PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 11(sp4): 01–10
https://doi.org/10.14719/pst.5947

HORIZON
e-Publishing Group
HePG

RESEARCH ARTICLE

Forecasting tomato's foe: Predicting groundnut bud necrosis disease using extended range weather dynamics

Senbagavalli G[1], Dheebakaran Ga[1]*, Sathyamoorthy NK[1], Renukadevi P[2], Kokilavani S[1], Balaji Kannan[3] & Ragunath KP[4]

[1]Agro Climate Research Centre, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[2]Department of Plant Pathology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[3]Department of Soil and Water Conservation Engineering, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[4]Centre for Water and Geospatial Studies, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Email: gadheebakaran@tnau.ac.in

OPEN ACCESS

ARTICLE HISTORY

Received: 18 October 2024
Accepted: 14 November 2024

Available online
Version 1.0 : 26 December 2024

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE

Senbagavalli G, Dheebakaran Ga, Sathyamoorthy N K, Renukadevi P, Kokilavani S, Kannan B, Ragunath K P. Forecasting tomato's foe: Predicting groundnut bud necrosis disease using extended range weather dynamics . Plant Science Today.2024;11(sp4):01-10. https://doi.org/10.14719/pst.5947

Abstract

Tomato (*Solanum lycopersicum* L.), a staple vegetable crop in the Solanaceae family, suffers significant yield losses due to the Groundnut Bud Necrosis Virus (GBNV). This thrips-transmitted virus can cause up to 100% yield reduction depending on the stage of infection. A study conducted in Coimbatore, Tamil Nadu, India during the summer of 2023 and 2024, investigated the epidemiology of GBNV. Using weather correlation analysis and Principal Component Analysis (PCA), key weather factors influencing the spread of thrips and GBNV were identified.

In 2023, the thrips population peaked in mid-April, followed by GBNV incidence in early May. In 2024, thrips peaked in early May, with GBNV incidence reaching its highest levels in the third week of May. This demonstrated a direct correlation between thrips population dynamics and GBNV progression, although variations in timing with observed between the two years. The analysis highlighted temperature and relative humidity as consistent, critical weather parameters influencing thrips populations and GBNV incidence, particularly with two-week time lags.

By correlating weather conditions with thrips and GBNV incidence across various time lags, this study contributes to the development of an extended-range weather forecast-based GBNV forewarning system. Such a system enhances preparedness and response strategies, mitigating the impact of GBNV on tomato crops and promoting food security. This multidisciplinary approach supports sustainable farming practices in the face of climate uncertainties while bolstering agricultural resilience.

Keywords

epidemiology; GBNV; PCA; thrips; tomato; weather

Introduction

Tomato (*Solanum lycopersicum* L.), a widely cultivated crop from the Solanaceae family, is renowned for its nutritional benefits and culinary versatility. With global production reaching around 180 million tons annually, tomato cultivation has witnessed a remarkable 165% increase over the past two decades (1). Rich in bioactive components, tomatoes are recognized as a "functional food," offering numerous health benefits and serving as a staple in daily nutrition (2). Ranking second to potatoes, tomatoes are among the most significant vegetable crops globally (3). This commercially important crop significantly contributes to global horticultural production (4), flourishing across tropical, temperate, and subtropical zones.

Worldwide, almost 4.76 million hectares are allocated for tomato cultivation, producing 182 million metric tons per year (5). China and India are the leading producers, contributing 31% and 13% of the global production, respectively (6). In India, tomato production is projected to reach 212.38 lakh tons in 2023-24, an increase from 204.25 lakh tons the previous year, reflecting a 3.98% growth (7). However, genetic vulnerabilities often challenge tomato cultivation in India (8) and frequent outbreaks of bacterial, viral, and fungal diseases (9). These issues can lead to yield losses exceeding 50% (10), posing significant challenges for the farming community (11).

Tomato plants are susceptible to several viral diseases, leading to symptoms like stunting, leaf curl, yellowing, mosaic, mottling, necrosis, and shoe-string effects on all plants, leaves, or fruits. Among these, GBNV, an Orthotospovirus, poses a significant threat to tomato cultivation, particularly for resource-poor farmers (12). Six of the eleven known tospovirus species worldwide have been identified in India (13). Groundnut Bud Necrosis Virus, prevalent in the country, can cause severe yield losses in tomato crops, sometimes reaching up to 100% (14).

The initial symptoms of GBNV infection include mild chlorotic patches on juvenile leaves, which subsequently advance to chlorotic rings and necrotic areas. The distinctive features of GBNV infection are terminal bud necrosis under field conditions, stunting, and leaf malformations. Plants infected at an early stage exhibit a bushy, stunted appearance and often succumb prematurely.

Thrips (Thysanoptera) are major pests impacting various food, feed, and fiber crops worldwide and serve as circulative and propagative vectors for tospoviruses (15, 16). Uniquely, only thrips that acquire the virus during their larval stage can transmit it as adults. For, successful transmission, thrips must acquire the virus, internalize it, and inoculate a susceptible host. Tospoviruses replicate in the salivary glands, midgut epithelial cells, and surrounding muscle tissues within the thrips (17).

Weather conditions play a pivotal role in influencing the incidence and severity of GBNV outbreaks by affecting the susceptibility of host plants and the activity of thrips vectors (18). Key factors, such as temperature, relative humidity, and rainfall patterns, are crucial in determining the life cycle of thrips and the dynamics of virus transmission. Research has shown that the spread and intensity of GBNV symptoms in cowpea plants are significantly higher at temperatures between 25-30°C compared to 15-20°C, indicating that warmer conditions enhance both virus transmission and symptom expression (19). Additionally, higher temperatures notably reduced the development time of *Thrips palmi,* with the egg-to-adult period decreasing from 35.7 days at 16°C to 9.6 days at 31°C (20).

Rainfall has a negative influence over thrips in groundnut crops (21). Correlation studies revealed a significant negative correlation between thrips population and factors such as minimum temperature, rainfall, rainy days, and evening relative humidity. Conversely, sunshine hours and morning relative humidity exhibit a significant positive correlation with thrips populations in tomato crops (22). Additionally, temperature positively correlates with the thrips population and GBNV incidence in tomatoes during the summer (16). Therefore, assessing the relative importance of these weather variables is essential for predicting GBNV outbreaks. Extended Range Weather Forecasts (ERWF) offer valuable insights into prevailing conditions two to three weeks in advance, and they can be used for better pest and disease management (23).

Principal Component Analysis (PCA), by reducing data dimensionality (24), efficiently analyzes and interprets key weather variables influencing the incidence of GBNV, providing insights into the interplay of meteorological factors. A multidisciplinary approach that integrates meteorological data, plant disease modeling, and agricultural management is essential for effective disease management. Integrating PCA findings into ERWF enhances disease prediction, enabling farmers to anticipate GBNV outbreaks, strengthen crop resilience, and promote sustainable agricultural practices.

This study aims to decipher the relationship between weather parameters and GBNV incidence in tomato crops through PCA and correlation analysis. Employing this approach to develop an ERWF framework will significantly aid in preventing future GBNV disease outbreaks, marking an important outcome of the present study.

Materials and Methods

Study area and period

A field survey was conducted during the summer months (January to May) of 2023 and 2024 to assess the incidence of GBNV and thrips. The study was focused on four fields in the Thondamuthur block of Coimbatore district, Tamil Nadu, India (11.0168° N, 76.9558° E) (Fig. 1.). This region, part of Tamil Nadu Western Agro Climatic Zone, is a key vegetable-growing area, with tomatoes constituting a substantial portion due to the favorable climate for their growth. As a representative region for tomato farming, Thondamuthur was selected to investigate recent GBNV outbreaks, which have caused substantial yield losses in tomato crops across Coimbatore and other Western Ghat districts.

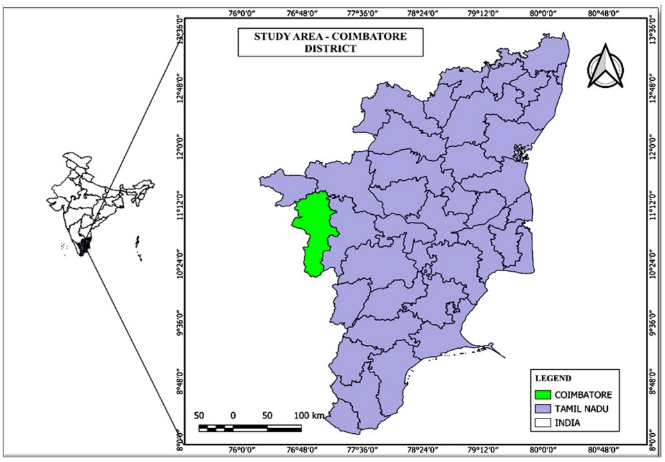

Fig. 1. Study area, Coimbatore, Tamil Nadu, India.

Understanding the weather dynamics influencing GBNV is essential for developing effective pest management strategies. Coimbatore experiences an annual average of 47 wet days, receiving 728 mm of rainfall, primarily during the northeast monsoon (358 mm). Being in a rain shadow region for the southwest monsoon, it records 198 mm of rainfall, with summer and winter contributing 152 mm and 20 mm, respectively. Situated at an elevation of 427 meters above sea level, the area has an average monthly maximum temperature (Tmax) of 31.9°C, a minimum temperature (Tmin) of 21.9°C, morning and evening relative humidity levels of 85% and 50%, respectively and an average wind speed of 7.7 km/h (TNAU Observatory, Coimbatore, 2024).

Epidemiology

The epidemiology of thrips population dynamics and GBNV disease incidence was studied in four selected farmer's fields within the study area. The same fields were used for observations in both years. Weekly data were collected using the roving survey method, starting from the vegetative stage and continuing until the late cropping stage. Thrips populations were assessed by tapping plant parts five times onto a cloth, with twenty plants per field randomly selected for observation.

The percentage of disease incidence (PDI) was calculated using Eqn. 1, which involved recording the number of plants exhibiting GBNV symptoms- such as chlorotic and necrotic spots, chlorotic and necrotic ring spots on leaves, plant chlorosis, flower bud malformation, leaf drooping, bud chlorosis, terminal bud necrosis, and stunted plant growth, in relation to the total number of plants examined, as per the following formula :

$$\text{Per cent GBNV incidence} = \frac{\text{Number of diseased plants}}{\text{Total number of plants observed}} * 100$$

....Eqn (1)

Data for mean thrips population (in numbers) and GBNV incidence (in percentage) were computed based on the Standard Meteorological Week (SMW) and used for further analysis.

Datasets used and analysis

Data on weather parameters, including morning and evening relative humidity (RHm, RHe), wind speed (WS), rainfall (RF), minimum and maximum temperature (Tmin, Tmax), solar radiation (SRn), sunshine hours (SSH), evaporation (EVP), and rainy days (RD), were collected daily and converted to SMW values. To assess the weather's impact on thrips and GBNV incidence, SMW-based datasets were utilized. Correlations between weather parameters, thrips population, and GBNV were analyzed using RStudio Version 2024.04.2 (Build 764) for three conditions: the corresponding week, one-week lag, and two-week lag. Fig. 2 and Fig. 3 describe the disease epidemiology and study flow, respectively.

Principal component analysis

Principal Component Analysis (PCA) is a versatile statistical technique that reduces data to its principal or essential components. This method explains most variance in all variables through a few principal components (PC1 (Eqn. 2), PC2 (Eqn. 3) which are linear combinations of the original variables. Using these essential components, PCA approximates the original data table efficiently (26).

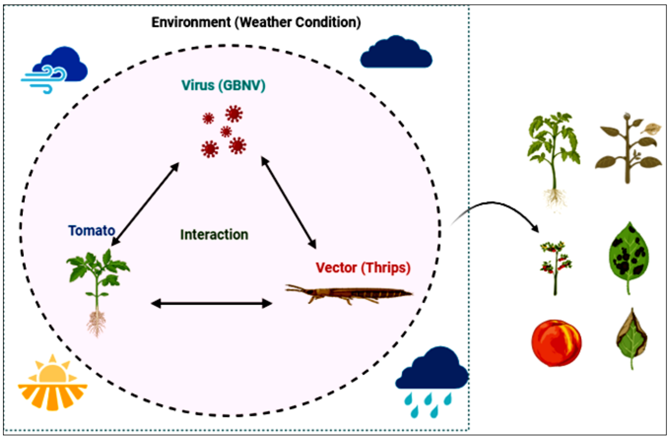

Fig. 2. Plant disease interaction with Weather conditions (Created in BioRender.com).

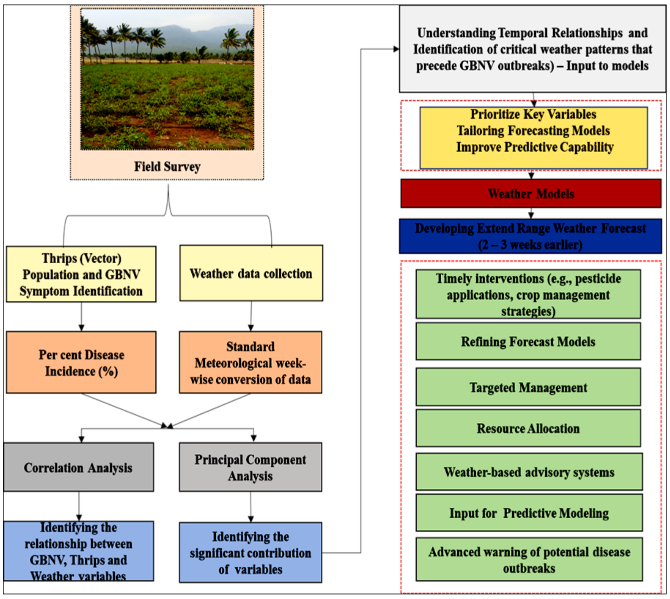

Fig. 3. Study Flow.

$$PC1 = \sum_{j=1}^{k} x_{1j}A_{1j} = x_{11}A_1 + x_{12}A_2 + \cdots + x_{1K}A_K$$

....Eqn (2)

$$PC2 = \sum_{j=1}^{k} x_{2j}A_j = x_{21}A_1 + x_{22}A_2 + \cdots + x_{2K}A_K$$

....Eqn (3)

Where, Eigen vectors - x_{ij} and $A_1, A_2 \ldots A_k$ - Original variables in data matrix

Results and Discussion

Population dynamics of thrips and GBNV incidence (%)

During the 2023 study period, thrips incidence began to appear in the fourth week of March (13th SMW). It peaked in the third week of April (16^{th} SMW), with a range of approximately 0 to 9 thrips per five tapings throughout the tomato cropping period. In 2024, thrips first appeared in the third week of March (12th SMW) and peaked in the first week of May (18th SMW), with a range of ~0 to ~10 thrips per five tapings. A study revealed thrips populations between 0.35 and 1.39 per shoot, with GBNV incidence varying from 20% to 48% across different areas (18). It was further observed that the thrips population increased from transplanting to the flowering and fruit development stages, then decreased as the crop matured, with rainfall contributing to the decline. The study's outcome indicated 8.4 and 10.3 thrips per three leaves, with PDI values of 42.5% and 45.1% in 2016 and 2017, respectively (14).

In 2023, GBNV symptoms first appeared in the fourth week of March (13th SMW) and peaked in the first week of May (18th SMW), with a range of 0% to 60%. In 2024, symptoms also began in the fourth week of March (13th SMW) but peaked later, in the third week of May (21st SMW), with a range of 0% to 70% (Fig. 4).

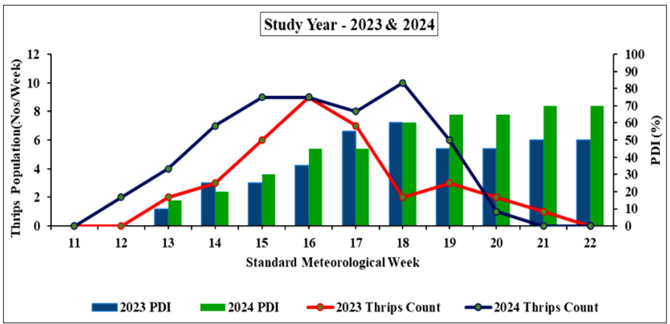

Fig. 4. Observed Thrips Population and GBNV incidence on Standard Meteorological Week (SMV).

The differences observed compared to a previous study, which reported a disease incidence of 35.3% in the same area, may be attributed to varying environmental conditions, weather variability, or changes in thrips population dynamics during the study period (25). Additionally, disease management practices or crop susceptibility variations could explain the increased incidence. Another study reported disease incidence ranging from 12.5% in Guledkoppa, Dharwad taluk, to a maximum of 94.4% in Kyalanur, Kolar district, during the summer season (27).

In 2023, thrips emerged earlier, peaking in mid-April, and GBNV symptoms peaked by early May. In 2024, thrips appeared slightly earlier again, peaking in early May, while GBNV symptoms peaked in the third week of May. This suggests that the buildup of thrips populations plays a significant role in the onset and progression of GBNV symptoms, with a slight timing shift between the two years.

Correlation between weather variables, GBNV and thrips

Weather variables were analyzed for correlations with parameters from the corresponding week, one-week lag, and two-week lag in both 2023 and 2024 (Fig. 5 - 10). In 2023, the thrips population showed the highest correlation with Tmax (0.55, non-significant), Tmax (0.60, significant at 10%) and Tmax (0.45, non-significant) for the same week, one-week lag and two-week lag, respectively. For GBNV incidence, the highest correlations were with Tmin (0.78, significant at 5%), Tmin (0.83, significant at 1%), and WS (-0.83, significant at 1%) for the same week, one-week lag and two-week lag, respectively. In 2024, the thrips population showed the highest correlation with Tmax (0.90, significant at 1%), Tmin (0.69, significant at 5%), and RHe (-0.66, significant at 10%) for the same week, one-week lag, and two-week lag, respectively. For GBNV incidence, the highest correlations were with RHe (0.74, significant at 5%), RHe (0.62, significant at 10%), and Tmin (0.74,

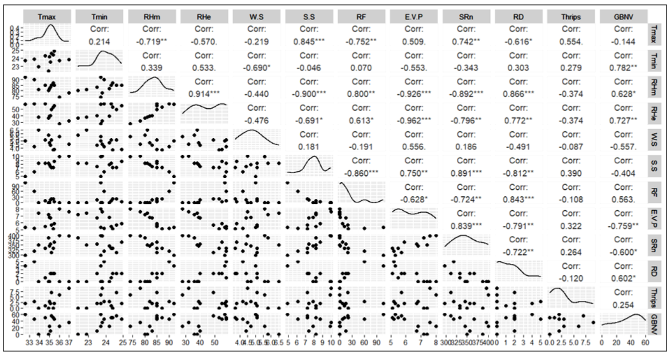

Fig. 5. Correlation among Thrips, GBNV, and Weather variables (2023 - Same week).

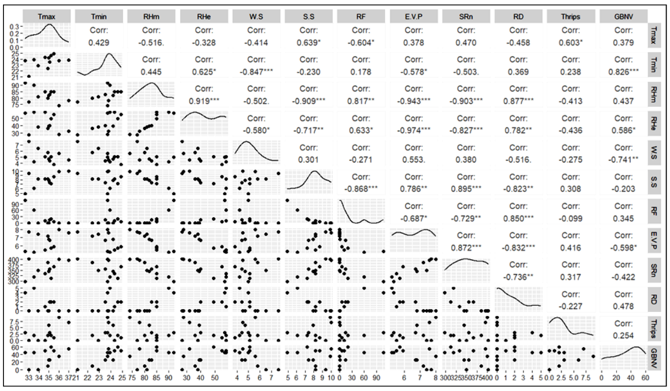

Fig. 6. Correlation among Thrips, GBNV, and Weather variables (2023 - Lag week 1).

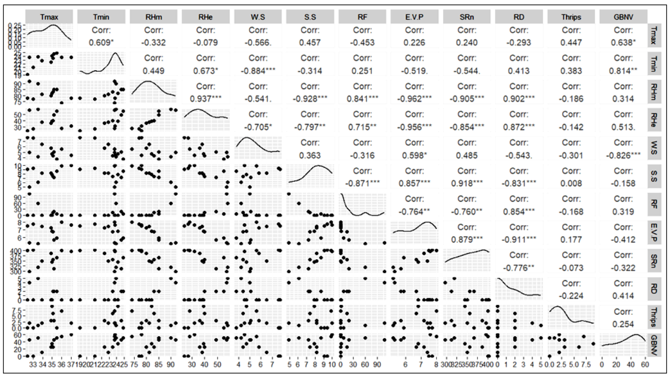

Fig. 7. Correlation among Thrips, GBNV, and Weather variables (2023 - Lag week 2).

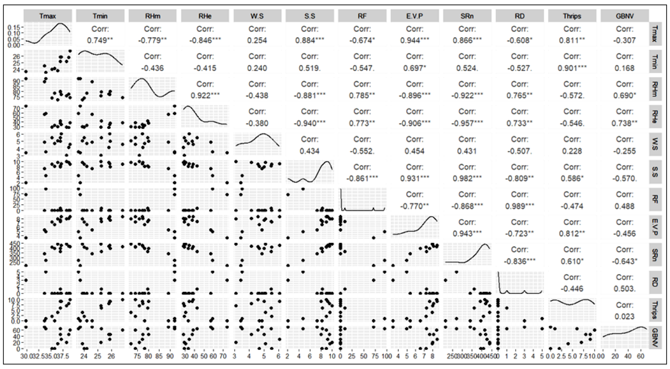

Fig. 8. Correlation among Thrips, GBNV, and Weather variables (2024 - Same week).

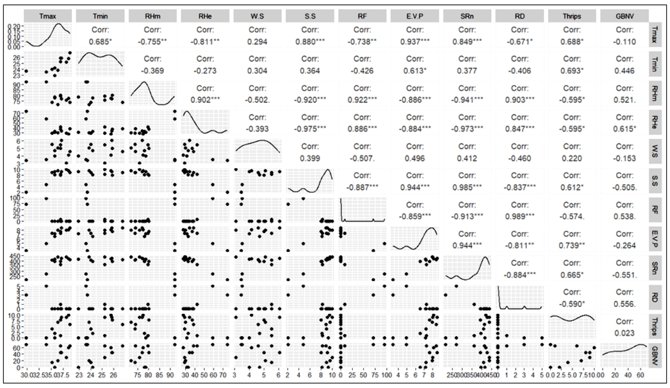

Fig. 9. Correlation among Thrips, GBNV, and Weather variables (2024 - Lag week 1).

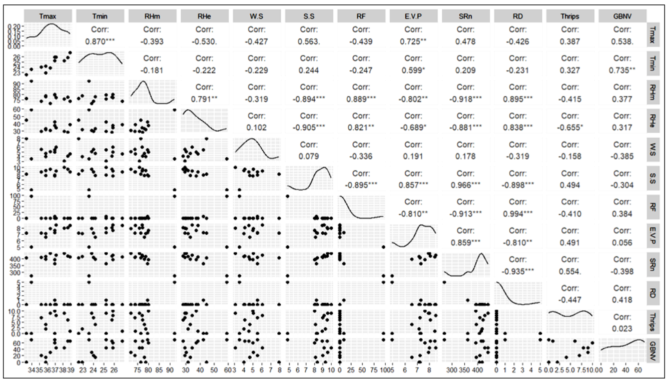

Fig. 10. Correlation among Thrips, GBNV, and Weather variables (2024 - Lag week 2).

significant at 5%) for the same week, one-week lag, and two-week lag, respectively.

Daytime temperature (Tmax) considerably influences the thrips' life cycle, where reproductive rates increase within ideal temperature ranges. A study observed that excessively high Tmax could stress host plants and raise the thrip death rates. Pests and crops might suffer when temperatures rise above certain thresholds (28). Extended periods of low temperatures can cause plant stress, making them more vulnerable to virus infections and insect attacks. For instance, when temperatures drop below specific thresholds, plants may exhibit reduced resistance to thrips and GBNV. Tmin affects thrips' survival and activity, as lower Tmin values can slow their development and reduce reproduction rates. It was also observed in a study that variables such as Tmin, RF, RD, and RHe had a significant negative correlation with the thrips population, while SSH and RHm showed a significant positive correlation (14). Another investigation revealed a weak correlation between weather parameters and GBNV, while a strong correlation between thrips populations and GBNV incidence in Raichur, Karnataka. In contrast, this study in Coimbatore demonstrated a stronger influence of weather on both thrips' populations and GBNV incidence (29). These variations are likely due to regional climate differences and local conditions.

The correlation between GBNV incidence and the thrips population was 0.25 in 2023 and 0.02 in 2024, indicating a weak, non-significant positive relationship. This suggests that while the thrips population may influence GBNV outbreaks, weather parameters likely play a more significant role in disease incidence. High temperatures accelerate the life cycle of thrips, increasing their population density, especially in arid environments with low humidity (30). Conversely, low temperatures and high humidity can reduce thrips activity and reproduction (31). Relative humidity is crucial for thrips survival. Lower night time RH increases mortality risk, while ideal morning RH improves feeding and reproductive behaviors (32). Additionally, high solar radiation and sunshine hours increase plant stress, making them more susceptible to thrips and GBNV spread. Rainy days disrupt thrips activity and reduce their populations due to excessive moisture, whereas high evaporation rates decrease soil moisture, increasing plant sensitivity (33- 36).

The findings indicate that Tmax, Tmin, RHm, and RHe were the most consistent weather parameters affecting both thrips populations and GBNV incidence across different time lags. Furthermore, wind speed significantly influenced GBNV incidence after a two-week lag in 2023. Understanding the correlation of weather variables with lag periods helps identify delayed effects on pest and disease dynamics, enhancing early detection and forecasting. This approach allows for targeted pest and disease management by addressing short- and long-term impacts, improving forecasting models, and facilitating timely, informed agricultural decisions.

Principal component analysis

The PCA approach was utilized to identify significant weather variables affecting GBNV incidences. The scree plot analysis, which presents the eigenvalues of the correlation matrix in descending order, indicated that the first two principal components (PC1 and PC2) accounted for approximately 80% to 90% of the variance. The scree plots for the 2023 corresponding week, one-week lag, and two-week lag, along with those for the 2024 corresponding week, one-week lag, and two-week lag, are depicted in Fig. 11 (a -f). PCA highlighted the most influential variables in the dataset, with PC1 explaining the maximum variance, followed by PC2 and subsequent components. The percentage of variance explained indicates how much information from the original data is retained by each component.

Table 1 indicates that PC1 and PC2 captured most of the dataset's variance. In 2023, the cumulative variance explained by the first two components ranged from 82% to 89%. In contrast, in 2024, it ranged from 85% to 86%, showing that the first two components effectively summarize much of the variability for both years. The percentage of cumulative variance varied across time lags. In 2024, PC1 explained a higher variance for the same week and one-week lag compared to 2023, indicating a stronger immediate influence of weather variables. However, at the two-week lag, PC2 contribution increased, suggesting a more distributed effect of weather variables on GBNV incidence (Table 1). Notably, the two-week lag influence was consistent between years, suggesting a stable relationship between weather and GBNV incidence over this period despite variations in other time frames. PCA graphs for the 2023- and 2024-time lags are depicted in Fig. 12(a - f).

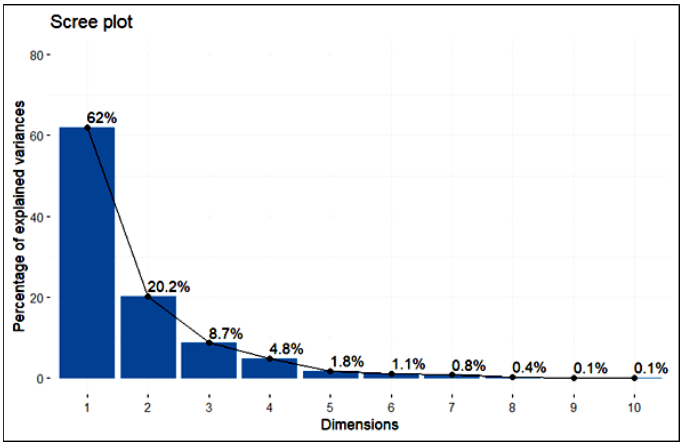

Fig. 11a. 2023 - Corresponding week.

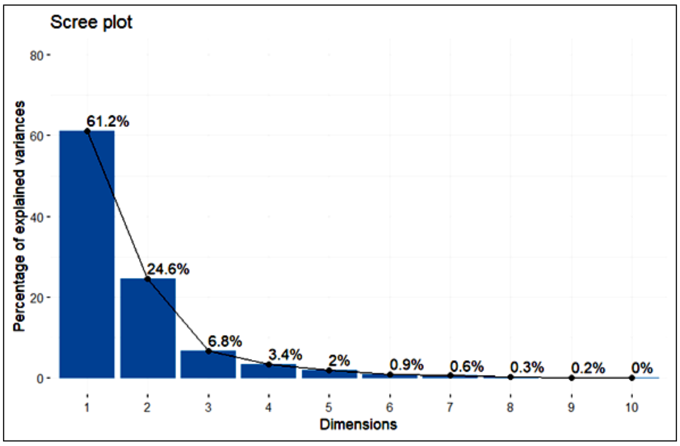

Fig. 11b. 2023 - Lag week 1.

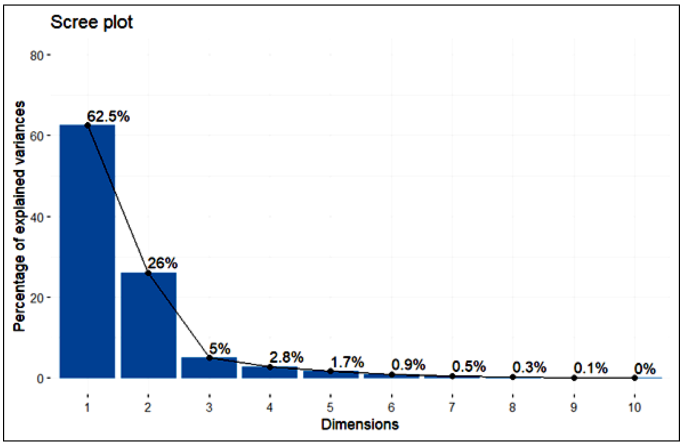

Fig. 11c. 2023 - Lag week 2.

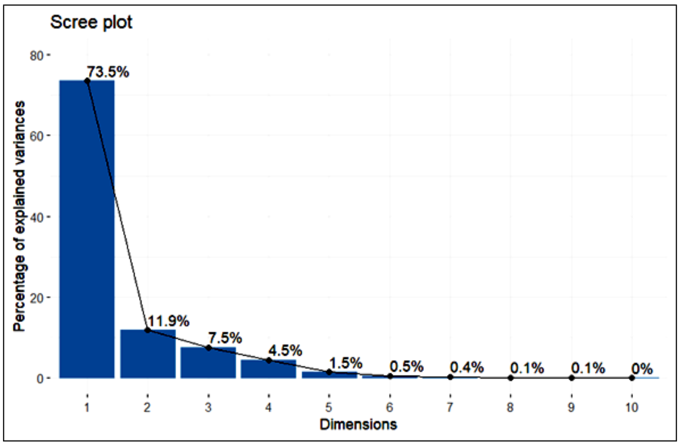

Fig. 11d. 2024 - Corresponding week.

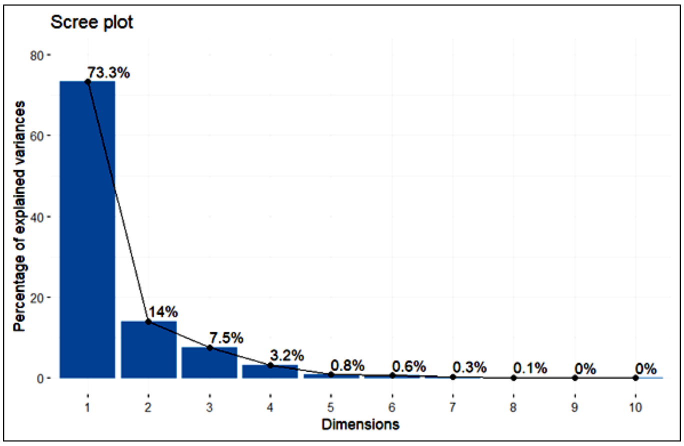

Fig. 11e. 2024 - Lag week 1.

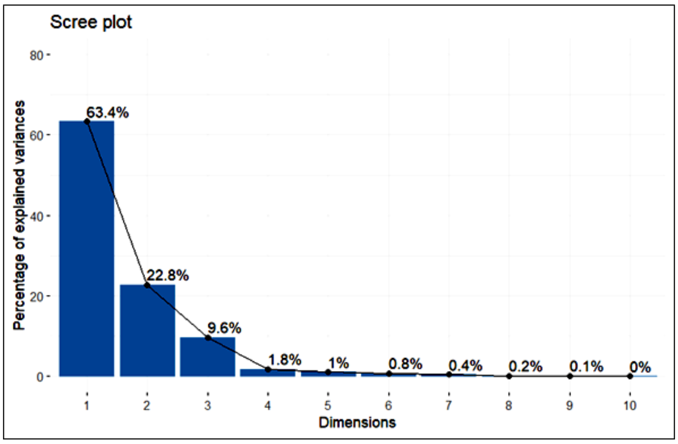

Fig. 11f. 2024 - Lag week 2.

Fig. 11a - 11f: Scree plot for 2023 corresponding week, 2023 lag week 1, 2023 lag week 2, 2024 corresponding week, 2024 lag week 1, 2024 lag week 2 (11a -11f respectively).

Table 1. Percentage of Variance Explained by Major Principal Components (PC).

Percentage of Variance Explained (%)				
Study Year	**Time lag (Week)**	**PC 1 (%)**	**PC 2 (%)**	**Cumulative Percentage (%)**
2023	0	62	20	82
	1	61	25	86
	2	63	26	89
2024	0	74	12	86
	1	73	12	85
	2	63	23	86

Variables with high positive loadings in PC1 positively impacted the components, suggesting that higher values of these variables were linked to higher component scores, potentially favoring GBNV incidence. Conversely, high negative loadings indicated that variables, such as higher relative humidity, contributed negatively, possibly correlating with reduced disease incidence. Tables 2 and 3 highlight the top two variables with the highest positive and negative loadings for each PC in 2023 and 2024. In 2023, variables such as Tmax, Tmin, RHm, and RHe were the most influential, with Tmax and Tmin being particularly significant in PC2 across all-time lags. Wind speed, RH, and rainfall also consistently influenced variability across lags. In 2024, nearly all-weather variables were significant contributors to GBNV development.

Groundnut Bud Necrosis Virus is among the most

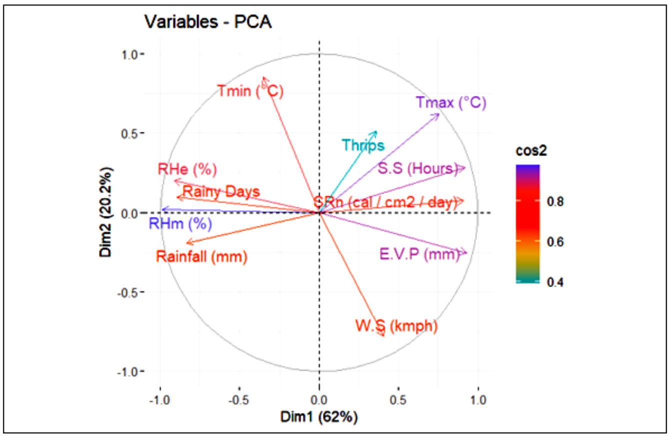

Fig. 12a. 2023 - Corresponding week.

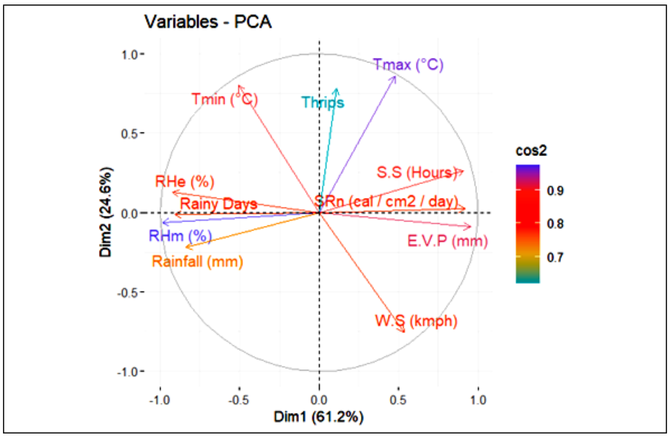

Fig. 12b. 2023 - Lag week 1.

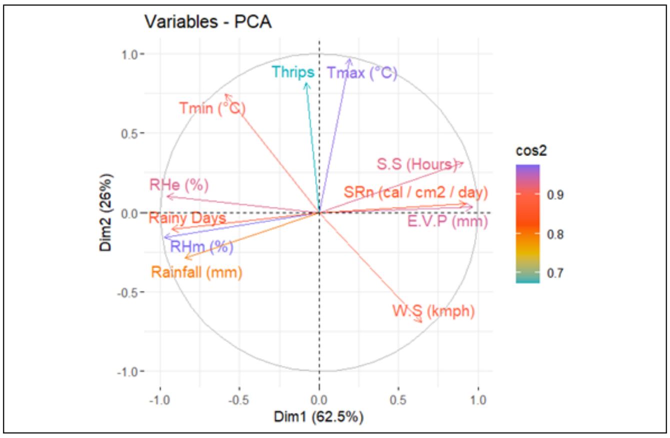

Fig. 12c. 2023 - Lag week 2.

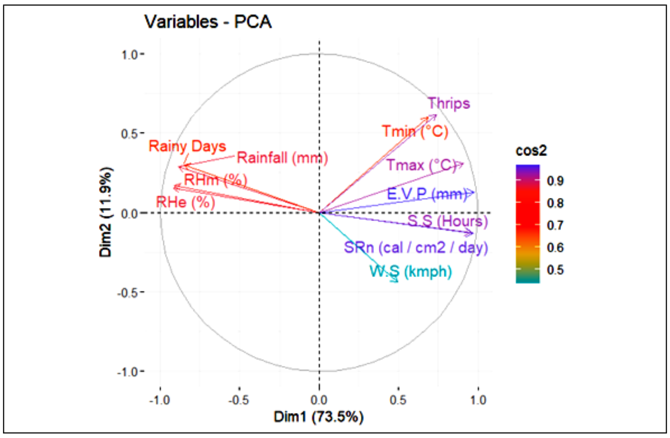

Fig. 12d. 2024 - Corresponding week.

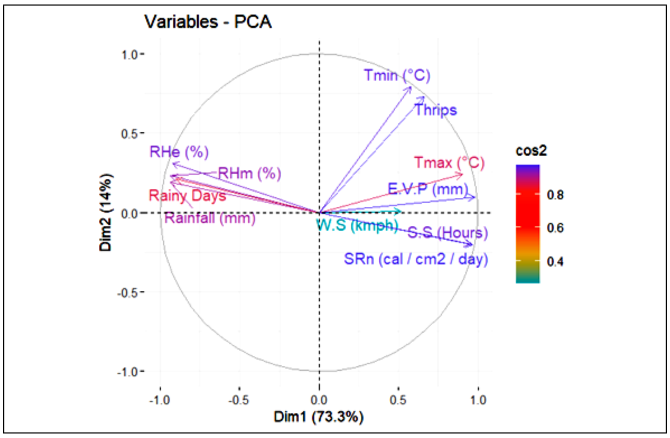

Fig. 12e. 2024 - Lag week 1.

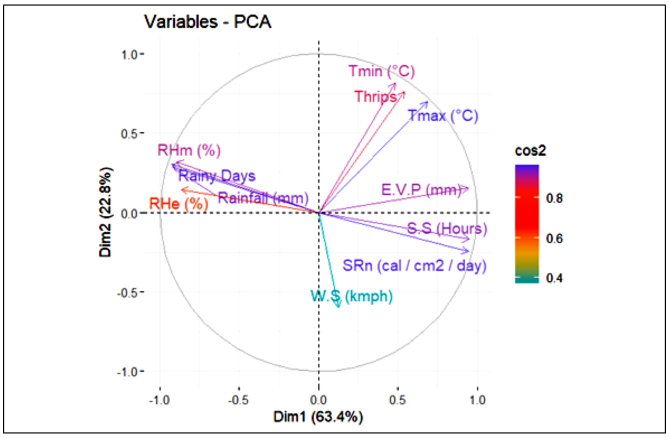

Fig. 12f. 2024 - Lag week 2.

Fig. 12. PCA graph for 2023 corresponding week, 2023 lag week 1, 2023 lag week 2, 2024 corresponding week, 2024 lag week 1, 2024 lag week 2 (12a - 12f respectively).

severe viral infections affecting tomatoes (37). In several states, including Tamil Nadu, GBNV has become endemic, with tomatoes accounting for 40% despite the broader host range of GBNV (13). Among the numerous hosts, tomatoes experience the most significant losses due to bud necrosis disease (BND) (38). A study found that BND on tomatoes results in yield losses of 30% to 100%, depending on the crop stage and season (39). Similarly, it was observed that weather conditions, such as prolonged dry spells, increased viral disease incidence, while rainy periods reduced it due to lower vector populations (12). Factors like temperature, RH, and prolonged sunshine hours favor thrips activity, multiplication, and population buildup (14). It was also noted that high temperatures and dry weather during summer facilitated thrips proliferation and increased GBNV incidence in tomato fields. At the same time, rainfall during the Kharif and Rabi seasons reduced thrips populations and disease incidence (40).

Integrating weather forecasts with epidemiological studies allows farmers to effectively anticipate and mitigate the impacts of tomato diseases. In India, GBNV is a significant *Orthotospovirus* affecting crops in the Leguminosae and Solanaceae families, such as groundnut, tomato, potato, mung bean, cowpea, and soybean. The findings of this study can be scaled up for verification in other agro-climatic regions and to develop a forewarning system that promotes wider adoption. This would help mitigate the risks of thrips-transmitted GBNV across multiple crops and regions. Such a collaborative approach supports sustainable

Table 2. Factor loading value of PC of corresponding weather values for the study year 2023.

Year	2023					
Time Lag	Time lag 0 (Week)		Time lag 1 (Week)		Time lag 2 (Week)	
Variable	PC1_Loadings	PC2_Loadings	PC1_Loadings	PC2_Loadings	PC1_Loadings	PC2_Loadings
Tmax (°C)	0.29	0.42	0.18	0.52	0.07	0.57
Tmin (°C)	-0.13	0.57	-0.20	0.49	-0.23	0.44
RHm (%)	-0.38	0.01	-0.38	-0.04	-0.37	-0.09
RHe (%)	-0.35	0.13	-0.36	0.08	-0.37	0.06
W.S (kmph)	0.16	-0.52	0.21	-0.46	0.25	-0.41
S.S (Hours)	0.35	0.19	0.35	0.16	0.35	0.18
Rainfall (mm)	-0.32	-0.13	-0.32	-0.13	-0.32	-0.17
E.V.P (mm)	0.36	-0.17	0.37	-0.05	0.37	0.02
SRn (cal / cm2 / day)	0.35	0.05	0.35	0.02	0.35	0.03
Rainy Days	-0.34	0.07	-0.35	-0.01	-0.35	-0.06
Thrips	0.14	0.34	0.04	0.47	-0.03	0.48

Table 3. Factor loading value of PC of corresponding weather values for the study year 2024.

Year	2024					
Time Lag	Time lag 0 (Week)		Time lag 1 (Week)		Time lag 2 (Week)	
Variable	PC1_Loadings	PC2_Loadings	PC1_Loadings	PC2_Loadings	PC1_Loadings	PC2_Loadings
Tmax (°C)	0.32	0.27	0.32	0.19	0.26	0.44
Tmin (°C)	0.24	0.53	0.20	0.64	0.18	0.52
RHm (%)	-0.32	0.15	-0.33	0.19	-0.34	0.20
RHe (%)	-0.32	0.14	-0.32	0.25	-0.33	0.09
W.S (kmph)	0.17	-0.38	0.18	0.01	0.05	-0.38
S.S (Hours)	0.34	-0.11	0.34	-0.16	0.36	-0.11
Rainfall (mm)	-0.31	0.25	-0.33	0.15	-0.35	0.18
E.V.P (mm)	0.34	0.11	0.35	0.08	0.36	0.10
SRn (cal / cm2 / day)	0.34	-0.12	0.34	-0.17	0.36	-0.16
Rainy Days	-0.30	0.26	-0.32	0.17	-0.35	0.19
Thrips	0.26	0.54	0.23	0.59	0.21	0.48

farming practices and enhances agricultural resilience amid climatic uncertainties. The study enables the development of predictive models to forecast GBNV outbreaks based on critical weather variables, such as temperature and humidity, two weeks in advance. This facilitates timely interventions and efficient resource allocation to effectively manage pest populations and disease incidence.

Conclusion

Principal Component Analysis (PCA) and time-lagged correlation techniques were utilized to optimize ERWF to effectively manage GBNV in tomato crops. These multidisciplinary methods empower farmers to implement targeted measures to control GBNV, thereby enhancing tomato production. The study revealed that weather parameters significantly influenced disease incidence and thrips populations in the Thondamuthur block of Coimbatore district, Tamil Nadu. Time-lag analysis conducted up to two weeks prior, demonstrated a strong correlation with meteorological factors, underscoring the pivotal role of weather in developing thrips and GBNV. These findings highlight the importance of accurate, two-week advanced weather forecasts for effective disease management.

Furthermore, the study emphasized that evaluating the relationship between weather parameters and disease incidence is crucial for improving model performance and ensuring reliable ERWF results. By leveraging these insights, farmers can anticipate and mitigate the impacts of GBNV more effectively, promoting sustainable and resilient agricultural practices. Future research may focus on developing predictive models and integrating forewarning tools for GBNV and thrips dynamics across diverse agro-climatic zones.

Acknowledgements

The authors thank the Centre for Water and Geospatial Studies and the Agro Climate Research Center for funding this research. Special thanks are extended to the Chairman and other staff members for their valuable feedback and constructive suggestions on the manuscript.

Authors' contributions

SG took observations, conducted the experiment, analyzed the data and wrote a manuscript. DGa guided the research by formulating the research concept and approving the final manuscript. SNK helped in summarizing and revising the manuscript. RP helped in collecting field survey data and summarizing and revising the manuscript. KS helped in editing, summarizing and revising the manuscript. BK helped in summarizing and revising the manuscript. RKP helped in editing, summarizing and revising the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None.

Declaration of generative AI and AI-assisted technologies in the writing process

None.

References

1. FAOSTAT. Crops Production Quantity [Internet]. Food and Agricultural Organization of the United Nations; 2022. Available from: http://www.fao.org/faostat/en/#data/QC
2. Martí R, Leiva-Brondo M, Lahoz I, Campillo C, Cebolla-Cornejo J, Roselló S. Polyphenol and L-ascorbic acid content in tomato as influenced by high lycopene genotypes and organic farming at different environments. Food Chem. 2018;239:148-56. https://doi.org/10.1016/j.foodchem.2017.06.102
3. Quinet M, Angosto T, Yuste-Lisbona FJ, Blanchard-Gros R, Bigot S, Martinez JP, et al. Tomato fruit development and metabolism. Front Plant Sci. 2019;10:1554. https://doi.org/10.3389/fpls.2019.01554
4. Anamika, Ghalawat S, Goyal M, Mehla S, Malik JS, Yadav E. Growth Trend in Area, Production and Productivity of Tomato in India and Haryana. Indian J Ext Educ. 2024;60(3):72-6. https://doi.org/10.48165/IJEE.2024.60314
5. FAO. World food and agriculture statistical yearbook [Internet]. Rome: Food and Agricultural Organization of the United Nations; 2022 [cited 2024 Oct 10]. Available from: https://doi.org/10.4060/cc2211en
6. Añibarro-Ortega M, Pinela J, Ćirić A, Martins V, Rocha F, Soković MD, et al. Valorisation of table tomato crop by-products: Phenolic profiles and *in vitro* antioxidant and antimicrobial activities. Food Bioprod Process. 2020;124:307-19. https://doi.org/10.1016/j.fbp.2020.09.006
7. Press Information Bureau [Internet]. Government of India. Delhi: Government of India; 2024. Available from: https://pib.gov.in/indexd.aspx?reg=3&lang=1
8. Panno S, Davino S, Caruso AG, Bertacca S, Crnogorac A, Mandić A, et al. A review of the most common and economically important diseases that undermine the cultivation of tomato crop in the mediterranean basin. Agronomy. 2021;11(11):2188. https://doi.org/10.3390/agronomy11112188
9. Aravintharaj R, Asokan R. Thrips vectors of tospoviruses on tomato in South India. Indian J Entomol. 2023;85(2):430-4. https://doi.org/10.55446/IJE.2021.366
10. Gupta SK, Sharma M, Mukherjee S. Buckeye rot of tomato in India: Present status, challenges and future research perspectives. Plant Dis. 2022;106(4):1085-95. https://doi.org/10.1094/PDIS-04-21-0861-FE
11. Kishorkumar C, Harish S, Karthikeyan G, Sharmila J, Varanavasiappan S, Nivedha M. Antiviral Efficacy of Bacillus sp. against groundnut bud necrosis orthotospovirus in Cowpea. Int J Plant Soil Sci. 2023;35(18):790-800. https://doi.org/10.9734/ijpss/2023/v35i183345
12. Nagendran K, Venkataravanappa V, Chauhan NS, Kodandaram MH, Rai AB, Singh B, et al. Viral diseases: A threat for tomato cultivation in Indo-Gangetic eastern plains of India. J Plant Pathol. 2019;101:15-22. https://doi.org/10.1007/s42161-018-0124-9
13. Basavaraj, Mandal B, Gawande SJ, Renukadevi P, Holkar SK, Krishnareddy M, et al. The occurrence, biology, serology and molecular biology of tospoviruses in Indian agriculture.In: Mandal B, Rao G, Baranwal V, Jain R, editors. A century of plant virology in India. Springer, Singapore. 2017.p.445-74. https://doi.org/10.1007/978-981-10-5672-7_20
14. Jamuna B, Bheemanna M, Hosamani AC, Ghante VN, Govindappa MR, Kavita K, et al. Population dynamics of thrips and bud necrosis virus disease on tomato. Int J Curr Microbiol Appl Sci. 2019;8(5):24-34. https://doi.org/10.20546/ijcmas.2019.805.004
15. Mandal B, Jain RK, Krishnareddy M, Krishna Kumar NK, Ravi KS, Pappu HR. Emerging problems of tospoviruses (Bunyaviridae) and their management in the Indian subcontinent. Plant Dis. 2012;96(4):468-79. https://doi.org/10.1094/PDIS-06-11-0520
16. Sharma MK. Molecular characterization, phylogenetic analysis and identification of thrips species occurring on vegetable crops in Chhattisgarh and Madhya Pradesh. Agriculture (Entomology). Masters [Thesis]. Department of Entomology; College of Agriculture, Jabalpur 482004; Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur, M.P 2021. https://krishikosh.egranth.ac.in/server/api/core/bitstreams/15b87fd8-d965-4d2c-bf16-31620480bedd/content
17. Ghosh A, Dey D, Timmanna, Basavaraj, Mandal B, Jain RK. Thrips as the vectors of tospoviruses in Indian agriculture. In: Mandal B, Rao G, Baranwal V, Jain R, editors. A century of plant virology in India. Springer, Singapore. 2017.p.537-61. https://doi.org/10.1007/978-981-10-5672-7_24
18. Rabeena I, Karthikeyan G, Usharani TR, Kennedy JS, Rajabaskar D. Temperature and rainfall influence the seasonal dynamics of thrips, *Frankliniella schultzei* and Groundnut bud necrosis virus incidences in tomato field. Pest Management in Horticultural Ecosystems. 2020;26(1):41-7. https://doi.org/10.5958/0974-4541.2020.00007.7
19. 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):227-34. https://doi.org/10.21859/ijb.1846
20. Yadav R, Chang NT. Effects of temperature on the development and population growth of the melon thrips, *Thrips palmi,* on eggplant, *Solanum melongena*. J Insect Sci. 2014;14(1):78. https://doi.org/10.1093/jis/14.1.78
21. Vennila S, Bhat M, Yadav SK, Nisar S, Kumar M, Tomar A, et al. Abundance, infestation and disease transmission by thrips on groundnut as influenced by climatic variability at Kadiri, Andhra Pradesh. J Agrometeorol. 2018;20(3):227-33. https://doi.org/10.54386/jam.v20i3.550

22. Jamuna B, Timmanna, Basavaraj YB, Baradevanal G, Bheemanna M, Srinivas AG. Influence of weather on thrips population and tospovirus disease incidence in tomato crop. AMA, Agricultural Mechanization in Asia, Africa and Latin America. 2023;54(10):15851-15862.

23. Chattopadhyay N, Rao KV, Sahai AK, Balasubramanian R, Pai DS, Pattanaik DR, et al. Usability of extended range and seasonal weather forecast in Indian agriculture. Mausam. 2018;69(1):29-44. https://doi.org/10.54302/mausam.v69i1.218

24. Hasan BM, Abdulazeez AM. A review of principal component analysis algorithm for dimensionality reduction. J Soft Comput Data Min. 2021;2(1):20-30. https://doi.org/10.30880/jscdm.2021.02.01.003

25. Suganyadevi M, Manoranjitham SK, Senthil N, Raveendran M, Karthikeyan G. Prevalence of Bud Blight of Tomato Caused by Groundnut bud necrosis virus in Tamil Nadu, India. Int J Curr Microbiol App Sci. 2018;7(11):734-42. https://doi.org/10.20546/ijcmas.2018.711.088

26. Greenacre M, Groenen PJF, Hastie T, D'Enza AI, Marcos A, Tuzhilina E . Principal component analysis. Nat Rev Methods Primers. 2022;2:100. https://doi.org/10.1038/s43586-022-00184-w

27. Manjunatha L, Patil MS, Thimmegowda PR, Mahantesha VSR, Nataraj K. Survey and incidence of bud blight disease of tomato in parts of Karnataka. J Plant Dis Sci. 2010;5(1):102-4.

28. Cao Y, Li C, Yang WJ, Meng YL, Wang JL, shang BJ, et al. Effects of temperature on the development and reproduction of *Thrips hawaiiensis* (Thysanoptera: Thripidae). J. Econ Entomol. 2018;111(2):755-60. https://doi.org/10.1093/jee/tox359

29. Vinaykumar HD, Govindappa MR, Manjesh VS. Epidemiology of bud necrosis disease of tomato caused by Peanut bud necrosis virus (PBNV) in Raichur district of Karnataka. Int J Chem Stud. 2019;7(3):4067-72.

30. Kaur S, Kular JS, Chandi RS. Biological parameters of *Thrips tabaci* Lindeman at different constant temperatures on Bt cotton. J Exp Zoology India. 2017;20(2):993-998.

31. Rhainds M, Cloutier C, Shipp L, Boudreault S, Daigle G, Brodeur J. Temperature-mediated relationship between western flower thrips (Thysanoptera: Thripidae) and chrysanthemum. Environ Entomol. 2007;36(2):475-83. https://doi.org/10.1093/ee/36.2.475

32. Kakei Y, Tsuchida K. Influences of relative humidity on mortality during the pupal stage of *Thrips palmi* (Thysanoptera; Thripidae). Appl Entomol Zool. 2000;35(1):63-7. https://doi.org/10.1303/aez.2000.63

33. Escobar-Bravo R, Nederpel C, Naranjo S, Kim HK, Rodríguez-López MJ, Glauser G, et al. Ultraviolet radiation modulates both constitutive and inducible plant defenses against thrips but is dose and plant genotype dependent. J Pest Sci. 2021;94:69-81. https://doi.org/10.1007/s10340-019-01166-w

34. Waiganjo MM, Gitonga LM, Mueke JM. Effects of weather on thrips population dynamics and its implications on the thrips pest management. Afr J Hort Sci. 2008;1:82-90.

35. Mahanta DK, Jangra S, Priti, Ghosh A, Sharma PK, Iquebal MA, et al. Groundnut bud necrosis virus modulates the expression of innate immune, endocytosis, and cuticle development-associated genes to circulate and propagate in its vector, *Thrips palmi*. Frontiers in Microbiology. 2022;13:773238. https://doi.org/10.3389/fmicb.2022.773238

36. Vijayalakshmi G, Ganapathy N, Kennedy JS. Influence of weather parameters on seasonal incidence of thrips and Groundnut bud necrosis virus (GBNV) in groundnut (*Arachis hypogea* L.). J Entomol Zool Stud. 2017;5(3):107-10.

37. Rai AK, Sadashiva AT, Basavaraj YB, Venugopalan R, Rao ES, Nandeesha P. Genetic analysis of bud necrosis disease caused by groundnut bud necrosis virus (GBNV) in tomato (*Solanum lycopersicum* L.). Euphytica. 2020;216:125. https://doi.org/10.1007/s10681-020-02657-z

38. Uma Maheswari K, Jain RK, Bhat AI, Ahlawat YS. Biological and molecular characterization of a Tospovirus isolate from tomato and its relationship with other Tospoviruses. Indian Phytopathol. 2003;56(2):168-73.

39. Venkata Ramana C, Venkata Rao P, Prasada Rao RDVJ, Kumar SS, Reddy IP, Reddy YN. Genetic analysis for Peanut bud necrosis virus (PBNV) resistance in tomato (*Lycopersicon esculentum* Mill.). In: III International Symposium on Tomato Diseases;2010 Jul 25-30; Ischia, Italy; p.459-63. Available from: https://www.actahort.org/books/914/914_88.htm https://doi.org/10.17660/ActaHortic.2011.914.88

40. Rabeena I, Chinnaiah C, Karthikeyan G, Usharani TR, Balakrishnan N, Kennedy JS, et al. Incidence of Groundnut bud necrosis virus (Bunyaviridae: Tospovirus) and associated vector (*Frankliniella schultzei* Trybom) in major tomato growing regions of Tamil Nadu and Karnataka. Pest Management in Horticultural Ecosystems. 2019;25(2):233-40.