E-ISSN: 2618-0618
P-ISSN: 2618-060X

NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; SP-8(12): 75-84
Received: 05-09-2025
Accepted: 07-10-2025

Dr. Tanmoy Das
Assistant Professor, Faculty of Agriculture, Arunachal University of Studies, Namsai, Arunachal Pradesh, India

Mayanglambam Somorjit Singh
Teaching Assistant, Department of Entomology, Rajiv Gandhi University, Arunachal Pradesh, India

Korimayum Rabina
Assistant Professor, Faculty of Agriculture, Arunachal University of Studies, Namsai, Arunachal Pradesh, India

Mayanglambam Sanjit Singh
Assistant Professor, Faculty of Agriculture, Arunachal University of Studies, Namsai, Arunachal Pradesh, India

Corresponding Author:
Dr. Tanmoy Das
Assistant Professor, Faculty of Agriculture, Arunachal University of Studies, Namsai, Arunachal Pradesh, India

Status and emerging threats of plant viruses in northeast India: Severity patterns, vector dynamics and sustainable management approaches

Tanmoy Das, Mayanglambam Somorjit Singh, Korimayum Rabina and Mayanglambam Sanjit Singh

DOI: https://www.doi.org/10.33545/2618060X.2025.v8.i12Sb.4333

Abstract
Plant viruses are a major problem for farmers in Northeast India because they grow a wide range of crops in unique agro-climatic conditions that make it easier for diseases to spread. Recent surveys have shown that many viruses can infect rice, vegetables, fruits and other horticultural crops in all states of the region. Viral diseases happen more often and are worse in certain crops and seasons, but they can affect 50-80% of crops during epidemics. Insects like aphids, whiteflies, leafhoppers and thrips that thrive in the area's warm, humid climate are the main way they spread. Climate change and more trade have also made it easier for new vectors and viruses to spread. For example, warmer winters could mean that insects that carry viruses stay around all year. Also, bringing in ornamental and vegetable seedlings has brought in new viruses. By figuring out when viruses were first introduced, we can ask questions about how they affected things. How hard was it for native species to deal with these viruses? Plant viruses are a well-known problem for farmers in Northeast India because they grow a lot of different crops and the weather is perfect for disease outbreaks. Recent surveys have shown that many viruses can infect rice, vegetables, fruits and other horticultural crops in all states of the region. Viral diseases happen more often and are worse in certain crops and seasons, but they can affect 50-80% of crops during epidemics. Insects like aphids, whiteflies, leafhoppers and thrips that thrive in the area's warm, humid climate are the main way they spread. Additionally, climate change and increased trade have led to new pressures from vectors and viruses. For example, warmer winters could mean that insects that carry viruses are around all year and bringing in ornamental and vegetable seedlings has made it easier for exotic viruses to spread. This makes us wonder what their effects are: How hard was it for native species to deal with these viruses?

Keywords: Plant virus, northeast India, viral disease epidemiology, insect vectors, integrated management, crop protection, sustainable agriculture

Introduction
The Northeastern part of India has eight states which in great variety of ecology and agriculture practices. These states include Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim and Tripura [11, 99]. In the states of the Northeastern part of India, agriculture involves the production of numerous crops such as vegetables like potato, tomato and chilies, as well as fruits like bananas and various spices such as turmeric and ginger. Rice yields the highest return and is the staple crop in the region. Meanwhile, the region's weather is very warm and has humidity for the whole year. In the subcontinent, such conditions creates conducive environment for crops transmission and for the breeding of crop damaging pests within the region [39, 106]. With regard to the farming in the region, the planted crops usually create a monoculture in farming fields. Most of the crops planted in the region and the in subcontinent as a whole are of the same family and are the same type of crops. There are many pests like leaf hoppers that mainly damages crops in the region. These pests reproduce quickly and the field monoculture is devastating in the region. The same pests also survive in areas of the region with warm temperate and pests in such areas reproduce quickly [50, 103]. Extreme and negative weather that is a result of climate change in the region cannot support the crops and pests of winter producing a negative impact of viruses spreading [99]. Also, the region has also increased

its trade and activities which has a negative impact of introducing various crops and viruses that attack the crops. An example of a negative impact of the region's increased activities and production of green house vegetables is the crop of viruses that newly attack and damage crops that were previously un-attacked [40]. As a result, farmers are seeing a change in the types of viruses that threaten their crops. For example, the Tomato leaf curl New Delhi virus (a begomovirus) is becoming more common in tomato crops in the northeast [100,84]. These factors that make the world more connected add to the region's usual virus pressures. Plant viruses often cause chronic yield losses rather than acute epidemics, making them easy to overlook. Symptoms like mosaic, yellowing, ringspots or stunting can be mistaken for nutrient deficiency or water stress [25, 97]. Historically, many viral diseases in the region went unreported or under-appreciated. However, growing awareness and research in recent decades have revealed that virtually every crop group in the Northeast is affected by one or more viruses. Surveys have found that incidence of infection commonly ranges from 20% to 50% in normal conditions and can exceed 80% during outbreaks [101, 1]. In addition, mixed infections (plants harboring multiple viruses) are common which common often resulting in severe disease complexes. This convergence of virus threats poses a significant risk to smallholder farmers, who rely on healthy crops for food and income [51]. A variety of traditional and high-value crops are at risk. Potato, tomato and capsicum (cash crops) are susceptible to aphid-borne viruses such as Potato virus Y (PVY) and Cucumber mosaic virus (CMV); banana plantations are susceptible to bunchy top disease (BBTV); citrus orchards are threatened by tristeza virus (CTV); and oilseeds and pulses are susceptible to mosaic and yellow mosaic viruses [59, 14]. Every virus outbreak or introduction puts more strain on farmers who are already struggling with scarce resources. Effective control is difficult and persuasive because viruses have no cure once plants are infected, so emphasis must be on prevention and sustainable management [81]. Plant viruses in the Northeast represent hidden threats that can undermine crop productivity and livelihoods unless addressed with integrated strategies [12, 14].

Due to the cultivation of a variety of crops and unique agroclimatic conditions that promote disease epidemics, plant viruses are widely recognized as a devastating obstacle to agriculture in Northeast India [60]. A variety of viruses infecting rice, vegetable, fruit and other horticultural crops in all states of the region have been described through recent surveys. Viral disease prevalence and severity vary by crop and season, but during epidemics, they can reach 50-80% [82, 100]. They are largely transmitted by insect vectors (aphids, whiteflies, leafhoppers, thrips) that flourish in the area's warm humidity. Furthermore, new vector and virus pressures have been brought about by climate change and increased trade [13,105]. For instance, warmer winters could keep virus-carrying insects around year-round and the import of ornamental and vegetable seedlings has opened up exotic virus establishing such past virus introductions allows us to ask questions about their impacts: How difficult were these viruses for indigenous species to cope with [102]. Plant viruses are well known as a devastating constraint to agriculture in Northeast India due to cultivation of diverse crops and exclusive agro-climatic conditions which facilitate disease epidemics [83]. Recent surveys have identified a range of viruses that infect rice, vegetables, fruit and other horticultural crops in every state in the region [61]. Viral disease prevalence and severity vary by crop and season, but during epidemics, they can reach 50-80% [41,14]. They are largely transmitted by insect vectors (aphids, whiteflies, leafhoppers, thrips) that flourish in the area's warm humidity [103]. Furthermore, new vector and virus pressures have been brought about by climate change and increased trade. Warmer winters, for example, may keep virus-carrying insects around all year round and the importation of vegetable and ornamental seedlings has made exotic viruses more accessible. Knowing about these previous virus introductions enables us to enquire about their effects: How difficult were these viruses for indigenous species to cope with? [26, 84].

Historical Context and Key Researchers

- Over the past 20 years, plant virology has become more popular in Northeast India. Initially, knowledge of viral diseases came from isolated case reports and overseas studies on similar agroclimates [84]. For example, mosaic symptoms in tobacco and peas were occasionally noted in Assam in the mid-20th century but received little follow-up. Formal research on plant viruses in the region began only with the establishment of dedicated pathology labs [62]. The timeline of virology research in the region spans from occasional case reports of mosaic and yellowing in the mid-20th century, to systematic surveys in the 2000s. For instance, in the 1980s, the Regional Agricultural Research Station, which was founded in Shillong in 1963, progressively expanded its plant virology capabilities. 1990s and early 2000s, state agricultural universities in Assam, Tripura and Manipur had active plant disease laboratories [52].
- These institutes have produced notable scientists. Numerous reports on virus outbreaks have been published by researchers at Assam Agricultural University and the ICAR Research Complex for NEH Region, including Drs. Nirmal Mandal, Somnath Roy and Amrita Banerjee [63]. One of the first thorough citrus surveys in the area was carried out in 2017 by Dr. A. K. Singh and associates, who discovered Citrus tristeza virus in Khasi mandarin orchards in Arunachal, Assam, Meghalaya, Nagaland, Sikkim and Tripura. Similarly, work by Palash Nath and co-workers (2019) identified Alfalfa mosaic virus in Assam potato fields (a first report for India) and by Banyumali and Deka (2019) on potato leafroll and other tuber viruses [85].
- Dr. R. Deka and his team at AAU Jorhat looked at rice and vegetable germplasm to see if they could handle viruses. Scientists from extension services, like J.K. Mahanta, have done field surveys in many states to find out how many people are getting the virus. ICAR-Indian Institute of Vegetable Research and ICAR-NRC on Citrus are two national institutes that have worked together from time to time to study crops in the Northeast [14].
- These joint efforts, which are often published in journals like Indian Phytopathology and Virus Disease, have slowly helped us learn more about the viruses in the area. Before the 2010s, most surveys were just descriptions, but now molecular diagnostics (ELISA, PCR) are widely used [64]. Recent genetic sequencing initiatives in Northeast India have started to identify virus strains, indicating that certain viruses in the hills are closely linked to those in Bangladesh and Myanmar, implying cross-border transmission [86]. The history of plant virology in the Northeast is one of quick learning. Before, plants with virus symptoms were ignored, but now researchers can quickly figure out what's wrong and fix it, thanks to the work of local scientists and institutions [1].

Viruses and Crop Diseases in Northeast India

The Northeast has a lot of different types of crops, so it has a lot of different types of plant viruses. There are a lot of RNA viruses, such as Potyviridae (Chilli veinal mottle virus, Potato virus Y), Geminiviridae (Chilli leaf curl virus, Bhendi yellow vein mosaic), Bromoviridae (Cucumber mosaic virus), Tospoviridae (Groundnut bud necrosis virus) and Closteroviridae (Citrus tristeza virus) [65]. Badnavirus (Rice tungro bacilliform virus) and Nanovirus (Banana bunchy top virus) are two DNA viruses that affect staple and perennial crops. Table 1 shows the most common viruses that have been found in Northeast states, as well as their main host crops and ways of spreading [27, 63].

Table 1: Major plant viruses identified in Northeast India, their host crops, vectors and areas of occurrence [66].

Virus (Abbreviation)	Virus Family/Genus	Major Host Crops (in NE India)	Vector (Transmission)	States/Regions Reported
Rice tungro bacilliform virus (RTBV)	Badnavirus (Pararetro)	Rice	Leafhoppers (*Nephotettix* spp.)	Assam, Manipur, Tripura
Rice tungro spherical virus (RTSV)	Waikavirus	Rice	Leafhoppers (*Nephotettix* spp.)	Assam, Tripura
Banana bunchy top virus (BBTV)	Nanovirus	Banana (cultivated and wild)	Aphids (*Pentalonia* spp.)	Assam, Nagaland
Papaya ringspot virus (PRSV-P)	Potyvirus	Papaya, some gourds	Aphids (*Myzus persicae* group)	Assam (*sporadic*)
Cucumber mosaic virus (CMV)	Cucumovirus	Cucurbits, Tomato, Solanaceous crops	Aphids (*Aphis*, *Myzus*)	Assam, Meghalaya, Tripura
Chilli veinal mottle virus (ChiVMV)	Potyvirus	Chilli peppers (Capsicum spp.)	Aphids (*Myzus/ Aphis*)	Meghalaya, Assam
Chilli leaf curl virus (ChiLCV)	Begomovirus	Chilli, Tomato	Whiteflies (*Bemisia tabaci*)	Assam
Tomato leaf curl New Delhi virus (ToLCNDV)	Begomovirus	Tomato, Okra, Cucurbits	Whiteflies (*Bemisia tabaci*)	Assam, Nagaland (*likely*)
Potato virus Y (PVY)	Potyvirus	Potato, Tomato	Aphids (*Myzus persicae*)	Assam
Potato leaf roll virus (PLRV)	Luteovirus	Potato	Aphids (*Myzus persicae*)	Assam
Alfalfa mosaic virus (AMV)	Alfamovirus	Potato, Alfalfa, Cowpea	Aphids; mechanical (sap)	Assam
Tobacco mosaic virus (TMV)	Tobamovirus	Tobacco, Tomato, Brassicas	Mechanical (tools, sap, clothing)	Assam
Mungbean yellow mosaic India virus (MYMIV)	Begomovirus	Mungbean, Urd bean	Whiteflies (*Bemisia tabaci*)	Meghalaya, Manipur
Bhendi (Okra) yellow vein mosaic virus (BhYVMV)	Begomovirus	Okra (Bhendi)	Whiteflies (*Bemisia tabaci*)	Assam

- Table 1 shows that there are a number of conclusions that can be made. First, a lot of viruses are common. For example, rice tungro (RTBV+RTSV) can be found in rice fields in Assam and Tripura and Citrus tristeza virus (CTV) can be found in all of the northeastern states that were surveyed. Second, many viruses attack important crops. For example, potato farmers in Assam have to deal with both PVY and PLRV, which are carried by aphids. Chilli farmers have to deal with potyviruses (ChiVMV) and begomoviruses (ChiLCV) [15]. Third, both annual and perennial crops are affected. Annual vegetable crops get diseases like mosaic and leaf curl, while perennial plantations (like bananas and citrus) build up viruses over time, which can cause slow declines [67].
- The variety of virus families in the area shows that management must also be varied [43]. For example, crops in the Northeast have at least a dozen different virus families and each one needs its own way to be found and controlled. A single crop can be infected by more than one virus. For example, CMV and a leaf curl virus are often found in chilli peppers at the same time [104]. There have been reports of synergistic co-infection; for example, a study in Assam found that chilli plants infected with two viruses had much worse mosaic and fruit deformation than plants infected with only one virus [2]. This mixed infection phenomenon highlights the necessity for integrated diagnostics (testing for multiple viruses) and multi-target management [68].
- Geographic surveys indicate that a lack of reported infections frequently signifies insufficient sampling rather than genuine absence [53]. For instance, Potato virus Y (PVY) has been confirmed in potatoes from Assam, but there hasn't been much testing in Meghalaya and Arunachal Pradesh. Because tubers move between states, it's safe to assume that PVY will eventually be reported there. Likewise, the Chilli veinal mottle virus (ChiVMV) found in Assam and Meghalaya suggests potential transmission to Tripura and Manipur if whiteflies migrate between greenhouses. Coordinated surveys and regional pathogen databases would help fill in these gaps [87].

Vector Dynamics and Ecology

In Northeast India, insect vectors are the main cause of plant virus outbreaks and endemic. Aphids, whiteflies, thrips and leafhoppers are some of the most important sap-sucking insects (Table 2) [54]. The local climate, cropping patterns and plants have had a big impact on these insect populations for a long time. For example, an early monsoon can cause aphids to multiply quickly on rice and vegetables. On the other hand, long dry spells can stop some vectors from reproducing but help others that can handle heat and dryness. Seasonal migrations are also important. For example, many whiteflies and aphids move from South India to the Northeast in the winter, when the weather is cooler, to reinvest crops [69,88]. The area has a mix of forests and farms that provide shelter for many vector species all year long [3]. Because viruses spread mostly through vectors, weather patterns that affect vector life cycles are very important and sticky [44]. For instance, warmer winters let more vector populations survive until spring and dry spells that aren't normal for the season can stress plants and make them more likely to get sick. Research in the area has shown that biodiversity, such as wild plants and forest patches, helps many insect species survive bad weather, giving them a constant source of potential virus carriers [89]. To control viruses in practice, you need to know how different insects live and how they interact with crops [16,28].

Table 2: Major virus vectors in Northeast India. Each vector category is associated with typical viruses and the crops they impact [45,70].

Vector Category	Example Species	Transmitted Viruses (examples)	Affected Crops
Aphids	*Myzus persicae, Aphis gossypii*	Potyviruses (PVY, ChiVMV, PRSV); Alfamovirus (AMV); Cucumovirus (CMV)	Potato, Tomato, Chilli, Cucumber, Papaya
Aphids	*Lipaphis erysimi*	Potyviruses of crucifers (e.g. Turnip mosaic)	Mustard, Rapeseed, Cabbage
Whiteflies	*Bemisia tabaci* complex	Begomoviruses (ChiLCV, MYMIV, BhYVMV)	Tomato, Chilli, Okra, Beans, Cucurbits
Whiteflies	*Trialeurodes vaporariorum*	Crinivirus (*Cucurbit viruses*), Begomoviruses	Cucurbits, Eggplant, Tobacco
Thrips	*Thrips palmi*	Orthotospoviruses (GBNV, related viruses)	Chilli, Tomato, Peanut
Thrips	*Scirtothrips dorsalis*	Orthotospoviruses (GBNV)	Chilli, Citrus ornamentals
Leafhoppers (rice)	*Nephotettix virescens, N. nigropictus*	Rice tungro viruses (RTBV + RTSV)	Rice
Leafhoppers (rice)	*Recilia dorsalis*	Rice grassy stunt virus (RGSV)	Rice
Planthoppers	*Sogatella furcifera*	Rice ragged stunt virus, RGSV	Rice
Nematodes	*Trichodorus* spp. (stubby-root nematodes)	Tobraviruses (Tobacco rattle virus, TRV)	Potato, Soybean
Parasitic vine	*Cuscuta reflexa* (dodder)	Can acquire multiple sap-transmitted viruses	Wide host range (connects fields)

- Table 2 shows that a lot of vectors can carry more than one virus and can infect a wide range of hosts. The green peach aphid (Myzus persicae), for instance, spreads both CMV and potyviruses like PVY, which makes it a major pest in many crops [90]. Leafhoppers on rice only spread rice viruses, while whiteflies on vegetables spread a variety of begomoviruses. Changes in vector populations over the course of the year are important. For example, rain can lower the number of whiteflies but raise the number of thrips, which changes which viruses become dominant [4,17].
- Cropping practices also have an effect on vector populations in Northeast India. Planting virus-resistant types can slow down the spread of the virus through vectors. On the other hand, using a lot of pesticides to kill one pest (like leafhoppers on rice) can accidentally help other pests (like thrips on groundnut) thrive [71]. Also, communal agro-ecosystems in the Northeast make it easy for viruses and vectors to move between fields of different farmers. Rice and pulse fields in the same village can, for instance, become sources of aphid-borne viruses for each other [29].
- Common field weeds are places where viruses can live. For example, some types of Amaranthus and Eupatorium that grow along field edges often have Cucumber mosaic virus or begomoviruses without showing any signs of illness [72]. These weeds let viruses and vectors live on between growing seasons. To stop disease cycles, it is best to manage weed hosts like Sesbania, Eupatorium and Parthenium around fields of vegetables and legumes [18].

Table 3: Occurrence of selected plant viruses in Northeast Indian states (✓ indicates recorded presence). Many pathogens occur in multiple states, often spreading via shared vectors and seed trade [56].

Virus	Arunachal Pradesh	Assam	Manipur	Meghalaya	Mizoram	Nagaland	Sikkim	Tripura
Rice tungro viruses (RTBV, RTSV)		✓	✓					✓
Banana bunchy top virus (BBTV)	✓	✓	✓	✓	✓	✓	✓	✓
Cucumber mosaic virus (CMV)		✓		✓				✓
Chilli veinal mottle virus (ChiVMV)		✓		✓				
Chilli leaf curl virus (ChiLCV)		✓						
Potato virus Y (PVY)		✓						
Potato leaf roll virus (PLRV)		✓						
Alfalfa mosaic virus (AMV)		✓						
Tobacco mosaic virus (TMV)		✓						
Mungbean yellow mosaic India virus (MYMIV)				✓				
Bhendi yellow vein mosaic virus (BhYVMV)		✓						
Citrus tristeza virus (CTV)	✓	✓	✓	✓		✓	✓	✓
Rice grassy stunt virus (RGSV)		✓						
Groundnut bud necrosis virus (GBNV)		✓						
Papaya ringspot virus (PRSV)		✓						

The table shows that farmers often face the same virus threats across state lines. A virus might not have been found yet in a certain state, but it could be waiting to be found. For example, the fact that there is no PVY in Meghalaya is probably due to a lack of testing, not because it is actually absent [5,19]. Additionally, vectors like whiteflies and aphids do not adhere to borders; a viral outbreak in Assam during one season frequently foreshadows infections in neighbouring Nagaland or Tripura in the subsequent season. So, regional cooperation in keeping an eye on things and quickly sharing information is important to stop new outbreaks from spreading [30].

Impact and Severity Patterns

- In the Northeast, the effects of plant viruses are mostly linked to how crops are grown and the weather. A lot of viruses cause big, long-term yield losses instead of sudden crop failures and damage [105]. When rice tungro is present, it can cut paddy yields by 30-60% in a year when it is most common, especially if the area grows varieties that are more likely to get it. Vegetable crops are also affected: fields of chilli peppers with a lot of ChiVMV or begomovirus infection may see a 40-70% drop in fruit yield [31].
- In real life, how bad it is depends on how things are done in

that area. Under high virus pressure, farmers say that whole patches of chilli or tomatoes can become unmarketable. For instance, when a begomovirus (ChiLCV) gets into a field of chilli, it can spread to more than half of the plants in just a few weeks, which can kill them [46]. In one outbreak in Assam, growing both chilli and tomatoes together caused the virus to spread to both crops at the same time, making losses worse. Epidemics of more than one virus can be worse than single infections. A traditional field study found that pepper plants that were first infected by one virus later became infected by another virus and the damage from both viruses was worse than from either virus alone [57].

- The severity is not the same throughout the region [32]. During heavy monsoons, tungro epidemics happen often in the low-lying, irrigated rice fields of Assam and Tripura. In the cooler highlands of Meghalaya and Arunachal, on the other hand, the virus is less common in rice [73]. A survey of older Khasi mandarin orchards found that older trees (over 10 years) had much higher CTV loads than young trees. This shows that the virus builds up over time [91]. Viruses can slowly kill banana and citrus orchards over the course of several years. Mixed infections make the disease worse: having more than one virus in a single host plant usually causes the worst symptoms [106]. Farmers often notice that when one virus starts in a mixed crop stand, other viruses quickly follow. In extreme cases, this can lead to almost complete crop loss [6, 20].

Emerging Challenges and Future Directions

- A number of new problems are likely to affect the spread of plant viruses in the Northeast. Climate change around the world is likely to make aphids, whiteflies and other vectors more active and able to live in more places. This could bring viruses that were only found in tropical areas to the hills of Northeast India [74]. For instance, if winters are warmer, vector populations may be able to survive all year and start infections early in the spring. Crops can get stressed out by rains or heat waves that aren't normal, which can make them more likely to get sick. These changes mean that viruses that used to be minor threats could become major ones [47].
- Growing trade of seedlings and planting materials between states and countries is also a danger. It's now common to bring subtropical vegetable and fruit cultivars from other Indian states or nearby countries and they may even bring new viruses with them [92]. The growth of protected cultivation (greenhouses and net-houses) to meet the demand for vegetables gives vectors new places to live and can cause viruses that only happened outside to spread. Surveillance must therefore encompass nurseries and greenhouse producers, in addition to open fields. For example, a recent virus outbreak in a tomato greenhouse in Meghalaya was linked to infected plants that were brought in from outside the state [58].
- New tools for managing viruses are coming from improvements in technology. High-throughput sequencing (HTS) can quickly find both known and new viruses in small samples. However, it takes money and expertise to understand the data [93]. In the future, it might be possible to find virus symptoms early over large areas using remote sensing drones or field sensors. However, these tools need to be tested in local conditions first [33]. On the biological front, new ideas are coming up, like gene-silencing sprays (RNA interference) and the creation of transgenic plants that can resist viruses. These have worked well in other parts of India. These could be good for crops in the Northeast, but right now they have to deal with regulatory and adoption issues [7].
- Policy and institutional actions will also have an effect on the future. Stronger phytosanitary rules at state borders, community seed banks that keep virus-free stock and farmer cooperatives that keep an eye on diseases together could all help stop the spread of viruses [34]. For instance, some citrus farmers in Assam now keep registered virus-free mother blocks for budwood. This is a good idea that should be used more often. Working together with other countries in the region (like doing surveys with Bangladesh or Myanmar) could help find viruses that cross borders early on [75]. Education and extension will be important. Teaching farmers how to spot early signs of a virus and how to respond correctly can make new threats easier to handle and more organised. In short, Northeast India will need flexible, forward-thinking plans to deal with these changing problems and situations [21].

Sustainable Management Approaches

To control plant virus diseases in the Northeast, you need long-term, all-around strategies. Viruses don't have a direct chemical cure for plants once they get infected, unlike fungal diseases [8,35]. So, prevention and a whole-person approach are important. Table 4 shows the different ways of doing things, from old-fashioned cultural practices to cutting-edge technologies [76].

Table 4: Strategies for sustainable management of plant viruses in Northeast India [48].

Strategy	Key Actions	Advantages / Notes
Resistant/Tolerant Cultivars	Develop and use crop varieties with genetic resistance to specific viruses (e.g., tungro-resistant rice, CMV-resistant squash).	Reduces infection rates and yield loss; sustainable long-term. Limitation: resistance genes may break down over time and are not yet available for all crops.
Clean Planting Material	Use certified virus-free seeds, tubers, seedlings or scions (obtained via tissue culture or heat therapy).	Prevents introduction of viruses at planting. Requires lab testing and certification programs.
Crop Rotation and Diversification	Rotate susceptible crops with non-hosts (e.g. legumes after tobacco); interplant with trap/intercrop species.	Breaks virus-vector cycles; reduces soil inoculum. Limitation: farmers need profitable alternative crops.
Rouging (Removal of Infected Plants)	Regular scouting and timely removal and destruction of symptomatic plants (especially in vegetable gardens and vineyards).	Removes local virus reservoirs. Effective early in disease buildup; labor-intensive.
Field Sanitation and Weed Control	Eliminate volunteer plants, weeds and crop residues that harbor viruses or vectors; clean farm tools and machinery.	Reduces alternative virus hosts and vector breeding sites. Involves routine effort.
Vector Management - Cultural	Adjust planting dates to avoid peak vector periods; use trap crops (e.g. planting okra as a trap for whiteflies).	Lowers vector landing rates. Requires local knowledge of vector phenology.
Vector Management - Biological	Conserve and release natural enemies (lady beetles, parasitic wasps, predatory mites) to control aphids, whiteflies, thrips.	Environmentally safe; supports long-term control. Usually slower acting; best combined with other methods.
Vector Management - Chemical	Apply selective insecticides targeting vectors (e.g. Imidacloprid for aphids, Spinosad for thrips) with caution.	Rapidly reduces vector numbers; can break virus cycles. Downside: resistance development, non-target effects and pesticide residues.

Effective control usually combines several of these measures [77]. For example, using a virus-resistant crop variety, coupled with certified clean seed, regular rogueing of infected plants and timely release of predatory insects can drastically lower virus incidence compared to any single approach alone [22].

Emerging Challenges and Future Directions

- There are new problems with the spread of plant viruses in the Northeast. Changes in the climate around the world are expected to make virus vectors like aphids and whiteflies live in more places and be active for longer periods of time. Viruses that used to live in tropical areas can now live in the Northeast's higher altitudes [78]. For example, warm winters can cause aphids to reproduce more quickly, which can lead to a virus that spreads quickly and starts earlier in the spring [94]. Unseasonal rains and heat waves can change how plants get sick. This means that changes to the virus that may have seemed unimportant at the time are now very important to public health [36].
- The growing trade in planting materials across state lines and around the world is another worry. Vegetables and fruits from subtropical regions are now often brought in from other Indian states and nearby countries, sometimes carrying hidden viruses [79]. The recent growth of greenhouse and polyhouse farming (to grow vegetables when they're not in season) has unintentionally made new virus niches [95]. Viruses such as Tomato leaf curl New Delhi virus and Begomovirus species are being found more and more in crops grown in greenhouses, which are warm, virus-friendly places. This means that surveillance is now needed for more than just farmers in open fields; it also needs to be done for greenhouse producers and nurseries [49].
- Progress in areas like science has both pros and cons. High-throughput sequencing (HTS), for instance, can quickly find both new and known viruses in plant samples. This can help find viral threats that weren't known before [23]. But the region is only just starting to get the money and skills it needs to use these tools. In the next few years, environmental DNA (eDNA) sampling and remote drone imaging may help the technology in agriculture find virus outbreaks early [9]. Conversely, research is being conducted worldwide on the application of biocontrol utilising RNA-interference (RNAi) sprays and advantageous endophytes, along with CRISPR-mediated resistance. It is possible that adapting these new methods for Northeast crops could lead to big breakthroughs, but we need to see how well they work in the field first, since research is still going on [96].
- Policy and institutional support will be the most important factors in determining future outcomes. Better quarantine measures, like those at state and international borders (like those between Myanmar and Bhutan), could stop new viruses from coming in. Community seed banks that keep virus-free germplasm of local crops also give farmers clean starting materials [38]. Along with farmer cooperatives, extension networks could help with area-wide management campaigns and make localized actions work better. For instance, it could help citrus growers work together to pool resources, which would make their efforts stronger, to support ámbito managed campaigns [97]. For example, citrus growers could work together to test their orchard trees every year and only use buds from certified mother plants [37].
- A coordinated plan is needed for the future: constant surveillance to find new viruses early, money spent on breeding for resistance and strong extension to put IPM into action on the ground [80]. Working together on projects with research centers and countries next door can help keep an eye on viruses that cross borders [98]. In short, Northeast India needs to stay alert and flexible, using both old and new ways of doing things to deal with new virus problems [10, 24].

Conclusion

Many plant viral infections can be treated, but they are still a growing problem for farming in Northeast India. This review found infections that hurt nearly all of the major crops in the area, which led to a drop in yield. Complicated cropping patterns and a climate that is resistant to viruses and insecticides make it easier for viruses to move around and stay in one place. We can still make big changes, though, because there are already or are being developed several effective management systems. Some of these are growing and distributing virus-resistant (tolerant) crops, controlling pests in an integrated way (including managing vectors and reservoirs) and making, distributing and using healthy planting materials. For instance, sound genotypes can help reduce losses from rice tungro and certified tubers can help keep PVY outbreaks under control. Crop rotation, good field management and weed control all help lower the main inoculums sterile source. Biological control, along with selective pesticides, keeps vector populations in check. Working together with farmers and reaching out to the community can help these changes have even more benefits. As we deal with the ever-changing problems of climate change, global trade and plant viral trade, this partnership is more important than ever. We need to keep studying to keep track of new viruses and find new ways to control them. It's encouraging that the Northeast has gone from being almost "virus ignorant" to watching and reacting. The farming groups in Northeast India can protect themselves well against viruses by keeping up this drive and combining old ways with new science. Getting good crop health in this area will take careful planning, creativity and teamwork, but it is possible if everyone works together.

References

1. van der Want JP, Dijkstra J. A history of plant virology. Arch Virol. 2006;151(8):1467-98. doi:10.1007/s00705-006-0782-3.
2. Alallam B, Altahhan S, Taher M, Mohd Nasir MH, Doolaanea AA. Electrosprayed alginate nanoparticles as CRISPR plasmid DNA delivery carrier: preparation, optimization and characterization. Pharmaceuticals (Basel). 2020;13(8):158. doi:10.3390/ph13080158.
3. Alamillo JM, Saénz P, García JA. Salicylic acid-mediated and RNA-silencing defense mechanisms cooperate in the restriction of systemic spread of plum pox virus in tobacco. Plant J. 2006;48(2):217-27. doi:10.1111/j.1365-313X.2006.02861.x.
4. Alcaide C, Rabadán MP, Moreno-Pérez MG, Gómez P. Implications of mixed viral infections on plant disease ecology and evolution. Adv Virus Res. 2020;106:145-69. doi:10.1016/bs.aivir.2020.02.001.
5. Alcaide C, Sardanyés J, Elena SF, Gómez P. Increasing temperature alters the within-host competition of viral strains and influences virus genetic variability. Virus Evol. 2021;7(1):veab017. doi:10.1093/ve/veab017.
6. Ambardar S, Gupta R, Trakroo D, Lal R, Vakhlu J. High throughput sequencing: An overview of sequencing chemistry. Indian J Microbiol. 2016;56:394-404.

doi:10.1007/s12088-016-0606-4.
7. Baker KK, Ramsdell DC, Gillett J. Electron microscopy: Current applications to plant virology. Plant Dis. 1985;69:85-91. doi:10.1094/PD-69-85.
8. Balodi R, Bisht S, Ghatak A, Rao KH. Plant disease diagnosis: Technological advancements and challenges. Indian Phytopathol. 2017;70:275-81. doi:10.24838/ip.2017.v70.i3.72487.
9. Bao D, Ganbaatar O, Cui X, Yu R, Bao W, Falk BW, *et al*. Down-regulation of genes coding for core RNAi components and disease resistance proteins via corresponding microRNAs might be correlated with successful Soybean mosaic virus infection in soybean. Mol Plant Pathol. 2018;19(4):948-60. doi:10.1111/mpp.12581.
10. Barzon L, Lavezzo E, Costanzi G, Franchin E, Toppo S, Palù G. Next-generation sequencing technologies in diagnostic virology. J Clin Virol. 2013;58:346-50. doi:10.1016/j.jcv.2013.03.003.
11. Batovska J, Lynch SE, Rodoni BC, Sawbridge TI, Cogan NOI. Metagenomic arbovirus detection using MinION nanopore sequencing. J Virol Methods. 2017;249:79-84. doi: 10.1016/j.jviromet.2017.08.019.
12. Cagliari D, Dias NP, Galdeano DM, dos Santos EÁ, Smagghe G, Zotti MJ. Management of pest insects and plant diseases by non-transformative RNAi. Front Plant Sci. 2019;10:1319. doi: 10.3389/fpls.2019.01319.
13. Calil IP, Fontes EPB. Plant immunity against viruses: antiviral immune receptors in focus. Ann Bot. 2016;119(5):711-723. doi: 10.1093/aob/mcw200.
14. Verma VK, Kumar A, Das S, Singh NU, Singh M, Tripathi K, *et al*. Book of Abstracts of the National Conference on Managing Agro-Biodiversity in North Eastern India (NCMAN), ICAR Research Complex for NEH Region, Umiam, Meghalaya, 23-25 October 2024. New Delhi: Indian Society of Plant Genetic Resources; 2024. p. 184.
15. Dalakouras A, Wassenegger M, Dadami E, Ganopoulos I, Pappas ML, Papadopoulou K. Genetically modified organism-free RNA interference: exogenous application of RNA molecules in plants. Plant Physiol. 2020;182(1):38-50. doi: 10.1104/pp.19.00570.
16. Damase TR, Sukhovershin R, Boada C, Taraballi F, Pettigrew RI, Cooke JP. The limitless future of RNA therapeutics. Front Bioeng Biotechnol. 2021;9:628137. doi: 10.3389/fbioe.2021.628137.
17. De Faria JC, Aragã FJ, Souza TL, Quintela ED, Kitajima EW, Ribeiro SD. Golden mosaic of common beans in Brazil: Management with a transgenic approach. APS Features. 2016. doi: 10.1094/APSFeature-2016-10.
18. de Ronde D, Butterbach P, Kormelink R. Dominant resistance against plant viruses. Front Plant Sci. 2014;5:307. doi: 10.3389/fpls.2014.00307.
19. de Ronde D, Lohuis D, Kormelink R. Identification and characterization of a new class of Tomato spotted wilt virus isolates that break Tsw-based resistance in a temperature-dependent manner. Plant Pathol. 2019;68(1):60-71. doi: 10.1111/ppa.12952.
20. Deleris A, Gallego-Bartolome J, Bao J, Kasschau KD, Carrington JC, Voinnet O. Hierarchical action and inhibition of plant Dicer-like proteins in antiviral defense. Science. 2006;313(5783):68-71. doi: 10.3410/f.1002046.374330.
21. Fang Y, Ramasamy RP. Current and prospective methods for plant disease detection. Biosensors. 2015;5:537-561. doi: 10.3390/bios5030537.
22. Fellers JP, Webb C, Fellers MC, Shoup Rupp J, De Wolf E. Wheat virus identification within infected tissue using nanopore sequencing technology. Plant Dis. 2019;103:2199-2203. doi: 10.1094/PDIS-09-18-1700-RE.
23. Filloux D, Fernandez E, Loire E, Claude L, Galzi S, Candresse T, Winter S, Jeeva ML, Makeshkumar T, Martin DP, *et al*. Nanopore-based detection and characterization of yam viruses. Sci Rep. 2018;8:17879. doi: 10.1038/s41598-018-36042-7.
24. Fletcher SJ, Reeves PT, Hoang BT, Mitter N. A perspective on RNAi-based biopesticides. Front Plant Sci. 2020;11:51. doi: 10.3389/fpls.2020.00051.
25. Franco-Zorrilla JM, Valli A, Todesco M, Mateos I, Puga MI, Rubio-Somoza I, *et al*. Target mimicry provides a new mechanism for regulation of microRNA activity. Nat Genet. 2007;39(8):1033-1037.
26. Grulke NE. The nexus of host and pathogen phenology: understanding the disease triangle with climate change. New Phytol. 2011;189(1):8-11. doi: 10.1111/j.1469-8137.2010.03568.x.
27. Guo L, Wu J, Chen R, Hong J, Zhou X, Wu J. Monoclonal antibody-based serological detection of Rice stripe mosaic virus infection in rice plants or leafhoppers. Virol Sin. 2020;35:227-234. doi: 10.1007/s12250-019-00186-1.
28. Hall RJ, Wang J, Todd AK, Bissielo AB, Yen S, Strydom H, *et al*. Evaluation of rapid and simple techniques for the enrichment of viruses prior to metagenomic virus discovery. J Virol Methods. 2014;195:194-204. doi: 10.1016/j.jviromet.2013.08.035.
29. Jo A, Ringel-Scaia VM, McDaniel DK, Thomas CA, Zhang R, Riffle JS, *et al*. Fabrication and characterization of PLGA nanoparticles encapsulating large CRISPR-Cas9 plasmid. J Nanobiotechnol. 2020;18(1):16. doi: 10.1186/s12951-019-0564-1.
30. Jones RAC. Plant virus ecology and epidemiology: historical perspectives, recent progress and future prospects. Ann Appl Biol. 2014;164(3):320-347. doi: 10.1111/aab.12123.
31. Jones RAC. Future scenarios for plant virus pathogens as climate change progresses. Adv Virus Res. 2016;95:87-147. doi: 10.1016/bs.aivir.2016.02.004.
32. Kim Y, Kim YJ, Paek KH. Temperature-specific vsiRNA confers RNAi-mediated viral resistance at elevated temperature in Capsicum annuum. J Exp Bot. 2021;72(4):1432-1448. doi: 10.1093/jxb/eraa527.
33. Kimathi RH, Wilisiani F, Mashiko T, Neriya Y, Miinda AE, Nishigawa H, *et al*. First report of Tomato chlorosis virus infecting tomato in Kenya. Sci Afr. 2020;7:e00286. doi: 10.1016/j.sciaf.2020.e00286.
34. Kinoti WM, Constable FE, Nancarrow N, Plummer KM, Rodoni B. Analysis of intra-host genetic diversity of Prunus necrotic ringspot virus (PNRSV) using amplicon next generation sequencing. PLoS ONE. 2017;12:e0179284. doi: 10.1371/journal.pone.0179284.
35. Kinoti WM, Constable FE, Nancarrow N, Plummer KM, Rodoni B. Generic amplicon deep sequencing to determine Ilarvirus species diversity in Australian Prunus. Front Microbiol. 2017;8:1219. doi: 10.3389/fmicb.2017.01219.
36. Kis A, Hamar É, Tholt G, Bán R, Havelda Z. Creating highly efficient resistance against wheat dwarf virus in barley by employing CRISPR/Cas9 system. Plant Biotechnol J. 2019;17(6):1004-1006. doi: 10.1111/pbi.13077.
37. Kitajima EW. Electron microscopy in plant virology: Past,

present and future. Microsc Microanal. 2004;10:212-213. doi: 10.1017/S1431927604881467.
38. Klap C, Luria N, Smith E, Bakelman E, Belausov E, Laskar O, *et al*. The potential risk of plant-virus disease initiation by infected tomatoes. Plants. 2020;9:623. doi: 10.3390/plants9050623.
39. Koch A, Kogel KH. New wind in the sails: improving the agronomic value of crop plants through RNAi-mediated gene silencing. Plant Biotechnol J. 2014;12(7):821-831. doi: 10.1111/pbi.12226.
40. Koch A, Wassenegger M. Host-induced gene silencing - mechanisms and applications. New Phytol. 2021;231(1):54-59. doi: 10.1111/nph.17364.
41. Konakalla NC, Kaldis A, Berbati M, Masarapu H, Voloudakis AE. Exogenous application of double-stranded RNA molecules from TMV p126 and CP genes confers resistance against TMV in tobacco. Planta. 2016;244(4):961-969. doi: 10.1007/s00425-016-2567-6.
42. Koonin EV, Makarova KS, Zhang F. Diversity, classification and evolution of CRISPR-Cas systems. Curr Opin Microbiol. 2017;37:67-78. doi: 10.1016/j.mib.2017.05.008.
43. Korner CJ, Klauser D, Niehl A, Dominguez-Ferreras A, Chinchilla D, Boller T, *et al*. The immunity regulator BAK1 contributes to resistance against diverse RNA viruses. Mol Plant Microbe Interact. 2013;26(11):1271-1280. doi: 10.1094/mpmi-06-13-0179-r.
44. Kørner CJ, Pitzalis N, Peña EJ, Erhardt M, Vazquez F, Heinlein M. Crosstalk between PTGS and TGS pathways in natural antiviral immunity and disease recovery. Nat Plants. 2018;4(3):157-164. doi: 10.1038/s41477-018-0117-x.
45. Kutluk Yilmaz N.D., Uzunbacak H., Arli-Sokmen M., Kaya R. Distribution of resistance-breaking isolates of beet necrotic yellow vein virus differing in virulence in sugar beet fields in Turkey. Acta Agricult. Scand. Sect. B Soil Plant Sci. 2018;68:546-554. doi: 10.1080/09064710.2018.1441432
46. Lavina A, Battle A. First report of Tomato spotted wilt virus infection of ficus species in Spain. Plant Dis. 1993;77:536. doi: 10.1094/pd-77-0536c
47. Lebeurier G, Hirth L. Effect of elevated temperatures on the development of two strains of tobacco mosaic virus. Virology. 1966;29(3):385-395. doi: 10.1016/0042-6822(66)90214-5
48. Lefeuvre P, Martin DP, Elena SF, Shepherd DN, Roumagnac P, Varsani A. Evolution and ecology of plant viruses. Nat Rev Microbiol. 2019;17(10):632-644. doi: 10.1038/s41579-019-0232-3
49. Lefterova MI, Suarez CJ, Banaei N, Pinsky BA. Next-generation sequencing for infectious disease diagnosis and management: A report of the Association for Molecular Pathology. J Mol Diagn. 2015;17:623-634. doi: 10.1016/j.jmoldx.2015.07.004
50. Makhotenko AV, Khromov AV, Snigir EA, Makarova SS, Makarov VV, Suprunova TP, *et al*. Functional analysis of coilin in virus resistance and stress tolerance of potato (*Solanum tuberosum*) using CRISPR-Cas9 editing. Dokl Biochem Biophys. 2019;484(1):88-91. doi: 10.1134/s1607672919010241
51. Maksimov IV, Sorokan AV, Burkhanova GF, Veselova SV, Alekseev VY, Shein MY, *et al*. Mechanisms of plant tolerance to RNA viruses induced by plant-growth-promoting microorganisms. Plants. 2019;8:575. doi: 10.3390/plants8120575
52. Zuo K, Gao W, Wu Z, Zhang L, Wang J, Yuan X, *et al*. Evolution of virology: science history through milestones and technological advancements. Viruses. 2024;16(3):374. doi: 10.3390/v16030374
53. Mallory A, Vaucheret H. Form, function and regulation of ARGONAUTE proteins. Plant Cell. 2010;22(12):3879-3889. doi: 10.1105/tpc.110.080671
54. Malmstrom CM, Melcher U, Bosque-Pérez NA. The expanding field of plant virus ecology: Historical foundations, knowledge gaps and research directions. Virus Res. 2011;159:84-94. doi: 10.1016/j.virusres.2011.05.010
55. Mang H-G, Qian W, Zhu Y, Qian J, Kang H-G, Klessig DF, *et al*. Abscisic acid deficiency antagonizes high-temperature inhibition of disease resistance through enhancing nuclear accumulation of resistance proteins SNC1 and RPS4 in Arabidopsis. Plant Cell. 2012;24(3):1271-1284. doi: 10.1105/tpc.112.096198
56. Marques de Carvalho L, Benda ND, Vaughan MM, Cabrera AR, Hung K, Cox T, *et al*. Mi-1-mediated nematode resistance in tomatoes is broken by short-term heat stress but recovers over time. J Nematol. 2015;47(2):133-140. doi: 10.21236/ad0610741
57. Mehle N, Gregur L, Bogožalec Košir A, Dobnik D. One-step reverse-transcription digital PCR for reliable quantification of different Pepino mosaic virus genotypes. Plants. 2020;9:326. doi: 10.3390/plants9030326
58. Menna A, Nguyen D, Guttman DS, Desveaux D. Elevated temperature differentially influences effector-triggered immunity outputs in Arabidopsis. Front Plant Sci. 2015;6:995. doi: 10.3389/fpls.2015.00995
59. Menzel W, Knierim D, Winter S, Hamacher J, Heupel M. First report of tomato brown rugose fruit virus infecting tomato in Germany. New Dis Rep. 2019;39. doi: 10.5197/j.2044-0588.2019.039.001
60. Midha MK, Wu M, Chiu KP. Long-read sequencing in deciphering human genetics to a greater depth. Hum Genet. 2019;138:1201-1215. doi: 10.1007/s00439-019-02064-y
61. Mittler R, Finka A, Goloubinoff P. How do plants feel the heat? Trends Biochem Sci. 2012;37(3):118-125. doi: 10.1016/j.tibs.2011.11.007
62. Lecoq H. Découverte du premier virus, le virus de la mosaïque du tabac: 1892 ou 1898? [Discovery of the first virus, the tobacco mosaic virus: 1892 or 1898?]. C R Acad Sci III. 2001;324(10):929-933. doi: 10.1016/s0764-4469(01)01368-3
63. Association for Advancement in Plant Protection. Plant Health Clinic Laboratory, Directorate of Research. https://www.aappbckv.org/gallery/1699008659Food%20Security%20Dilemma.pdf
64. Mumford R, Boonham N, Tomlinson J, Barker I. Advances in molecular phytodiagnostics - new solutions for old problems. Eur J Plant Pathol. 2006;116(1):1-19. doi: 10.1007/s10658-006-9037-0
65. Nezhad AS. Future of portable devices for plant pathogen diagnosis. Lab Chip. 2014;14:2887-2904. doi: 10.1039/C4LC00487F
66. Pooggin MM. Small RNA-omics for plant virus identification, virome reconstruction and antiviral defense characterization. Front Microbiol. 2018;9:2779. doi: 10.3389/fmicb.2018.02779
67. Prasch CM, Sonnewald U. Simultaneous application of heat, drought and virus to Arabidopsis plants reveals significant shifts in signaling networks. Plant Physiol. 2013;162(4):1849-1866. doi: 10.1104/pp.113.221044

68. Qi G, Chen J, Chang M, Chen H, Hall K, Korin J, *et al*. Pandemonium breaks out: disruption of salicylic acid-mediated defense by plant pathogens. Mol Plant. 2018;11(12):1427-1439. doi: 10.1016/j.molp.2018.10.002
69. Qin C, Li B, Fan Y, Zhang X, Yu Z, Ryabov E, *et al*. Roles of dicer-like proteins 2 and 4 in intra- and intercellular antiviral silencing. Plant Physiol. 2017;174(2):1067. doi: 10.1104/pp.17.00475
70. Rang FJ, Kloosterman WP, de Ridder J. From squiggle to basepair: computational approaches for improving nanopore sequencing read accuracy. Genome Biol. 2018;19:90. doi: 10.1186/s13059-018-1462-9
71. Rani A, Donovan N, Mantri N. The future of plant pathogen diagnostics in a nursery production system. Biosens Bioelectron. 2019;145:111631. doi: 10.1016/j.bios.2019.111631
72. Rank AP, Koch A. Lab-to-field transition of RNA spray applications - how far are we? Front Plant Sci. 2021;12:755203. doi: 10.3389/fpls.2021.755203
73. Ratcliff F, Harrison BD, Baulcombe DC. A similarity between viral defense and gene silencing in plants. Science. 1997;276(5318):1558-1560. doi: 10.1126/science.276.5318.1558
74. Scholthof KB, Adkins S, Czosnek H, Palukaitis P, Jacquot E, Hohn T, *et al*. Top 10 plant viruses in molecular plant pathology. Mol Plant Pathol. 2011;12:938-954. doi: 10.1111/j.1364-3703.2011.00752.x
75. Seal S, Turaki A, Muller E, Kumar PL, Kenyon L, Filloux D, *et al*. The prevalence of badnaviruses in West African yams (*Dioscorea cayenensis-rotundata*) and evidence of endogenous pararetrovirus sequences in their genomes. Virus Res. 2014;186:144-154. doi: 10.1016/j.virusres.2014.01.007
76. Singh A, Permar V, Basavaraj A, Bhoopal ST, Praveen S. Effect of temperature on symptoms expression and viral RNA accumulation in groundnut bud necrosis virus-infected Vigna unguiculata. Iran J Biotechnol. 2018;16(3):227-234. doi: 10.21859/ijb.1846
77. Singh DP, Turner NC, Rawson HM. Effects of radiation, temperature and humidity on photosynthesis, transpiration and water use efficiency of oilseed rape (*Brassica campestris* L.). Biol Plant. 1982;24(2):130. doi: 10.1007/bf02902859
78. Sisterson MS. Transmission of insect-vectored pathogens: effects of vector fitness as a function of infectivity status. Environ Entomol. 2009;38(2):345-355. doi: 10.1603/022.038.0206
79. Banerjee A, Sharma S, Singh R, Ranebennur H, Dutta S, Ngachan SV. Recent advances in plant virus research in north-east India. 2015
80. Stevens RB. Plant Pathology: An Advanced Treatise, Volume III: The Diseases, Population, Epidemics and Control. Academic Press Inc., London; 1960. pp. 357-429. doi: 10.1016/b978-0-12-395678-1.50016-3
81. Stobbe AH, Roossinck MJ. Plant virus metagenomics: What we know and why we need to know more. Front Plant Sci. 2014;5:150. doi: 10.3389/fpls.2014.00150
82. Sun S, Lian S, Feng S, Dong X, Wang C, Li B, Liang W. Effects of temperature and moisture on sporulation and infection by Pseudoperonospora cubensis. Plant Dis. 2017;101(4):562-567. doi: 10.1094/pdis-09-16-1232-re
83. Tyler AD, Mataseje L, Urfano CJ, Schmidt L, Antonation KS, Mulvey MR, *et al*. Evaluation of Oxford Nanopore's MinION sequencing device for microbial whole genome sequencing applications. Sci Rep. 2018;8:10931. doi: 10.1038/s41598-018-29334-5
84. Banerjee A, Sharma S, Singh R, Ranebennur H, Dutta S, Ngachan SV. Recent advances in plant virus research in north-east India. 2015
85. Singh AK, Meetei NT, Singh BK, Mandal N. High incidence of citrus tristeza virus in mandarin (Citrus reticulata) in North-East states of India. Virus Dis. 2017;28(4):401-407. doi: 10.1007/s13337-017-0411-7
86. Das S, Srinivas K, Milton AAP, Khan S, Wahlang L, Kylla H, *et al*. Epidemiology of lumpy skin disease in Northeast India and a new method for rapid field diagnosis. AMB Express. 2025;15(1):85. doi: 10.1186/s13568-025-01891-9
87. Venkatesh J, Kang BC. Current views on temperature-modulated R gene-mediated plant defense responses and tradeoffs between plant growth and immunity. Curr Opin Plant Biol. 2019;50:9-17. doi: 10.1016/j.pbi.2019.02.002
88. Vinayarani G, Madhusudhan KN, Deepak SA, Niranjana SR, Prakash HS. Detection of mixed infection of tobamoviruses in tomato and bell pepper by using RT-PCR and duplex RT-PCR. Int J Plant Pathol. 2011;2:89-95. doi: 10.3923/ijpp.2011.89.95
89. Wang A, Krishnaswamy S. Eukaryotic translation initiation factor 4E-mediated recessive resistance to plant viruses and its utility in crop improvement. Mol Plant Pathol. 2012;13(7):795-803. doi: 10.1111/j.1364-3703.2012.00791.x
90. Wang W-N, Tarafdar JC, Biswas P. Nanoparticle synthesis and delivery by an aerosol route for watermelon plant foliar uptake. J Nanoparticle Res. 2013;15(1):1417. doi: 10.1007/s11051-013-1417-8
91. Yu I, Parker J, Bent AF. Gene-for-gene disease resistance without the hypersensitive response in Arabidopsis dnd1 mutant. Proc Natl Acad Sci USA. 1998;95(13):7819. doi: 10.1073/pnas.95.13.7819
92. Zamora M, Méndez-López E, Agirrezabala X, Cuesta R, Lavin JL, Sánchez-Pina MA, *et al*. Potyvirus virion structure shows conserved protein fold and RNA binding site in ssRNA viruses. Sci Adv. 2017;3:1-7. doi: 10.1126/sciadv.aao2182
93. Zechmann B, Zellnig G. Rapid diagnosis of plant virus diseases by transmission electron microscopy. J Virol Methods. 2009;162:163-169. doi: 10.1016/j.jviromet.2009.07.032
94. Zhan X, Zhang F, Zhong Z, Chen R, Wang Y, Chang L, *et al*. Generation of virus-resistant potato plants by RNA genome targeting. Plant Biotechnol J. 2019;17(9):1814-1822. doi: 10.1111/pbi.13102
95. Zhang K, Chooi WH, Liu S, Chin JS, Murray A, Nizetic D, *et al*. Localized delivery of CRISPR/dCas9 via layer-by-layer self-assembling peptide coating on nanofibers for neural tissue engineering. Biomaterials. 2020;256:120225. doi: 10.1016/j.biomaterials.2020.120225
96. Zhang M, Ye J, He JS, Zhang F, Ping J, Qian C, *et al*. Visual detection for nucleic acid-based techniques as potential on-site detection methods: A review. Anal Chim Acta. 2020;1099:1-15. doi: 10.1016/j.aca.2019.11.056
97. Singh AK, Meetei NT, Singh BK, *et al*. High incidence of citrus tristeza virus in mandarin (Citrus reticulata) in North-East states of India. Virus Dis. 2017;28:401-407. doi: 10.1007/s13337-017-0411-7
98. Sanabam R, Chanu NT, Sharma SK, *et al*. Genetic diversity of Chilli veinal mottle virus infecting different chilli

landraces in North East India indicates the possibility of transboundary movement of virus. 3 Biotech. 2018;8:357. doi: 10.1007/s13205-018-1382-0

99. Meetei NT, Singh AK, Singh BK, *et al*. Disease incidence and molecular indexing of viruses infecting King chilli (*Capsicum chinense* Jacq) in North East India. Indian Phytopathol. 2020;73:117-124. doi: 10.1007/s42360-019-00169-y
100. Gaur RK, Singh M, Rao GP. Molecular characterization of sugarcane mosaic virus isolate from North Eastern Region of India. Sugar Tech. 2003;5:149-153. doi: 10.1007/BF02943626
101. Gautom T, Hazarika DJ, Goswami G, *et al*. Exploring the genetic diversity and recombination analysis of Citrus tristeza virus isolates prevalent in Northeast India. Indian Phytopathol. 2020;73:145-153. doi: 10.1007/s42360-020-00199-x
102. Karmakar A. Studies on genetic variability and distribution of begomoviruses affecting economically important crops of sub-himalayan plains of North-East India. 2023. https://ir.nbu.ac.in/handle/123456789/5472
103. Datta S, Das B, Budhauliya R. Distinct begomovirus complexes infecting adjacently growing plants in Northeast India—A report. Indian Phytopathol. 2019;72:523-530. doi: 10.1007/s42360-019-00170-5
104. Devi HC, Sharma SK, Devi KS, *et al*. Pathogenic and genetic diversity of chilli veinal mottle virus associated with U-morok (*Capsicum chinense*) decline in Manipur state of North East India. Indian Phytopathol. 2022;75:1221-1229. doi: 10.1007/s42360-022-00566-w
105. Banerjee A, Roy S, Behere GT, Roy SS, Dutta SK, Ngachan SV. Identification and characterization of a distinct banana bunchy top virus isolate of Pacific-Indian Oceans group from North-East India. Virus Res. 2014;183:41-49
106. Das T, Banerjee A. Distribution, molecular characterization and diversity of banana bunchy top virus in Tripura, India. Virus Dis. 2018;29(2):157-166.