Asian Journal of Biochemistry, Genetics and Molecular Biology

Volume 16, Issue 4, Page 21-34, 2024; Article no.AJBGMB.113987
ISSN: 2582-3698

Current Strategies for Management of Plant Viruses and Future Perspectives: Enhancing Crop Health, Yield and Productivity

Akshita Soni [a], Ram Prasad Kushvaha [a] and Sunil Kumar Snehi [a*]

[a] Department of Microbiology, Barkatullah University, Bhopal - 462026, M.P, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/AJBGMB/2024/v16i4368

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/113987

Review Article

Received: 25/12/2023
Accepted: 29/02/2024
Published: 07/03/2024

ABSTRACT

Plant viruses pose significant threats to agricultural productivity and food security worldwide. This article explores various management strategies employed to overcome the impact of plant viruses on crops, with a focus on enhancing crop health and productivity. It underscores the need for proactive management strategies to minimize yield losses, reduce disease spread, and maintain sustainable crop production through preventive measures such as Conventional and Non-conventional approaches by highlighting the key methods such as the use of resistant cultivars, cultural practices, vector control, thermos, electro, and chemotherapy, along with CRISPR, RNAi, and nanotechnology. This review article provides an overview of the current management approaches employed for controlling plant viruses.

**Corresponding author: E-mail: sunilsnehi@gmail.com;*

Keywords: *Plant viruses; preventive measures; cultural practices; nanotechnology; CRISPR; RNAi; AI.*

1. INTRODUCTION

"Plant viruses pose significant challenges to global agriculture, impacting crop health, reducing productivity, and threatening food security. In plants, among all the disease-causing pathogens, viruses are the most harmful, as they cause about 40% of total crop losses. Globally, more than twenty-five families of plant viruses are known to infect a variety of crop species, leading to higher economic losses" [1]**.** "The highest impact occurs with emerging diseases infected with DNA or RNA viruses, which are transmitted by vectors and are defined by a rapid increase in disease incidence, geographical range, and pathogenicity. There are many factors that drive the emergence of viruses: a) Areas which are totally based on monocrops with low genetic range and excessive plant density, that are prone to pathogens and pests; b) Plant material like germplasm and live plants which enables viruses movements via vectors to new areas and environments; c) Change in climate and humidity, which also affect the distribution vicinity of hosts and vectors simultaneously impacting the prevalence and spread of plant viruses; d) the potential of viruses for speedy mutation, evolution, and adaptation contributing to the challenges in controlling and treating viral infections" [2-4].

"In today's scenario, curing virus-infected plants is not easy at all, unlike bacteria or fungi, which can be easily treated with antibacterial or antifungal agents or biocontrol agents, respectively. So, disease management strategies play a vital role in preventing viruses from entering plants. Specific tools for virus diagnostics and identification are used for setting up and evaluating disease management". [76] By understanding the modes of transmission, infection mechanisms, and factors influencing virus spread, effective control measures can be implemented. This article provides a comprehensive review of the management of plant viruses, highlighting conventional and non-conventional approaches and emerging strategies. Conventional strategies such as cultural practices, sanitation, vector control, chemical control, and quarantine measures continue to play crucial roles in plant virus management. However, the development of resistant crop varieties through natural resistance, breeding, and genetic engineering approaches has shown great promise. Furthermore, the emergence of new technologies such as RNA interference (RNAi), genome editing, nanotechnology applications, and the utilization of biocontrol agents offer exciting avenues for future virus management. Integrating these technologies with approaches like integrated pest management (IPM), and artificial intelligence (AI) applications can provide more effective and sustainable solutions. Managing plant viruses is of utmost importance to protect agricultural systems and sustain crop productivity by employing integrated approaches and adopting preventive measures, utilizing diagnostic tools, incorporating genetic resistance, and implementing appropriate cultural practices, the detrimental impact of plant viruses on crop health and productivity can be mitigated.

2. DISEASE MANAGEMENT OF PLANT VIRUSES

Eradication of viruses from diseased plants is difficult due to their speedy mutation, evolution and adaptation for efficient and sturdy manage, it's important to remember the genetic variety and evolution of virus populations and feature unique, fast, and reliable diagnostic approaches. Here are some commonly used strategies for plant virus disease management that can be broadly categorized into conventional and non-conventional methods (Fig. 1.).

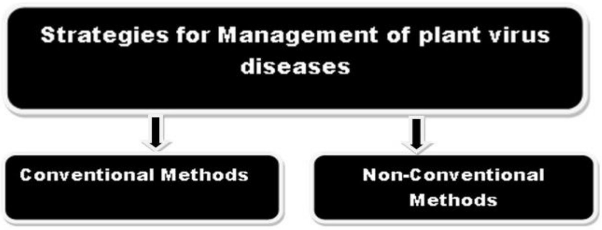

Fig. 1. Strategies for management of plant viruses

2.1 Conventional Methods

Conventional strategies typically involve the use of Virus-free plant propagation through in vitro techniques coupled with various therapies like thermotherapy, chemotherapy, and electrotherapy, Cultural practices, pest control, and host resistance have been successfully employed for plant virus management (Fig. 2.).

2.1.1 *In vitro* propagation

In vitro propagation involves the growth and development of plant tissues in a controlled laboratory environment, typically on nutrient media. Meristematic tissues, such as shoot apical meristems or axillary buds, are used as starting materials due to their high regeneration potential. “The advantage of in vitro propagation is that it allows the production of a large number of plants in a short period of time while maintaining virus-free status Most commercially cultivated orchid plants are generally infected with cymbidium mosaic virus (CyMV) and odontoglossum ringspot virus (ORSV). Two methods were used in order to generate virus-free plants: meristem culture and thin section culture with chemotherapy. Meristems (0.10 mm to 1.00 mm) were excised from infected axillary shoots of an infected monopodial orchid hybrid (*Mokara* Char Kuan ‘Pink’) and cultured in modified vaccine and wet medium. Only larger meristem explants survived and the regenerated plantlets remained virus-infected” [5].

2.1.2 Chemotherapy and thermotherapy

“Chemotherapy is based on antiviral drugs such as Ribavirin to inhibit or disrupt specific steps of the virus life cycle, such as nucleoside analogues, which inhibit replication, and protease inhibitors, which prevent protein processing”[6].”Thermotherapy involves subjecting infected plant materials or explants to elevated temperatures, typically ranging from 37°C to 40°C thermotherapy should inactivate viruses by using viral RNA breakage, viral particle disruption or coat protein rupture. Previous studies have shown that exposing plants to thermotherapy can be effective for ACLSV, ASGV, ApMV (*Apple mosaic virus*), and ASPV eradication in diseased apple cultivars” [7].

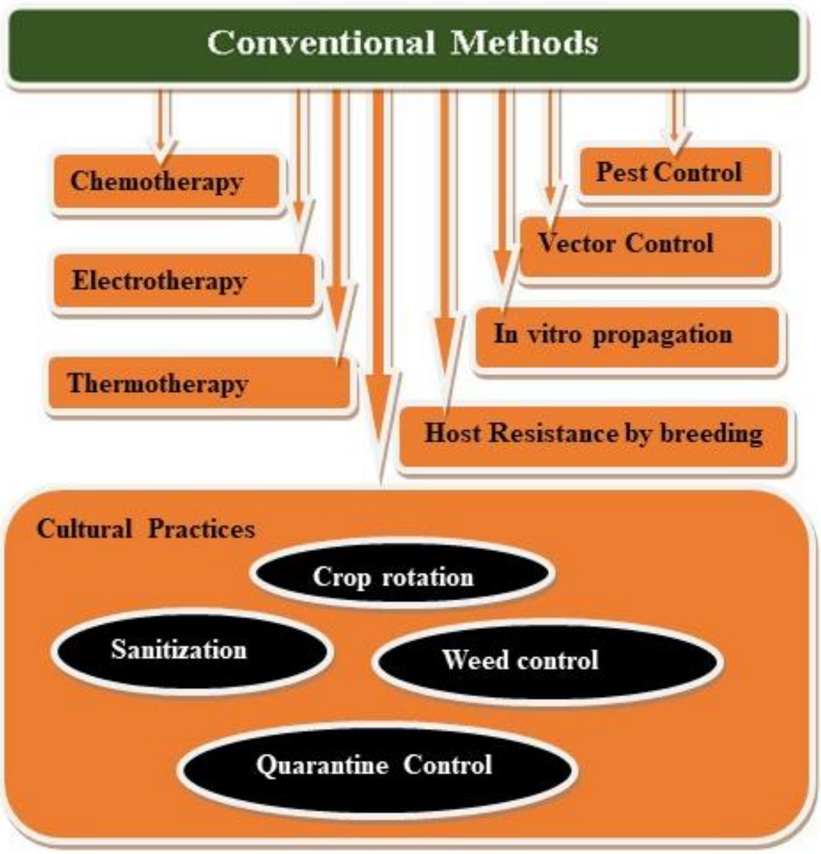

Fig. 2. Conventional Methods for management of plant viruses

Table 1. Chemotherapy was employed to eliminate some viruses

S. No.	Crops	Virus susceptibility	References
1.	Potato Virus	*Potato virus S* (PVS), *Potato virus A* (PVA) and *Potato virus M* (PVM)	[8]
2.	Vitis vinifera	*Grapevine Fanleaf Virus* (GFLV)	[9]
3.	Cassava	*Cassava Brown Streak Virus* (CBSV).	[10]

2.1.3 Electrotherapy

Electrotherapy, also known as electrofusion or electroporation, involves the application of an electric current to plant tissues. This technique disrupts the cell membranes and allows the introduction of antiviral agents or other therapeutic molecules into the cells. Electrotherapy has been explored for the control of systemic plant viruses by introducing antiviral RNA molecules or other nucleic acids into infected tissues. Electrotherapy was successful in eliminating *Potato virus X* PVX [11].

2.1.4 Cultural practices

Crop rotation: Rotating crops can help break the disease cycle by reducing the buildup of viral pathogens in the soil. Different crops act as hosts for different viruses, preventing the continuous presence of the same virus by adjusting planting density to minimize contact between plants, and implementing irrigation methods that avoid splashing water and potential virus spread[12].

Sanitation: Proper sanitation measures, such as removing infected plant debris, can reduce the source of inoculum and prevent the spread of viruses. Practicing good sanitation measures can help manage viral diseases. Additionally, cleaning tools and equipment to prevent mechanical transmission and using virus-free planting material are important sanitation practices[13]. “The sanitated plants must be evaluated and confirmed to be virus-free with very sensitive techniques such as real-time qPCR. This approach has been assayed recently with a plant virus, *Tobacco Mosaic Virus* (TMV), resulting in a loss of viral infectivity”[14].

Weed control: Weeds can act as reservoirs for plant viruses, serving as hosts for viral pathogens and potential vectors, so effective weed management can help reduce the spread of viruses by mechanical, chemical, or cultural methods.

Host Resistance: Developing and utilising resistant plant varieties is an effective strategy for virus disease management. Breeding programs aim to introduce genetic resistance to specific viruses into crop plants, making them less susceptible to infection or reducing the severity of symptoms. Breeding for resistance to plant viruses can involve selecting natural resistance genes or introducing them through genetic engineering. Genetic modification techniques, such as transgenic approaches, can be used to introduce specific resistance genes into susceptible plant species. For example, genetically engineered crops with resistance to *Papaya ringspot virus* (PRSV) have been successfully developed by Palukaitis et al. [20].

Table 2. Weed plants which can be infected by viruses.

S. No.	Weed species	Viruses’ susceptibility	References
1.	Dandelion (*Taraxacum officinale*)	*Dandelion Yellow Mosaic Virus, Dandelion Curly Top Virus.*	[15]
2.	Common chickweed (*Stellaria media*)	*Chickweed Yellows Virus*	[16]
3.	Purslane (*Portulaca oleracea*)	*Cucumber Mosaic Virus*	[17]
4.	Broadleaf plantain (*Plantago major*)	*Broadleaf Plantain Mottle Virus, Cucumber Mosaic Virus*	[18]
5.	Pigweed (*Amaranthus spp.)*	*Pigweed Mosaic Virus*	[19]

Vector Control: maximum plant viruses are transmitted with the aid of arthropod vectors, especially aphids, whiteflies, and thrips. Translocation of begomoviruses via whitefly causes *Tomato Yellow Leaf Curl Virus* (TYLCV) infection, which is a major threat to tomato crops. Peppers, cucurbits, eggplants, and beans are also infected with begomoviruses transmitted by vectors. Hence, Controlling the insect vectors responsible for transmitting viruses can significantly reduce disease spread [21].

2.2 Non-Conventional Methods

Non-conventional methods for plant virus management involve innovative approaches that go beyond traditional cultural practices and chemical control. Here are some strategies for the disease management of plant viruses (Fig. 3.).

2.2.1 Biological control

Beneficial microorganisms, such as bacteria, fungi, and viruses, can be used as biocontrol agents to suppress plant viruses. They can either directly inhibit viral replication or induce systemic resistance in plants against viruses[22]. Use of parasitic wasps has been successful in controlling aphid vectors of plant viruses, biopesticides are used to control insect vectors or directly inhibit viral replication in plants. Baculoviruses and entomopathogenic fungi have shown potential as biocontrol agents for vector management [23].

2.2.2 Plant activators

Plant activators are compounds that induce systemic acquired resistance (SAR) in plants, making them more resistant to viral infections. They activate the plant's immune response and strengthen natural defence mechanisms [30].

2.2.3 RNA interference (RNAi)

RNAi-based strategies involve the introduction of small RNA molecules that target viral RNA, thereby triggering sequence-specific degradation of the viral genetic material. This can effectively reduce viral replication and the development of symptoms. RNAi has been successfully used to confer resistance to various plant viruses, including *Tomato yellow leaf curl virus* and *Potato virus Y* (PVY) [30].

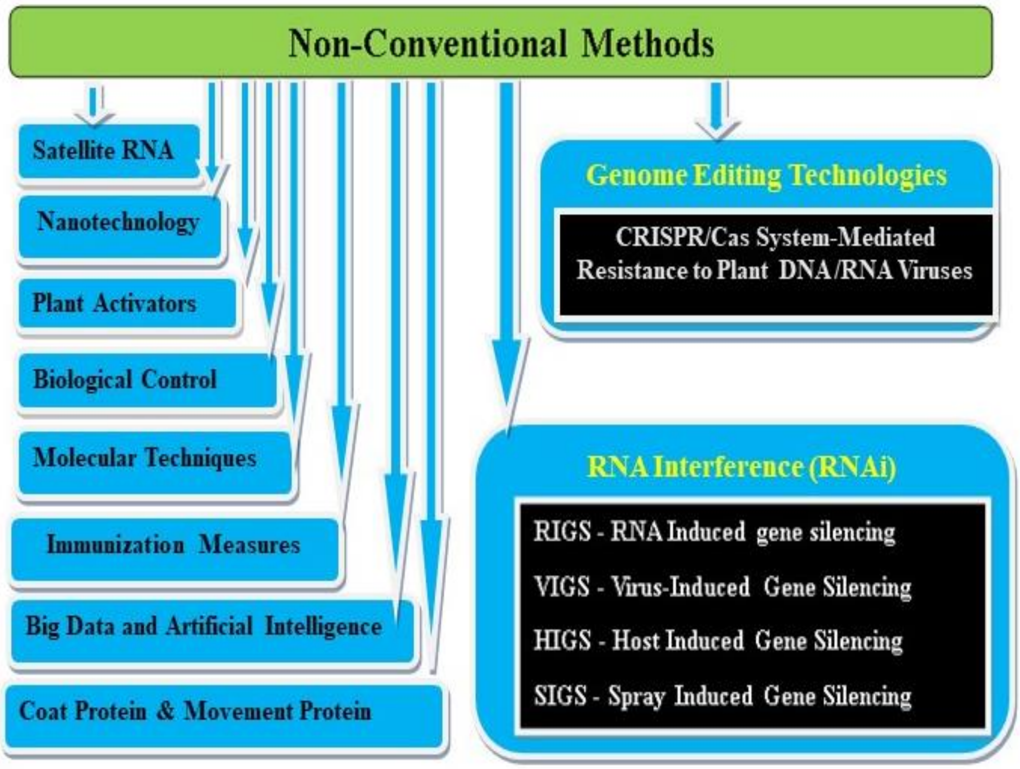

Fig. 3. Non-Conventional Methods for management of plant viruses

Table 3. Biocontrol agents used to suppress plant viruses

S. No.	Crops	Virus susceptibility	Biocontrol agent	vectors	References
01	Tomato	*Tomato yellow leaf curl virus (TYLCV)*	*Encarsia formosa*	Whitefly	[24]
02	Potato	*Potato virus Y (PVY)*	*Aphidius ervi*	Aphids	[25]
03	Citrus	*Citrus tristeza virus (CTV)*	*Tamarixia radiata*	Asian citrus psyllid	[26]
04	Cucumber	*Cucumber mosaic virus (CMV)*	*Aphidius colemani*	Aphids	[22]
05	Pepper	*Pepper mild mottle virus (PMMoV)*	*Orius insidiosus*	Thrips	[27]
06	Bean	*Bean common mosaic virus (BCMV)*	*Aphidoletes aphidimyza*	Aphids	[28]
07	Cotton	*Cotton leaf curl virus (CLCuV)*	*Trichogramma chilonis*	Cotton leafhopper	[29]
08	Wheat	*Wheat streak mosaic virus (WSMV)*	*Coccinella septempunctata*	Aphids	[30]

2.2.3.1 RNA induced gene silencing

"RNA Induced gene silencing: Gene silencing is triggered by small RNA (sRNA) molecules. sRNAs are small interfering RNA (siRNA) and microRNA (miRNA). The silencing process is initiated when long dsRNAs are cleaved into small fragments (21–25 nts) of sRNAs with the help of the Dicer (DCL) enzyme inside the cytoplasm" [31,32]**.** **"**Now these sRNA duplexes unwind themselves and are loaded into the RISC, where the stable strand is selected as the guide strand and the second strand is the passenger strand, which is later discarded. Guide strands integrate into the RISC and activate it. An essential member of the RISC is the Argonaut (AGO) protein. After loading the guide strand, the AGO protein, by its endo-nucleolytic action, mediates the repression or degradation of the targeted mRNA" [33,34]**.** **"**Cleavage of targeted mRNA is initiated 10–12 nt away from the region's centre, recognized by the guide sRNA"[32]. **"**The mechanism is accomplished by amplifying sRNA molecules through RNA-dependent RNA polymerase (RDRs) enzymes. RDRs produced double-stranded RNA, which was further cleaved and processed by DCLs and continued in the next round of RNA silencing"[35].

2.2.3.2 Virus-Induced Gene Silencing (VIGS)

"Virus-Induced Gene Silencing (VIGS): In VIGS, the viral genome is manipulated by deleting the disease-causing genes, and then cloning can be performed for the modification of the viral genome cDNA into a binary vector. Viruses that lack gene silencing or weak suppressors are potential targets as VIGS vectors"[36, 37]**.** **"**The specific silenced gene is cloned into the MCS of the binary vector The recombinant virus then enters the plant cells through an Agrobacterium-mediated transformation or DNA bombardment into the host cells. Once the recombinant virus enters the plant cell, RNA-dependent RNA polymerase (RdRp) transcribes the viral RNA and transgene"[38]. "Double-stranded RNAs (dsRNAs) are generated and further cleaved by Dicer into 21–25 nts long siRNA now these siRNAs further loaded into the RISC that targeted the complementary DNA"[37]. "The *Tobacco mosaic virus* (TMV), *Tomato golden mosaic virus* (TGMV), and *Potato virus X* (PVX) belong to the first generation of the VIGS vector system, which causes the short-term silencing of endogenous gene expression and leaf chlorosis" [39].

2.2.3.3 Host-Induced Gene Silencing (HIGS)

"It is based on the plant's natural immune system, which utilizes RNA-induced silencing to defend against the viral infection. HIGS is further advanced to VIGS, which silences the pathogenic genes inside plants by targeting the specific genes of the pathogen inside the host plant"[40,41]. "In HIGS, transgenic plants are generated by introducing an inverted repeat sequence inside the plant genome. Double-stranded RNAs are produced as small RNAs inside the transgenic plants, introduced either through Agrobacterium or VIGS. The improvement of efficient, resistant, and polycistronic miRNA and the fusion of multiple genes in hairpin RNA are efficient and successful" [42]. "Infections towards the *wheat streak mosaic virus* (WSMV) have been decreased using a coat protein and a full-period viral replicase (Nib) gene" [43].

2.2.3.4 Spray Induced Gene Silencing (SIGS)

"It is an advanced RNA silencing strategy for disease control. It is used for monocot and dicot pathogen infections and has been used for crop protection based on findings that plant pathogens can uptake dsRNA, which is applied externally"[44,45]. "This dsRNA then silences the targeted pathogen genes, which is critical for disease improvement. SIGS is an eco-friendly and advanced strategy for pathogen control at pre-harvesting and post-harvesting stages and offers fewer off-target effects. The topical application of dsRNA confers resistance against *Alfalfa mosaic virus* (AMV), *Pepper mild mottle virus* (PMMoV), and *Tobacco etches virus* (TEV). SIGS had been performed by the low-pressure spraying of siRNAs, which was previously reported to fail GFP silencing. However, the problem was overcome by spraying siRNA at high pressure, which successfully silenced the GFP. Further investigation is required to optimize the high-pressure spraying technology against targeted tissues"[46].

2.2.4 Genome editing technologies

Techniques such as CRISPR-Cas9 play major role in modifications of plant genome, including editing of viral susceptibility genes. This approach shows promise in developing virus-tolerant crops by disrupting essential viral genes or host susceptibility factors (Fig. 4.).

After plant viruses enter plant cells, the viral genome is uncoated and transcribed, or translated, with the help of host factors. Plant viruses then multiply their genomes in the nucleus or cytoplasm. The viral genome DNA or RNA can be targeted, destroyed, or interfered with by CRISPR/Cas9 or CRISPR/Cas13 (or FnCas9) systems in the nucleus or in the cytoplasm, respectively, which inhibits viral infection. In addition, the mutation or deficiency in host susceptibility factors edited by the CRISPR/Cas9 system also perturbs viral infection. However, some new viral variants might be generated as by-products when CRISPR/Cas systems edit the viral genome, which might increase the risk of viral evolution.

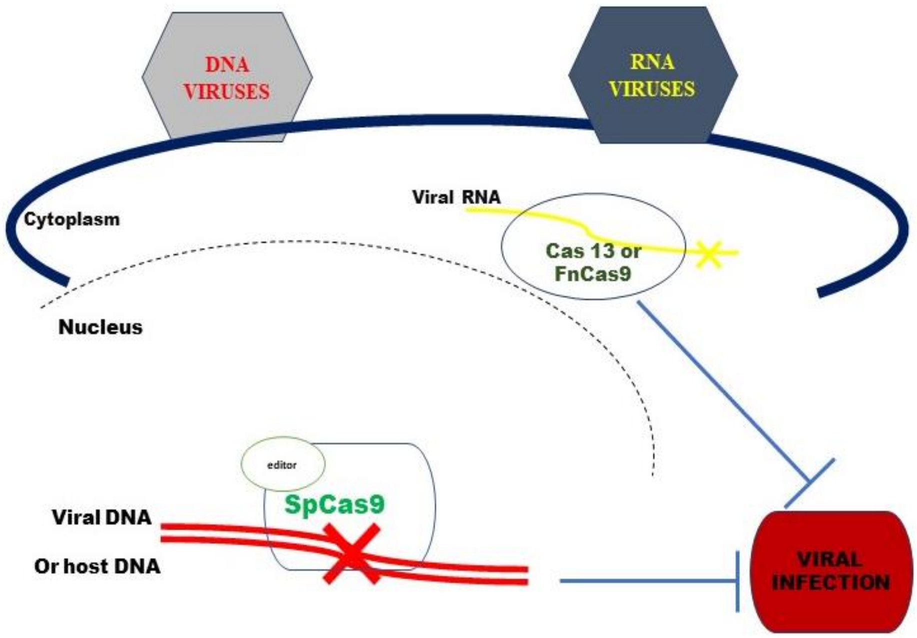

Fig. 4. Schematic representation of class 2 CRISPR/Cas systems to confer resistance to plant viruses

2.2.4.1 CRISPR/Cas system-mediated resistance to plant DNA viruses

"Geminiviridae and Caulimoviridae are two major destructive plant DNA virus families that contain 485 species with single-stranded DNA (ssDNA) genomes and 85 species with double-stranded DNA (dsDNA) genomes. Before the emergence of the CRISPR/Cas systems, zinc finger nucleases (ZFNs) and transcription activator-like effector nucleases (TALENs) were applied to manipulate host and viral DNAs in plants. ZFN- and TALEN-mediated resistance to several geminivirus, including *Tomato Yellow Leaf Curl China virus* (TYLCCV) and *Tobacco Curly Shoot Virus* (TbCSV), by targeting the viral genomic replication-associated region has been reported"[47,48]. "CRISPR/Cas9 constructs with single guide RNAs (sgRNAs) targeting the viral replication-associated region, or intergenic region (IR), have exhibited effective DNA interference and conferred viral resistance against *Beet Severe Curly Top Virus* (BSCTV), *Cotton Leaf Curl Multan Virus* (CLCuMuV), and *Bean Yellow Dwarf Virus* (BeYDV) in transgenic Nicotiana benthamiana or Arabidopsis thaliana plants"[49,50]. "Targeting the *Tomato Yellow Leaf Curl Virus* (TYLCV) genome with Cas9-single guide RNA at the sequences encoding the coat protein (CP) or replicase (Rep) resulted in efficient virus interference, as evidenced by the low accumulation of the TYLCV. DNA genome in the transgenic tomato and N. benthamiana plants CRISPR/Cas9-triggered mutations in the open reading frame (ORF), but not the geminivirus IR, are capable of replication and whole-body movement, thus circumventing the CRISPR/Cas9 machinery. Using this system via a single sgRNA targeting the conserved stem-loop sequence of the origin of replication in the intergenic region of TYLCV, we were also able to confer broad-spectrum resistance to other geminiviruses in plants, including the monocomponent geminivirus, beet curly top virus (BCTV), and the bicomponent geminivirus MeMV" [51]. "The CRISPR/Cas9 system combined with sgRNAs targeting the motility protein (MP) or CP regions conferred resistance to wheat dwarf virus (WDV) and banana streak virus (BSV), respectively" [52]. "In addition, CRISPR/Cas9-mediated immunity has been recently utilized to defend against plant dsDNA viruses. A. thaliana transgenic plants consistently expressing both Cas9 protein and sgRNAs targeting the CP region of *cauliflower mosaic virus* (CaMV) in the Caulimoviridae family conferred effective resistance to this species" [53].

2.2.4.2 CRISPR/Cas system-mediated resistance to plant RNA viruses

"RNA targeting and editing CRISPR-associated proteins were Cas9, derived from Francisella novicida (FnCas9), and Cas13a (formerly called C2c2), from Leptotrichia shahii (LshCas13a) it is the first Cas13 ortholog for programmable RNA-targeting activities, which expanded the application of CRISPR/Cas systems from DNA to RNA" [54]. "LshCas13a are programmed to cleave ssRNA viruses in plants by targeting viral RNA shows resistance towards TMV, *Rice Stripe Mosaic Virus* (RSMV), and *Southern Rice Black-Streaked Dwarf Virus* (SRBSDV) in transgenic tobacco and rice harbouring. By targeting the P3-, NIb-, or CP-coding sequences in the *potato virus Y* (PVY) genomic region, this CRISPR/Cas13a system also showed its effectiveness in interfering with and inhibiting PVY infection" [55]. "Researchers found that Cas13d showed great advantages over Cas13a, Cas13b, or other Cas13 variants when it was used to interfere with TuMV infection by targeting the GFP, CP, or HC-Pro regions in the TuMV-GFP genome" [56].

2.2.5 Nanotechnology

Nanotechnology has emerged as a promising field for the management of plant viruses. It involves the manipulation and application of materials at the nanoscale level to achieve desired outcomes. Several approaches utilizing nanotechnology have been explored for the detection, prevention, and treatment of plant virus infections. Nanoparticles can be used to deliver antiviral agents or RNA molecules to plants, targeting viral replication and reducing viral load [57].

2.2.5.1 Nanosensors for virus detection

Nanosensors can be used for the rapid and sensitive detection of plant viruses. These sensors are designed to recognize specific viral components or nucleic acids. For instance, gold nanoparticles functionalized with viral-specific antibodies or aptamers can be used to detect and quantify virus particles in plant samples [48].

2.2.5.2 Nanocarriers for targeted delivery

Nanoparticles can serve as effective carriers for delivering antiviral agents to plant cells. Functionalized nanoparticles can be loaded with antiviral compounds or siRNA molecules targeting viral genes. These nanoparticles can be designed to specifically target infected cells or tissues, thereby reducing off-target effects [58].

2.2.5.3 Nanovaccines for plant protection

Nanotechnology offers a platform for developing nanovaccines against plant viruses. Nanoparticles can be engineered to display viral antigens, mimicking the virus's structure. These nanovaccines stimulate the plant's immune system, leading to enhanced resistance against viral infections. Carbon nanotubes, liposomes, and virus-like particles are examples of nanocarriers used for nanovaccines delivery [59].

2.2.5.4 Nanoparticle-mediated RNA interference (RNAi)

RNAi-based approaches can be used to silence viral genes and inhibit viral replication. Nanoparticles can be utilized to deliver small interfering RNA (siRNA) molecules into plant cells, thereby triggering RNAi-mediated antiviral responses. Various nanoparticles, such as liposomes, carbon nanotubes, and dendrimers, have been investigated for efficient siRNA delivery [60].

2.2.6 Artificial Intelligence (AI)

The integration of big data and artificial intelligence (AI) has significant potential for managing plant viruses through predictive modelling and precision control strategies. Predictive modelling: AI techniques, including machine learning and data mining, can analyse historical and real-time data on environmental factors, host plant characteristics, and virus spread patterns to develop predictive models. These models can forecast virus outbreaks, identify high-risk areas, and guide targeted surveillance and management strategies by proactively predicting virus spread, farmers can implement timely preventive measures. Precision control strategies: big data and AI enable the development of precision control strategies for managing plant viruses. By integrating data from various sources, including weather data, crop growth parameters, and disease records, AI algorithms can optimize the timing and dosage of interventions such as pesticide applications or cultural practices. This approach helps minimize the use of chemical inputs and reduces the risk of resistance development [61].

Various Artificial Intelligence Models have been developed including:

Large Language Model (LLM): These are systems that use large-scale neural networks to understand and generate human-like language. Notable developments in large language models, especially the introduction of GPT-3 [62].

Convolutional Neural Network (CNN): It uses convolutional layers to automatically and adaptively learn spatial hierarchies of features from input images. Proposed by Yann LeCun in the early 1990s, CNNs gained prominence in the mid-2010s with breakthroughs in image recognition tasks [63,64].

Recurrent Neural Network (RNN)): A type of neural network architecture designed to recognize patterns in sequences of data. RNNs are well-suited for tasks involving sequential data, such as time series analysis and natural language processing. While the concept of RNNs dates back to the 1980s, their resurgence and success in various applications, especially in natural language processing, gained momentum in the mid2010s [65,66].

Generative Adversarial Network (GAN): GANs consist of two neural networks, a generator, and a discriminator, which are trained simultaneously through adversarial training. GANs are used for generating new, realistic data instances, such as images [67,68].

Support Vector Machine (SVM): Its are effective in high-dimensional spaces and are particularly useful in tasks like image classification and handwriting recognition. Proposed by Vladimir Vapnik and Corinna Cortes in the 1990s, SVMs gained popularity in the early 2000s and became a staple in machine learning applications [69].

K-Nearest Neighbors (**KNN):** A simple and effective algorithm used for classification and regression tasks. KNN makes predictions based on the majority class or average of the k-nearest data points in the feature space. It is widely applied in various fields since the 1960s [70].

Deep Neural Network (DNN): A neural network with three or more layers, including an input layer, one or more hidden layers, and an output layer. Deep neural networks are capable of learning intricate representations and are used in various applications [71].

Long Short-Term Memory (**LSTM):** A type of recurrent neural network architecture designed to overcome the limitations of traditional RNNs in capturing longterm dependencies in sequential data. LSTMs are widely used in natural language processing and speech recognition [72].

Reinforcement Learning (RL): An area of machine learning where an agent learns to make decisions by interacting with an environment. The agent receives feedback in the form of rewards or penalties, allowing it to learn optimal strategies over time [73,74].

Bidirectional Encoder Representations from Transformers (**BERT):** A pre-trained natural language processing model based on transformer architecture. BERT is particularly effective in understanding the context of words in a sentence and is used for various language-related tasks. Introduced by Google AI in 2018, BERT brought a breakthrough in natural language processing by capturing contextual information bidirectionally [75].

3. CONCLUSION

The management of plant viruses is a critical aspect of protecting agricultural crops and ensuring global food security. Both conventional and non-conventional methods have been employed to mitigate the impact of viral diseases on plants. Conventional methods such as crop rotation, sanitation, vector control, and resistant varieties have proven effective in reducing virus transmission and minimizing crop damage. Non-conventional methods, including cross-protection, RNA interference, and plant vaccines, offer innovative approaches to enhance plant resistance and control viral infections. These methods have shown promise in providing long-term solutions by targeting the viruses directly or inducing plant immunity. Furthermore, emerging technologies have opened up new avenues for plant virus management. Genome editing techniques like CRISPR-Cas9 allow precise modifications to plant genomes, enabling the development of virus-resistant crops. Next-generation sequencing facilitates rapid and accurate virus detection, while nanotechnology offers novel delivery systems for antiviral agents. Remote sensing combined with artificial intelligence allows for early detection and monitoring of virus-induced changes in crop health.

It is crucial to continue research and development in plant virus management to stay ahead of evolving viral strains and their vectors. Collaboration between scientists, farmers, and policymakers is essential to implementing effective management strategies, promoting awareness, and developing sustainable agricultural practices. It is necessary to continue research and development in these areas to enhance plant virus management practices, reduce the impact of plant viruses on crop production, and safeguard global food security.

ACKNOWLEDGEMENT

The authors are thankful to the Head, Department of Microbiology, and the Vice Chancellor of Barkatullah University, Bhopal for providing facilities.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Maksimov IV, Sorokan AV, Burkhanova GF, Veselova SV, Alekseev VY, Shein MY, Avalbaev AM, Dhaware PD, Mehetre GT, Singh BP, Khairullin RM. Mechanisms of Plant Tolerance to RNA Viruses Induced by Plant-Growth-Promoting Microorganisms. Plants Basel. 2019;8(12): 575.
2. Anderson PK, Cunningham AA, Patel NG, Morales FJ, Epstein PR, Daszak P. Emerging infectious diseases of plants: pathogen pollution, climate change and agrotechnology drivers. Trends Ecol Evol. 2004;19(10):535-44.
DOI: 10.1016/j.tree.2004.07.021
3. Jones RA. Plant virus emergence and evolution: origins, new encounter scenarios, factors driving emergence, effects of changing world conditions, and prospects for control. Virus Res. 2009; 141(2):113-30.
DOI: 10.1016/j.virusres

4. Elena SF, Fraile A, García-Arenal F. Evolution and emergence of plant viruses. Adv Virus Res. 2014;88:161-91.
5. Albouy J, Flouzat C, Kusiak C, Tronchet M. Eradication of orchid viruses by chemotherapy from in-vitro cultures of Cymbidium. InVII International Symposium on Virus Diseases of Ornamental Plants 1988;234:413-420.
6. Panattoni A, Luvisi A, Triolo E. Elimination of viruses in plants: Twenty years of progress. Span. J. Agric. Res.2013;11: 173–188.
7. Wang MR, Cui ZH, Li JW, Hao XY, Zhao L, Wang QC. In vitro thermotherapy-based methods for plant virus eradication. Plant Methods. 2018;14:87.
   DOI: 10.1186/s13007-018-0355-y
8. Bettoni JC, Mathew L, Pathirana R, Wiedow C, Hunter DA, McLachlan A, Khan S, Tang J, Nadarajan J. Eradication of *Potato Virus S*, *Potato Virus A*, and *Potato Virus M* From Infected *in vitro*-Grown Potato Shoots Using *In vitro* Therapies. Front Plant Sci. 2022; 13:878733.
   DOI: 10.3389/fpls.2022.878733.
9. Weiland, Carlos, Cantos, Manuel, Troncoso A. Perez-Camacho. Regeneration of Virus-Free Plants By In Vitro Chemotherapy of GFlV (Grapevine Fanleaf Virus) Infected Explants of Vitis Vinifera L. Cv 'Zalema'. Acta Horticulturae. 2004; 652:463-466.
10. Mwangangi, Maureen & Ateka, Elijah & Nyende, Aggrey Bernard & Kagundu, Abed. Elimination of Cassava Brown Streak Virus from Infected Cassava.2020; 4:13-41.
11. Meybodi D & Mozafari Hashjin, Javad & Babaeiyan, N & Rahimian, Heshmat. Application of Electrotherapy for the Elimination of Potato Potyviruses. Journal of Agricultural Science and Technology. 2011;13.
12. Gray SM and N Banerjee. Mechanisms of arthropod transmission of plant and animal viruses. Microbiol Mol Biol Rev. 1999; 63(1):28-48
13. Roossinck MJ.*Plant virus ecology.* PLoS Pathog.2013;9(5):1003304.
14. Díaz-Martínez L, Brichette-Mieg I, Pineño-Ramos A, Domínguez-Huerta G, Grande-Pérez A. Lethal mutagenesis of an RNA plant virus via lethal defection. Sci Rep. 2018;8(1):1444. doi: 10.1038/s41598-018-19829-6.
15. Kassanis B. A virus attacking lettuce and dandelion. Nature.1944;154(3896):16-16.
16. Hill E, Renner K, Sprague C. *Henbit (Lamium amplexicaule), Common Chickweed (Stellaria media), Shepherd's-Purse (Capsella bursa-pastoris),* and *Field Pennycress (Thlaspi arvense):* Fecundity, Seed Dispersal, Dormancy, and Emergence. Weed Sci. 2014;1:97-106.
17. Friess N and J Maillet. Influence of *cucumber mosaic* virus infection on the intraspecific competitive ability and fitness of purslane *(Portulaca oleracea).* New Phytol.1996;132(1):103-111.
18. Xu L and J Ming. Development of a multiplex RT-PCR assay for simultaneous detection *of Lily symptomless virus, Lily mottle virus, Cucumber mosaic virus, and Plantago asiatica mosaic virus* in Lilies. Virol J. 2022;19(1):219.
19. Shingote PR, Wasule DL, Parma VS, Holkar SK, Karkute SG, Parlawar ND, Senanayake DMJB. An Overview of Chili Leaf Curl Disease: Molecular Mechanisms, Impact, Challenges, and Disease Management Strategies in Indian Subcontinent. Front Microbiol. 2022; 13:899512.
   DOI: 10.3389/fmicb.2022.899512.
20. Palukaitis P and F García-Arenal. *Cucumoviruses.* Advances in virus research. 2003;62:241-323.
21. Czosnek H, Hariton-Shalev A, Sobol I, Gorovits R, Ghanim M. The Incredible Journey of Begomoviruses in their whitefly vector. Viruses. 2017;9(10):273.
22. Alves MN. Insights on the interaction between Rutaceae genotypes and the ‘Candidatus liberibacter asiaticus’ bacterium; 2022.
23. Czosnek H. ‘Tomato yellow leaf curl virus (leaf curl)’, CABI Compendium. CABI; 2022.
   DOI: 10.1079/cabicompendium.55402.
24. He Y, Jiang W, Ding W, Chen W, Zhao D. Effects of PVY-Infected Tobacco Plants on the Adaptation of Myzus persicae (Hemiptera: Aphididae). Insects. 2022; 13(12):1120.
25. Moreno P, Ambrós S, Albiach-Martí Mr, Guerri J, Pena L. Citrus tristeza virus: a pathogen that changed the course of the citrus industry. Molecular plant pathology. 2008;9(2):251-68.
26. Antignus Y, Lachman O, Pearlsman M, Maslenin L, Rosner A. A new pathotype of Pepper mild mottle virus (PMMoV)

overcomes the L 4 resistance genotype of pepper cultivars. Plant Disease. 2008;92 (7):1033-7.

27. Feng X, Poplawsky AR, Nikolaeva OV, Myers JR, Karasev AV. Recombinants of Bean common mosaic virus (BCMV) and genetic determinants of BCMV involved in overcoming resistance in common bean. Phytopathology. 2014;104(7):786-93.
28. Sohrab SS, Kamal MA, Ilah A, Husen A, Bhattacharya PS, Rana D. Development of Cotton leaf curl virus resistant transgenic cotton using antisense ßC1 gene. Saudi journal of biological sciences. 2016;23(3):358-62.
29. Singh K, Wegulo SN, Skoracka A, Kundu JK. Wheat streak mosaic virus: a century old virus with rising importance worldwide. Molecular Plant Pathology. 2018;19(9): 2193-206.
30. Pumplin N, Voinnet O. RNA silencing suppression by plant pathogens: Defence, counterdefence and counter-counter-defence. Nat. Rev. Microbiol. 2013;11:745-760.
31. Zamore PD, Tuschl T, Sharp PA, Bartel DP. RNAi: double-stranded RNA directs the ATP-dependent cleavage of mRNA at 21 to 23 nucleotide intervals. cell. 2000; 101(1):25-33.
32. Blackwell J, Newbold C, Turner M, Vickerman K, editors. RNA interference: advances and questions. Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences. 2002;357(1417):65-70.
33. Haley B and PD Zamore. Kinetic analysis of the RNAi enzyme complex. Nat Struct Mol Biol.2004;11(7):599-606.
34. Martinez J and T Tuschl. RISC is a 5′ phosphomonoester-producing *RNA* endonuclease. Genes & development. 2004;18(9):975-980.
35. Wassenegger M and G Krczal. Nomenclature and functions of RNA-directed RNA polymerases.Trends in plant science. 2006;11(3):142-151.
36. Voinnet O. *RNA silencing* as a plant immune system against viruses. Trends in Genetics. 2001;17(8):449-459.
37. Morel JB, Godon C, Mourrain P, Béclin C, Boutet S, Feuerbach F, Proux F, Vaucheret H. Fertile hypomorphic Argonaute (ago1) mutants impaired in post-transcriptional gene silencing and virus resistance. The Plant Cell. 2002;14(3):629-39.
38. Dalmay T, Hamilton A, Rudd S, Angell S, Baulcombe DC. An RNA-dependent RNA polymerase gene in Arabidopsis is required for posttranscriptional gene silencing mediated by a transgene but not by a virus. Cell. 2000;101(5):543-53.
39. Ruiz MT, O Voinnet, and DC Baulcombe, Initiation and maintenance of virus-induced gene silencing. Plant Cell. 1998;10(6):937-46.
40. Harvey JJ, Lewsey MG, Patel K, Westwood J, Heimstädt S, Carr JP, Baulcombe DC. An antiviral defense role of AGO2 in plants. PloS one. 2011;6(1):14639.
41. Hu Q, Niu Y, Zhang K, Liu Y, Zhou X. Virus-derived transgenes expressing hairpin RNA give immunity to Tobacco mosaic virus and Cucumber mosaic virus. Virology journal. 2011;8:1-1.
42. Akbar S, Tahir M, Wang MB, Liu Q. Expression analysis of hairpin RNA carrying Sugarcane mosaic virus (SCMV) derived sequences and transgenic resistance development in a model rice plant. BioMed Research International; 2017.
43. Sivamani E, Brey CW, Talbert LE, Young MA, Dyer WE, Kaniewski WK, Qu R. Resistance to wheat streak mosaic virus in transgenic wheat engineered with the viral coat protein gene. Transgenic Research. 2002;11:31-41.
44. Chaloner, T., J.A.L. van Kan, and R.T. Grant-Downton, *RNA* 'Information Warfare' in Pathogenic and Mutualistic Interactions. Trends Plant Sci. 2016;21(9):738-748.
45. Wang M, Weiberg A, Lin FM, Thomma BP, Huang HD, Jin H. Bidirectional cross-kingdom RNAi and fungal uptake of external RNAs confer plant protection. Nature plants.2016;2(10):1-0.
46. Kalyandurg PB, Sundararajan P, Dubey M, Ghadamgahi F, Zahid MA, Whisson SC, Vetukuri RR. Spray-induced gene silencing as a potential tool to control potato late blight disease. Phytopathology®. 2021;111 (12):2168-75.
47. Chen W, Qian Y, Wu X, Sun Y, Wu X, Cheng X. Inhibiting replication of begomoviruses using artificial zinc finger nucleases that target viral-conserved nucleotide motif. Virus Genes. 2014;48: 494-501.
48. Cheng X, Li F, Cai J, Chen W, Zhao N, Sun Y, Guo Y, Yang X, Wu X. Artificial TALE as a convenient protein platform for

engineering broad-spectrum resistance to begomoviruses. Viruses.2015;7(8):4772-82.
49. Baltes NJ and DF Voytas, Enabling plant synthetic biology through genome engineering. Trends Biotechnol. 2015; 33(2):120-31.
50. Ji X, Zhang H, Zhang Y, Wang Y, Gao C. Establishing a CRISPR–Cas-like immune system conferring DNA virus resistance in plants. Nature Plants. 2015;1(10):1-4.
51. Ali Z, Abulfaraj A, Idris A, Ali S, Tashkandi M, Mahfouz MM. CRISPR/Cas9-mediated viral interference in plants. Genome biology. 2015;16:1-1.
52. Kis A, Tholt G, Ivanics M, Várallyay É, Jenes B, Havelda Z. Polycistronic artificial miRNA-mediated resistance to W heat dwarf virus in barley is highly efficient at low temperature. Molecular Plant Pathology. 2016;17(3):427-37.
53. Liu Y, Zhang D, Alocilja EC, Chakrabartty S. Biomolecules detection using a silver-enhanced gold nanoparticle-based biochip. Nanoscale research letters. 2010; 5:533-8.
54. Abudayyeh OO, Gootenberg JS, Konermann S, Joung J, Slaymaker IM, Cox DB, Shmakov S, Makarova KS, Semenova E, Minakhin L, Severinov K. C2c2 is a single-component programmable RNA-guided RNA-targeting CRISPR effector. Science. 2016;353 (6299):5573.
55. Zhang T, Zheng Q, Yi X, An H, Zhao Y, Ma S, Zhou G. Establishing RNA virus resistance in plants by harnessing CRISPR immune system. Plant Biotechnology Journal. 2018;8:1415-23.
56. Mahas A, Aman R, Mahfouz M. CRISPR-Cas13d mediates robust RNA virus interference in plants. Genome biology. 2019;20:1-6.
57. Youssef AM, El-Sayed HS, Islam EN, El-Sayed SM. Preparation and characterization of novel bionanocomposite based on garlic extract for preserving fresh Nile tilapia fish fillets. RSC advances. 2021;11(37):22571-84.
58. Hiragond CB, Han JW, Kim JY, Choi YJ. Nanotechnology-based interventions for the control of plant viruses. Plant Pathol. 2019;35(1):1-10.
59. Islam W, Ali T Khan, AR Khan, MA Khan. Nanovaccines for plant diseases: Challenges and future perspectives. Environmental Sci. and Poll. Res.2019;22: 22121-22130.
60. Wen AM, Shukla S, Saxena P, Aljabali AA, Yildiz I, Dey S, Mealy JE, Yang AC, Evans DJ, Lomonossoff GP, Steinmetz NF. Interior engineering of a viral nanoparticle and its tumor homing properties. Biomacromolecules. 2012;13(12):3990-4001.
61. Kar A and A Kar. Deep Learning, Predictive Modelling and Nano/Bio-Sensing Technologies for Mitigation of the COVID-19 Pandemic in Proceedings of International Conference on Computational Intelligence, Data Science and Cloud Computing. Singapore: Springer Singapore; 2021.
62. Brown TB, Mann B, Ryder N, Subbiah M, Kaplan J, Dhariwal P, Neelakantan A, Shyam P, Sastry G, Askell A, Language Models Are Few-Shot Learners. Adv Neural Inf Process Syst; 2020.
63. 63. LeCun Y, Bottou L, Bengio Y, Haffner P. Gradient-Based Learning Applied to Document Recognition. Proceedings of the IEEE.1998;86:2278-2323.
DOI: 10.1109/5.726791
64. Celeghin A, Borriero A, Orsenigo D, Diano M, Méndez Guerrero CA, Perotti A, Petri G, Tamietto M. Convolutional Neural Networks for Vision Neuroscience: Significance, Developments, and Outstanding Issues. Front Comput Neurosci 2023;17:1153572.
DOI: 10.3389/FNCOM.2023.1153572/BIBTEX
65. Hochreiter S, Schmidhuber J. Long Short-Term Memory. Neural Comput 1997;9:1735-1780.
DOI: 10.1162/NECO.1997.9.8.1735
66. Goodfellow IJ, Pouget-Abadie J, Mirza M, Xu B, Warde-Farley D, Ozair S, Courville A, Bengio Y. Generative Adversarial Nets. Adv Neural Inf Process Syst 2014; 27.
67. Cortes C, Vapnik V, Saitta L. Support-Vector Networks Editor. Machine Leaming 1995; 20:273–297.
68. Suzuki T, Hasebe T, Miyazaki T. Quantum support vector machines for classification and regression on a trapped-Ion Quantum Computer. arxiv.org 2023.
69. Daulay RSA, Efendi S. Suherman review of literature on improving the KNN Algorithm. Transactions on Engineering and Computing Sciences. 2023;11:63-72.
DOI: 10.14738/TECS.113.14768

70. Cover TM, Hart PE. Nearest Neighbor Pattern Classification. IEEE Trans Inf Theory 1967;13:21–27,
DOI: 10.1109/TIT.1967.1053964
71. Bengio Y, Courville A, Vincent P. Representation Learning: A Review and New Perspectives. IEEE Trans Pattern Anal Mach Intell. 2012;35:1798-1828.
DOI: 10.1109/TPAMI.2013.50
72. Liu F, Li J, Wang L. PI-LSTM: Physics-informed long short-term memory network for structural response modeling. Eng Struct. 2023;292:116500.
DOI:10.1016/J.ENGSTRUCT.2023.116500
73. Sutton RS, Barto AG. Reinforcement Learning: An Introduction. IEEE Trans Neural Netw 1998; 9:10541054.
DOI: 10.1109/TNN.1998.712192
74. Liu Z, Xu B. Researches Advanced in the Application of Reinforcement Learning. In Proceedings of the 2nd 928 International Conference on Artificial Intelligence, Automation, and High-Performance Computing (AIAHPC 2022); SPIE-Intl Soc Optical Eng. 2022:134.
75. Devlin J, Chang MW, Lee K, Google KT. Language, A.I. BERT: Pre-Training of Deep Bidirectional Transformers for Language Understanding. In Proceedings of the Proceedings of the 2019 Conference of the North; Association for Computational Linguistics: Stroudsburg, PA, USA. 2019:4171-4186.
76. Cao Y, Zhou H, Zhou X, Li F. Control of plant viruses by CRISPR/ Cas system-mediated adaptive immunity. Frontiers in Microbiology. 2020; 11:593700.

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/113987