and new methods of control, including biocontrol and gene editing, can be used to counteract them (Abdelkhalek and Hafez, 2021; Abdelkhalek and Hafez, 2019; Roonjho *et al*., 2022).

Viruses transmitted by aphids cause serious diseases in plants and are also difficult to manage (Dedryver *et al*., 2010). They are transmitted by aphids in both persistent and non-persistent manners, thus affecting viral diseases in crops (Jayasinghe *et al*., 2021). Within plant-infecting RNA viruses spread by aphids, potyviruses cause significant losses in global crop productivity (Gadhave *et al*., 2020). The host-pathogen communication between plant viruses and aphid vectors has the ability to manipulate various defence mechanisms of the host plant, which consequently favours the growth of the aphid population (Wu and Ye, 2020). This is causing aphid-transmitted viruses not only to lower crop yield but also to reduce crop quality, and they modify the responses of the plants and cause insect infestation (Moya-Ruiz *et al*., 2023). These viruses have the potential of being of significant economic and food security relevance as regards crop security, including cereals or cucurbits, among other plants. Aphid-transmitted barley yellow dwarf virus caused a 39 percent decrease in wheat yield in Australia (Valenzuela and Hoffmann, 2014). An urgent problem is the presence of the cucurbit aphid-borne yellows virus (CABYV) that is known to spread rapidly and is already a major problem in the Mediterranean warm zones as well as in Asia, where outbreaks have been critical (Rabadan *et al*., 2025). All these effects portend the complexities that must be employed in the management of the virus.

Scope and Objectives of the Review

This review organizes current knowledge on the biology, ecology, and epidemiology of aphid-transmitted plant viruses. It emphasizes virus transmission mechanisms, host interactions, and the environmental factors shaping disease dynamics. Classical and emerging management strategies, ranging from cultural and biological control to advanced molecular and digital innovations, are evaluated in this study. The review clarifies the challenges posed by aphid-virus interactions and highlights pathways toward sustainable management.

Goals of the Review

- To examine the mechanisms of aphid-transmitted viruses in crop systems.
- To identify the economic and ecological impacts of aphid-transmitted viruses on agriculture.
- To evaluate existing and emerging management strategies for the sustainable control of these viruses.

Research Questions

- What are the major aphid species responsible for transmitting economically important plant viruses?
- How do aphid-virus interactions differ across persistent, semi-persistent, and non-persistent transmission modes?
- What are the principal challenges in controlling aphid-transmitted plant viruses under field conditions?
- Which integrated approaches offer the greatest promise for sustainable management of aphid-transmitted viruses?

Innovation and Contribution

This review organizes traditional, cutting-edge molecular and biotechnological approaches to plant virus management. It highlights the role of climate change in expanding aphid-virus interactions and emphasizes future-oriented solutions, including RNA interference (RNAi), CRISPR-based gene editing, nanotechnology, and artificial intelligence. The review aims to provide a framework for sustainable strategies against aphid-transmitted plant viruses by bridging applied pest management with advanced innovations.

Structure of the Paper

This review is organized into thematic sections. Section 2 outlines the biology and ecology of aphids, with emphasis on their life cycle and environmental responses. Section 3 reviews the mechanisms of different modes of virus transmission. Section 4 discusses host range and virus specificity, while Section 5 highlights epidemiological dynamics and environmental influences. Section 6 examines diagnostic and monitoring tools for virus detection and forecasting. Section 7 presents integrated vector management strategies, followed by Section 8 on challenges and knowledge gaps. Section 9 explores future directions and innovations, and Section 10 concludes with recommendations for sustainable management.

Biology and Ecology of Aphids

Life Cycle and Dispersal Mechanisms

Aphids have multifaceted life cycles involving sexual and asexual reproduction with the ability of parthenogenesis to increase their population quickly without mating (Sandhi and Reddy, 2020). They show phenotypic plasticity, in that they can either develop winged forms or wingless forms depending on environmental conditions (Grantham *et al.*, 2016). The transmission of viruses is of great significance when winged forms spread to geographically extensive areas that promote viral infection on new host plants (Guo *et al.*, 2023).

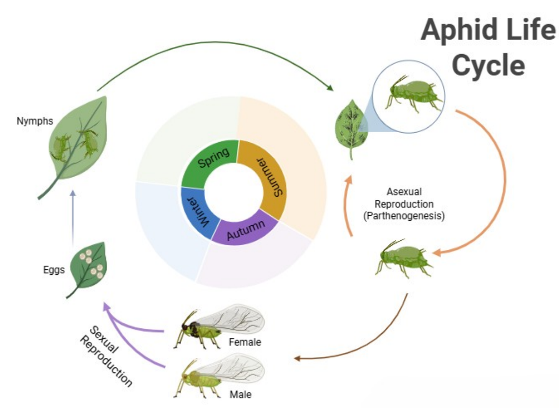

Figure 1: Aphid Lifecycle

The aphid life cycle is illustrated in **Figure 1.** It is far more complicated, being structured around sexual and asexual reproduction with close correspondence to the seasonal changes of the environment. In the summer, weather conditions favouring their survival, aphids can asexually reproduce by means of the process called parthenogenesis, which is expressed when females mate and increase their population by producing genetically identical offspring (Wang *et al.*, 2024). These wingless females, known as the stem mothers, lay numerous generations of live descendants (nymphs), which grow into mature stem mothers in a short span of time and continue the process of parthenogenetic reproduction. This process enhances the development of the exponentially growing population after a given duration of time. The onset of autumn switches reproduction mode to sexual reproduction. They give birth to winged males and sexual females who, in turn, reproduce through mating, thus producing fertilized eggs. These eggs are deposited on perennial hosts and can enter to state of dormancy in winter, hence continuously enriching species existence in case of adverse winter circumstances. In spring, these eggs that have overwintered hatch as nymphs, start the cycle again (Grantham *et al*., 2016). This switching between reproductive modes, together with seasonal morphological shifts, like seasonal wing growth/loss, allows aphids to quickly colonize their host plants whilst still ensuring genetic variation across generations and resistance to natural selection (Barberà *et al*., 2018).

Environmental Influences

Population dynamics of aphids are subject to a lot of factors of influence, which include temperature, availability of hosts, natural enemies, and environmental conditions. Temperature is key to planning plant budburst and aphid emergence, and it could cause a mismatch, which may affect the population growth (Senior *et al*., 2020). A non-additive effect on the population of aphids can result where there is an effect on the aphid spatial distribution and population size due to the availability of hosts, especially through the genetic quality and diversity of plants (Underwood, 2009). Aphids interact with their natural enemies, including parasitoids and predators, in both mutual and antagonistic relationships, with such interactions being mainly negative (they reduce the number of aphids due to predation and parasitism) (Sanchez *et al*., 2019). Environmental conditions, including the availability of artificial light at night and the land structures, have the capacity to alter the abundance of aphids, and components like the season precipitation during the growing season period and the destruction of habitat significantly influence the population variability (Sanders *et al*., 2015; Whitney *et al*., 2016).

Virus Transmission Mechanisms

Transmission Modes

Plant viruses transmitted by aphids are classified into three categories based on the type of transmission and interaction process with the vector, which include non-persistent, semi-persistent, and persistent modes of transmission (Gadhave *et al*., 2019). In the non-persistent mode, viruses are acquired and inoculated within seconds to minutes during brief epidermal probing, and they are rapidly lost from the vector's stylet. Such viruses rely on high aphid mobility and frequent probing to spread rapidly across host populations (Carr *et al*., 2020; Ng & Perry, 2004).

In semi-persistent transmission, viruses are retained for several hours to days in the foregut but are not circulative. This allows vectors to transmit efficiently within fields, although dispersal potential is lower than non-persistent viruses. Examples include Cauliflower mosaic virus, which is restricted to localized outbreaks but can still cause significant crop losses under favourable environmental conditions (Pinheiro *et al*., 2019; Stevens and Lacomme, 2017).

Persistent transmission involves a more intimate interaction, where viruses circulate within the aphid's body and often reach the salivary glands, enabling long-term transmission throughout the aphid's life. These viruses are epidemiologically significant because they require longer feeding periods for acquisition but are retained for weeks or even a lifetime (Mattia *et al*., 2020). Barley yellow dwarf virus (BYDV), transmitted by *Rhopalosiphum padi* and *Sitobion miscanthi* through persistent mode in wheat and barley, causes yield reductions of up to 39% in cereals (Girvin *et al*., 2017). In South Asia, including Pakistan, BYDV is a serious constraint to wheat production, with symptom-based surveys confirming widespread incidence (Ibrahim & Shah, 2015). Such examples illustrate how persistent transmission contributes directly to agricultural losses and highlight the importance of integrating virus-vector epidemiology into management strategies.

Host Range and Virus Specificity

Crop and Weed Hosts

The aphid-transmitted viruses have a remarkably wide range of host species. The presence of weeds within and around crops is of epidemiological significance because it serves as a virus reservoir, and this also aids the evolution of the virus. Aphid-transmitted viruses have been revealed to have tremendous variation in the host range of various virus species, as illustrated in Table 1.

Table 1: Major aphid species, host plants, associated plant viruses, and modes of viral transmission.

Aphid species	**Host plants**	**Virus Transmitted**		**Reference**
		Virus	Mode of Transmission	
Aphis gossypii	Polyphagous (cucurbits) *Gossypium hirsutum* *Carica papaya*	Papaya ringspot virus (PRSV)	Non-persistent	(Kalleshwaraswamy & Kumar, 2008) (Mauck *et al*., 2010) (Carmo-Sousa *et al*., 2016) (Gadhave *et al*., 2019)
		Zucchini yellow mosaic virus (ZYMV)	Non-persistent	
		Cucumber mosaic virus (CMV)	Non-persistent	
		Cucurbit aphid-borne yellows virus (CABYV)	Persistent	
Myzus persicae	(more than 40 families) Brassicaceae and Solanaceae families	Potato leafroll virus (PLRV)	Persistent	(Pinheiro *et al*., 2017) (Pinheiro *et al*., 2019) (Casteel *et al*., 2014)
		Potato virus Y (PVY)	Non-persistent	
		Turnip mosaic virus (TuMV)	Non-persistent	
Acyrthosiphon gossypii	Polyphagous (Cucurbitaceae, Solanaceae, and Rutaceae families)	Cucumber mosaic virus (CMV)	Non-persistent	(Charaabi *et al*., 2008)
Diuraphis noxia	Poaceae family (*Triticum aestivum* and *Hordeum vulgare*)	Barley yellow dwarf virus (BYDV)	Persistent	(El Bouhssini *et al*., 2010)
Rhopalosiphum maidis	*Zea mays*, *Sorghum bicolor* and *Hordeum vulgare*	Maize yellow dwarf virus (MYDV)	Persistent	(Chen *et al*., 2019) (Nault *et al*., 2009)
		Barley yellow dwarf virus (BYDV)	persistent	
		Sugarcane mosaic virus (SCMV)	Non-persistent	
		Cucumber mosaic virus (CMV)	non-persistent	
Rhopalosiphum padi	(winter) *Prunus padus* (summer) (Cereals) *Hordeum vulgare*	Barley yellow dwarf virus (BYDV)	Persistent	(Leather *et al*., 1989)
Rhopalosiphum rufiabdominalis	(Cereals) *Hordeum vulgare*, *Triticum aestivum*, and *Avena sativa*	Barley yellow dwarf virus (BYDV)	Persistent	(Ingwell *et al*., 2012)
Sitobion miscanthi	(Cereals) *Hordeum vulgare*, *Dactylis glomerata*	Barley yellow dwarf virus (BYDV)	Persistent	(Sunnucks *et al*., 1998)

	and *Secale cereale*			
Aphis glycines	*Glycine max*	Soybean mosaic virus (SMV)	Non-persistent	(Clark & Perry, 2002) (Hill *et al.*, 2001)
		Bean Yellow Mosaic Virus (BYMV)	Non-persistent	
		Alfalfa mosaic virus (AMV)	Non-persistent	
Aphis fabae	*Vicia faba, Beta vulgaris, Chenopodium album*, and *Tanacetum vulgare*	Bean common mosaic virus (BCMV)	Non-persistent	(Völkl & Stechmann, 1998) (Wamonje *et al.*, 2020)
		Bean common mosaic necrosis virus (BCMNV)	Non-persistent	
		Cucumber mosaic virus (CMV)	Non-persistent	
Aphis craccivora	(Legumes) *Vigna unguiculata, Medicago sativa* and *Robinia pseudoacacia*	Groundnut rosette virus (GRV)	Semi-persistent	(Angelella *et al.*, 2018) (Murant, 1990)
		Groundnut rosette assistor virus (GRAV)	Semi-persistent	
		Cowpea aphid-borne mosaic virus (CABMV)	Non-persistent	
Schizaphis graminum	(Poaceae family) *Triticum aestivum, Hordeum vulgare* and *Avena sativa*	Barley yellow dwarf virus (BYDV)	Non-persistent	(Power, 1996)
Melanaphis sacchari	*Sorghum bicolor* and *Sorghum halepense*	Sugarcane yellow leaf virus (SCYLV)	Non-persistent	(Medina *et al.*, 2017) (Chinnaraja & Viswanathan, 2015)
Acyrthosiphon pisum	*Vicia faba*	Pea enation mosaic virus (PEMV)	Persistent	(Schwartzberg *et al.*, 2011) (Hodge & Powell, 2008)
		Bean yellow mosaic virus (BYMV)	Non-persistent	

The association between the common aphid vectors, their host vegetables, the name of the transmitted virus and the nature of virus transmission is briefly summarized in **Table 1**. This indicates that aphids are also effective vectors of many economically significant plant viruses, and polyphagous and host-specific species contribute to virus epidemics in many crop production systems. Notably, *Aphis gossypii*, *Myzus persicae* and *Rhopalosiphum maidis* are species that have a wide range of preferences, covering multiple plant families, including the Cucurbitaceae, Solanaceae, and Poaceae. These aphid species are known to spread the viruses, including Papaya ringspot virus (PRSV), cucumber mosaic virus (CMV), potato virus Y (PVY), and barley yellow dwarf virus (BYDV) via different transmission methods, mainly non-persistent and persistent transmission modes (Pinheiro *et al.*, 2019; Gadhave *et al.*, 2019). Cucumber mosaic virus (CMV), which infects a wide host range of more than 1,200 species, including cucurbits and solanaceous vegetables, is transmitted by *Aphis gossypii* and *Myzus persicae* (Mauck *et al.*, 2010). In South Asia, particularly in India and Pakistan, CMV is a major threat to cucurbits and solanaceous crops, leading to severe economic losses (Ghosh *et al.*, 2021).

Cereal-infesting aphid species (*Diuraphis noxia*, *Rhopalosiphum padi* and *Sitobion miscanthi)* are commonly implicated in the persistence of viruses, specifically BYDV and Potato leafroll virus (PLRV), due to their extended feeding, prolonging the transfer of viruses (El Bouhssini *et al.*, 2010; Sunnucks *et al.*, 1998; Leather *et al.*, 1989). On the contrary, persistent mode is not common in viruses PRSV, ZYMV, SMV, and BCMV, indicating a rapid searching interaction with aphids that makes it hard to regulate vectors. Epidemiologically, the diversity of aphid-virus interactions is demonstrated by the existence of semi-persistent forms in legumes and persistent forms in cereals (Angelella *et al*., 2017; Ingwell *et al*., 2012).

Epidemiology and Environmental Dynamics

Transmission Dynamics

Aphid-transmitted plant viruses can be transmitted through primary or secondary vector transmission. Patterns of space and time and aphid migration, and the behaviour of the vectors influence the dynamics of the transmission of the virus. Primary spread means the process of a virus contagion to a crop field by foreign objects, and secondary spread occurs within the field. The efficiency of virus spread within crops is dependent on the vector behaviour, population growth speeds, and movements and is defined by the infection rate and environmental conditions (Shaw *et al*., 2017).

The spread of aphid-transmitted viruses is highly complicated due to most of factors, including the temporal and spatial fluctuations, the speed at which aphids migrate, as well as the behaviour of the vehicle. Presence of natural enemies induces very different spatio-temporal dynamics of cucumber mosaic virus (CMV) and cucurbit aphid-borne yellows virus (CABYV). In the aphid parasitoid *Aphidius colemani*, there was an increase in the early movement of the aphids, leading to an increase in CMV diffusion in the short term. Nevertheless, parasitism may restrict the occurrence and transmission of viruses with persistent infections to considerable levels in the long term, as in the case of CABYV (Krieger *et al*., 2023).

The migratory aspect of aphids, or the trend of how they migrate, is extremely vital to the detection of the transmission of plant viruses. Viral infections tend to produce biochemical changes in plants, depending on the infection, which influences the behaviour of aphids. Such modifications can amplify or decrease plant unresponsiveness to aphid feeding, which can affect the spread of the viruses. Specific viruses infect their host and go ahead to produce volatiles that attract but inhibit settlement by aphids, which enable them to transfer viruses quickly (Carr *et al*., 2020). But, even indirect forces, like virus competition in hosts or vectors, may change the behaviour of vectors showing preference or aversiveness to infected plants, which affects the prevalence and success of viruses (Clemente-Orta *et al*., 2024; Leybourne *et al*., 2024).

Environmental Factors

The impact of climate drivers, including temperature, humidity and rainfall, on the reproduction of aphids and the transmission of the virus is complex, and so is the effect of climate change on aphid phenology and epidemiology of the virus (Jeger *et al*., 2023). The moderation of these interactions was carried by landscape features. Another important determinant is temperature, which has significant effects on the aphid populations. With the rise of warmer temperatures, aphid generations tend to reproduce more due to faster rates of development as well as longer growing periods (Ma *et al*., 2024). But it hurts excessive temperatures. Phenology of a species may change, intuitively resulting in a mismatch between aphids and their food plants or predators, and thus, possibly influencing their population dynamics (Senior *et al*., 2020). In tropical and subtropical agroecosystems, aphid-transmitted viruses are particularly damaging due to environmental fluctuations that favour aphid population surges. Potato virus Y (PVY), transmitted by *Myzus persicae* and *Aphis gossypii*, causes up to 50% yield reduction in susceptible varieties in Pakistan (Abbas *et al*., 2020).

The climate determines the physiology and behaviour of aphids, including the rates of their virus transmission. The transmission and acquisition of viruses by aphids is influenced by temperature. In addition, alterations of plant biochemistry mediated by climate and caused by viral infection may also influence the natural behaviour of aphid feeding towards further transmission dynamics (Donnelly *et al*., 2019). There has been a changing impact of climate change on aphid phenology, thus influencing viral epidemiology. The warmer temperature may cause aphids to advance their life cycle and thus increase virus transmissions due to feeding earlier in the year (Ma *et al*., 2024). They also influence the relationships between aphids and host plants because of changes in the rainfall distribution and the rising number of severe weather conditions (Senior *et al*., 2020).

The key tenets that influence the dynamics and spread of aphids are landscape characteristics like crop diversification or field margins. Crop diversity potentially influences aphid colonization and virus transmission via a variety of ways, including altering available host plants and influencing the microclimate and the agricultural systems (Martay *et al*., 2016). Natural aphid predators may be used as refuges in field margins, thereby aiding in the control of aphid populations and, in effect, reducing the rate of transmission of viruses (Lewis *et al*., 2025).

Modelling Virus Spread

The epidemiology patterns of the plants, which are transmitted through aphids, play a role in the study of how such viruses spread and the mechanisms. The spread of aphids and the viruses they carry is increasingly monitored using Geographic Information Systems (GIS) and remote sensing. GIS technology offers very potent spatial data analysis and mapping tools that will enable the researchers to investigate the distribution of disease and any environmental factor that will determine the behaviour of the vectors (Sangeetha *et al*., 2024). GIS can perform simple mapping and elaborate spatial analysis techniques, which are essential in predicting the spread of a disease and defining the high-risk zones. GIS may be supplemented by remote sensing as it can provide high-resolution pictures of the crop health and habitat of the respective vectors at large scales, hence enhancing this revelation and consequently aiding the development of the apprehension measures (Moya-Ruiz *et al*., 2023).

Despite the progress, current models used to model and monitor the spread of a virus are limited and lack adequate data. Spatial and temporal data integration is also difficult to achieve because the ability to achieve dynamic space-time analysis is not usually found in traditional GIS applications and is essential in the conclusion of strong epidemiological inference. The actual interactions of viruses, vectors, and their life spaces are not always fully considered in the models and may therefore provide an inadequate picture of the state of the disease model. In addition, the quality and resolution of input data required by the GIS-based models may vary and, in some cases, may not suffice to perform the detailed analysis required by management decision support (Forkuo *et al*., 2025; Saran *et al*., 2020).

Detection, Monitoring, and Forecasting Diagnostic Tools

With the appearance of serological and molecular techniques of aphid-transmitted virus detection and surveillance, there have been immense advancements. The technique of enzyme-linked immunosorbent assay (ELISA) is prolific in identifying specific antibodies, hence allowing the epidemiological study at large, and extensive diagnostics (Grossegesse *et al*., 2023). At the molecular level, reverse transcription polymerase chain reaction (RT-PCR) and loop-mediated isothermal amplification (LAMP) are more sensitive and faster and are thus perfect for the detection of viral RNA. They are complemented by diagnostics based on CRISPR that offer precise and potentially on-demand tests. In addition, high-throughput sequencing offers the option of extensive virus identification and characterization, which opens the door to newfound possibilities of tracking viral species and their development at a scale never seen before (Gaafar & Ziebell, 2020).

Aphid Monitoring

Aphid monitoring is one of the key steps in pest management that can be complemented by other technologies. Conventional tools, including yellow sticky traps, only assess the densities of winged aphids at the dispersal stage and cannot be representative of broader population levels, because they do not capture non-flighted offspring (Grupe *et al*., 2023). Thus, the combination of remote sensing and Unmanned Aerial Vehicles (UAVs) has been gaining traction with UAVs fitted with multiple sensors, including hyperspectral and multispectral sensors capable of providing high precision in terms of locating and detecting aphid populations (Ren *et al*., 2025; Alsadik *et al*., 2024). The integration of these high-resolution sources of information with the digital platform can improve the results of analysis and integration of data on the ground and air, as well as contribute to effective pest management decisions and minimize anecdotal approaches (Vanegas *et al*., 2018).

Forecasting Systems

Weather-based models are vital in forecasting aphid breaks by evaluating weather conditions and through pest dynamics simulation algorithms (such as bird cherry-oat aphid population dynamics in barley crops) (Morgan, 2000). Together with the implementation of technologies, these models could predict migrations and the peak populations of aphids and improve the early warning systems (Chaturvedi *et al*., 2025). Besides, there are advantages related to citizen science and farmer networks since they help to provide insight into the process and collect vast quantities of environmental and phenological data with the help of an engaging approach. Such participation not only improves data capture but also increases awareness of the biodiversity and climate change phenomena, which is also evidenced in Ireland's biodiversity monitoring programs (Chandler *et al*., 2016). This form of collaboration that operates on community involvement and technology is also essential to the formation of entire-scale pest management and forecast systems.

Integrated Vector Management (IVM)

Cultural Control

Cultural control methods are vital in the sustainable management of aphids in crop environments. The most important practices include crop rotation, the modification in the date of planting, and intercropping, which disturb the life cycle of aphids because the habitat/time has been changed (the crops will not have the host) and the frequency of infestation is decreased (Luna & House, 2020). The use of trap crops and barrier plants is are biological deterrents which distract aphids from main crops and present a physical obstacle to blocking their way, thus reducing the effect (Khan *et al*., 2019). Elimination of weed hosts and other infected plant debris is a very important sanitation aspect in aphid removal, thereby limiting their spread (Luo *et al*., 2022). These cultural measures can control aphid populations and are efficient in enabling ecological stability as well as protecting the efforts used in controlling the pests by reducing the application of the chemicals that are employed in controlling these aphids.

Biological Control

Biological control of aphids implements all the natural enemies (parasitoids, predators, and entomopathogenic fungi) ever existed to restrain the aphid population in the agricultural context. This method will result in sustainable agriculture as the ecology will be balanced, besides the minimization of the use of chemical pesticides. Other biological control programs involve using parasitoids of several orders, such as Hymenoptera, esp. and Diptera, including *Aphidius ervi*, which is a typical parasitoid of pea aphids with a delayed, yet considerable reduction in aphid population (Goelen *et al*., 2017). *Aphidius colemani* is another good parasitoid, but with the combination of predatory midges, generalist predators like *Orius majusculus* may complement the aphid parasitism by improving direct predation (Rocca & Messelink, 2016). When lady beetles (*Coccinella septempunctata*) and lacewings (*Chrysoperla plorabunda*) are used together, they can reduce the growth of the aphid population until the predators have a synergistic effect (meaning that their action together in combination is greater than their actions individually); however, the interaction is not always synergistic (Wilberts *et al*., 2023).

Chemical Control

The most remarkable aphid mediators are neonicotinoids, which are effective because of their effects on the nerve endings of insects. Nonetheless, these insecticides should be used in a well-managed manner by ensuring that these insecticides are not used in an exaggerated manner, thus leading to non-target effects, particularly the negative non-target effects on the good insects and other ecological organisms. Neonicotinoids (imidacloprid and acetamiprid) are versatile, systemic, and have been reported they be very often employed as seed treatment to maximize efficacy but minimize the number of applications (Lv *et al*., 2023). Although they are effective, these insecticides have a very severe issue regarding resistance. Due to differing neonicotinoid resistances, wheat aphids make it difficult to control the pest since management strategies are a challenge (Xu *et al*., 2022). The occurrence of such resistance is typically driven by the overexpression of enzymes to detoxify the chemical and, in many other instances, mutation at target sites that require a measure of chemical rotation and integrated pest management techniques to slow down the development of resistance (Mottet *et al*., 2024). Therefore, the timing of application and proper use of aphid resistance are important determinants of the success of these control agents in dealing with aphids.

Host Plant Resistance

The use of resistant cultivars remains a cornerstone of integrated virus management. Conservation of genetic resources provides opportunities for sustainable host-vector management through resistance breeding (Al-Bazik, 2024). Another approach in breeding virus-resistant crop varieties is through introducing the resistant genes, as the N gene of Potato virus Y (PVY), and the use of transgenics RNA interference (RNAi) and coat protein resistant. The mechanism of resistance interjection is successfully used through traditional breeding, that is, through the selective breeding of plants with naturally acquired genes that provide resistance to specific viruses (Anwar and Kim, 2020). However, the traditional methods are usually time-consuming and less adaptable to a rapidly evolving viral strain, less adaptable. Transgenic processes, on the other hand, are better because they have the capacity to impart instant disease resistance in plants through direct loading of resistant genes into the plant genome. The technology of RNAi decreases the accumulation of the virus through the degradation of viral RNA, and the coat protein-induced resistance provides an opportunity to express viral proteins that suppress an infection (Singer *et al*., 2021). However, there are still matters regarding the sustainability of the resistance, as viruses can reproduce and overcome single-gene resistance.

Mechanical and Physical Controls

Efficacy and scalability of control of aphid populations may differ when physical and mechanical methods such as reflective mulches, row covers, and sticky traps are applied between different cropping systems. The use of reflective mulches (particularly made of silver plastic) has been seen to be very promising in the impediment of those diseases brought about by aphids and in alleviating aphid populations to enhance crop productivity (Böckmann & Meyhöfer, 2016). Row covers, especially in areas with hot and humid climatic conditions, such as Florida, have helped to contain aphid populations and associated viral infections in zucchini, thereby having a very positive impact on increasing the yields, especially when the covers are in use during the initial stages of plant growth (Dongiovanni *et al*., 2023). Sticky traps, especially flat sticky ones, although inferior to the other type of traps, suction traps, have been found to offer a scalable crop system monitoring tool as an effective determinant of population densities of some species of aphids captured by the traps (Otieno *et al*., 2018).

Integrated Approaches

Hybrid strategies are being employed in integrated pest management (IPM) of aphids to improve the effectiveness and sustainability of this aphid. These techniques have been known to integrate biological, chemical and cultural control measures to minimize the aphid population and the number of chemical pests. Geotechnical crops (GE), which produce Bacillus thuringiensis(Bt) proteins, will help augment biological mechanisms in controlling aphid infestation in various crops and localities (Anderson *et al*., 2019). Besides, digital twins and decision support systems (DSSs) offer new possibilities to track in real-time the population of aphids to intervene with the help of data. The tools can also greatly benefit decision-making by indicating an aphid outbreak and establishing whether any intervention is required and when it is required, as has been proven in the case of pepper aphid management (Dai *et al*., 2024). The problem with the use of decision tools is, however, usually related to weak local implementation and access, where user adoption can be addressed through community platforms that publish tested models and enable expanded use (Rossi *et al*. 2023). To improve the adoption of integrated strategies, strengthening extension networks is important. Efficient integrated pest and virus management strategies require effective extension services, particularly in Pakistan, where structural gaps in advisory systems persist (Shair *et al*., 2024).

Challenges and Knowledge Gaps

Biological Complexity

Management of viruses that are spread by aphids is equally a huge task to tackle biologically, significantly due to the high aphid multiplication rate and virological adaptability of the viruses. The high-reproduction rates and complex life cycles make aphids good vectors due to the rate of their population growth and distributing potential throughout a crop (Stevens & Lacomme, 2017). This fast reproduction is supplemented by the process of adaptive evolution of the viruses, which enables them to gain new strains able to overcome the plant immune systems and the vectors of transmission (Gadhave *et al*., 2020). In addition, the combination of interactions of more than one virus with a vector gives rise to another complexity. Potyviruses, usually spread by Aphids, have varied host-vector interactions with their hosts that influence the behaviour of the Aphid and transmission dynamics of the virus (Gadhave *et al*., 2020). There may be significant dependence between ecological elements, and in most cases, it is hard to interrupt the transmission process with traditional control interventions due to this multipartite interaction (Pinheiro *et al*., 2019). These multi-virus and multi-vector effects are important to understand to create viable management approaches to controlling the transmission of aphid-transmitted viruses in the agricultural field (An *et al*., 2022).

Regional and Field-Level Gaps

Globally significant progress has been made in understanding aphid-transmitted viruses. However, there are still major gaps in tropical and subtropical agroecosystems. Regional data remains fragmented despite the importance of aphid-transmitted viruses in South Asia. Barley yellow dwarf virus (BYDV) and Cucumber mosaic virus (CMV) cause significant losses in wheat and cucurbits in Pakistan, yet systematic epidemiological studies from Pakistan are scarce, limiting the development of locally adapted management strategies (Jayasinghe *et al*., 2021; Jamshed *et al*., 2024). These gaps hinder the formulation of evidence-based recommendations and highlight the urgent need for region-specific research. The interaction between viruses and their vectors, aphids, is are complex molecular functioning. This discipline has been riddled with complexity in the recent past because of the adaptability of aphid and plant viruses with respect to the environment in tropical and subtropical systems. Furthermore, the fact that aphids host symbiotic microorganisms, including the common bunyavirus, which has been explored in several species of aphids, indicates the complexity of host–parasite interactions that could influence the dynamics of virus transmission in the said areas (Stevens and Lacomme, 2017; An *et al*., 2022).

Future Directions and Innovations

Biotechnological Tools

Nanotechnology, gene-editing, and artificial intelligence (AI) procedures like CRISPR/Cas are transforming agriculture by increasing early detection of infecting viruses, crop resistance, and disease prediction. Nanotechnology could be key in the determination of viruses, and its sensitivity, specificity and cost are far superior to the traditional methods. Material advances in the field of nanosensors made it possible to create tools that can detect the presence of viruses at very low concentrations and issue early warnings to stop the spread (Li *et al*., 2021). Gold nanoparticles, quantum dots, and magnetic nanoparticles are among the most used nanomaterials in biosensors because of their distinct physical and chemical properties that increase their detection levels (Kang *et al*., 2021). Applications of nanotechnology in the agricultural sector have great potential to decrease the reliance on pesticides by offering exact delivery mechanisms of pesticides and other agricultural chemicals, which not only reduce the possible adverse effects on the environment but also exterminate aphids better (Yadav, 2017).

The CRISPR/Cas is deemed to be one of the most revolutionary in the field of Aternity biotechnology because it can ensure the precision of control between the genome editing process and the ability of the crops to be resistant to the biotic stressors and aphid vectors (Gan & Ling, 2022). CRISPR/Cas can make the plants resistant to aphid attack by editing the genes and reducing the adverse effects of the transmission of a virus (Dong & Fan, 2024). This is because it enables the development of crops with better resistance properties without adding foreign DNA to them, which is desirable when wanting to reduce GMO-related controversies (Chen *et al.*, 2019). Moreover, these changes might help implement sustainable farming processes by reducing reliance on chemical pest control and increasing crop resilience to climate change (Rajput *et al.*, 2021).

AI and Decision Support

Artificial Intelligence and machine learning can transform the rendering and control the spread of the aphid-like virus proliferation. These technologies can provide complex inputs of multiple sources, such as weather conditions, soil conditions and crop conditions, to predict outbreaks of diseases. The advantage of AI models is the ability to be extremely accurate in discovering possible hotspots of diseases and pre-emptive measures to effectively manage the situation, hence maximizing the use of resources and reducing the loss of economic opportunities (Gonzalez-Rodriguez *et al.*, 2024). Moreover, with machine learning, the presence of viruses in crops can be detected automatically through the application of high-performing image recognition tools that are better than a human (Zhang *et al.*, 2024). Finally, AI contributes to making the real-time monitoring and the decision-making process viable to find sustainable approaches to managing diseases in agriculture (Guo *et al.*, 2023).

Policy and Global Collaboration

This is relevant in enhancing international efforts towards coordination in exchanging information and controlling the aphid-transmitted vegetable viruses. Potyviruses are widespread worldwide, and their viruses harm crops that are important for food security (Gadhave *et al.*, 2020). This may result in major agricultural losses, and the management of these pests, therefore, becomes key in the sustenance of food production (Linz *et al.*, 2015). The movement of plant viruses by aphids depends on some complicated cyclicities, like aphid biology, morphology, and interactions of the virus and aphid (Jayasinghe *et al.*, 2021). Identification of these interactions is central to developing good managerial practices. International cooperation promotes the exchange of scientific knowledge and technology within the agricultural systems (Stevens & Lacomme, 2017). Such viruses need an effective surveillance system because they have spread across the world. Information related to aphid-transmitted viruses, such as those related to cucurbit crops in Spain, is critical for decision-making (Moya-Ruiz *et al.*, 2023). If there are epidemiological studies that involve two or more researchers, the surveillance programs can be improved, and effective interventions can be timely. The transmission has bottlenecks in virus populations through which aphids transmit viruses, and this underscores the effect of stochastic events in the transmission of viruses. International collaboration can be used to develop strategies for impeding the virus and aphid population, as they are the key concepts of sustainable agriculture and minimization of the consumed pesticides (Linz *et al*., 2015).

Conclusion

The fear of hazards to the agricultural sector through the aphid-borne plant viruses has developed as a major stronghold concern on a global scale due to the massive loss incurred in terms of yield and the resulting disruption of food security. These viruses can infect a large number of plant species and can be transferred by aphids both persistently and non-persistently, thereby affecting the epidemiology of crop viral diseases. Not only does transmission interact with time and space dynamics, but it also aphid movement and how vectors behave. Temperature, humidity, rainfall, and topography of climatic conditions also play a significant role in determining such interactions. The spread of aphids and viruses has been traced and forecasted by utilizing epidemiological models, geographic information systems (GIS) and remote sensing. The monitoring and detection of viruses has been improved by the development of serological and molecular diagnostic tools. The control and regulation of aphid population and halt the development of transference of the viruses are implemented by integrated vector management strategies that include adoption of cultural, biological, chemical, host plant resistance, and mechanical/physical strategies. Nevertheless, challenges persist because of the complex biological relationships between aphids and viruses, the high rate of aphid reproduction, and the evolution of viral laxity. The situation is characterized by a knowledge gap as to the way in which such interactions should occur in field conditions, predominantly the tropical and subtropical regions. The future trends relate to the use of technologies in biotechnology, AI, decision support systems, and reduced international collaboration in enhancing the virus detection process, crop resistance, and predicting disease and developing effective management options in a sustainable way.

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