

# MULTIVARIATE ANALYSIS OF WEATHER FACTORS ASSOCIATED WITH BLACK THRIPS, THRIPS PARVISPINUS INFESTATION IN CHILLI IN TELANGANA

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## ABSTRACT

Thrips, in particular the invasive black thrips, *Thrips parvispinus* (Karny) have become a serious pest of chilli (*Capsicum annuum* L.) in Telangana, India. Understanding the relationship between weather variables and thrips population is vital in developing effective integrated pest management (IPM) strategies. A four-year field experiment (2022-2025) was conducted at the Vegetable Research Station, Sri Konda Laxman Telangana Horticultural University, Mulugu, Siddipet District, Telangana, in Kharif seasons (SMW 32-52 to SMW 1-5) to investigate the influence of nine weather variables (Temp\_Max, Temp\_Min, RH\_I, RH\_II, Rainfall, Rainy Days, Sunshine, Wind-speed, Evaporation) on thrips populations on leaves and flowers. Stepwise multiple regression, Pearson correlation, Principal Component Analysis (PCA) and K-Means clustering analyses were used to derive this information. The pooled regression model for flower thrips had an excellent predictive capability ( $R^2 = 0.951$ , adjusted  $R^2 = 0.945$ ), where Temp\_Min ( $\beta = -1.29$ ,  $p < 0.001$ ), Evaporation ( $\beta = -6.59$ ,  $p < 0.001$ ) and Rainfall ( $\beta = -0.064$ ,  $p < 0.01$ ) were significant negative contributors. Correlation analysis revealed Temp\_Min as the strongest negative correlation with flower thrips ( $r = -0.90$ ,  $p < 0.001$ ). PCA revealed that the first two principal components (PCs) accounted for 82.23% of the variation in the pooled data, with PC1 (Wet/Humidity axis: 59.12%) and PC2 (Thermal/Evaporation axis: 23.11%) being the most significant. K-Means analysis of the pooled data revealed the most distinct separation ( $k=2$ , silhouette=0.43) into "Wet-humid" and "Dry-sunny" weather groups. The predictive models developed here can be used as effective tools for weather-based early warning systems to predict thrips outbreaks in chilli.

**KEYWORDS:** Chilli; *Thrips parvispinus*; Weather parameters; Stepwise regression; Principal Component Analysis; K-Means clustering; Population dynamics; Integrated Pest Management

## INTRODUCTION

Chilli (*Capsicum annuum* L.) is one of the most important commercial spice and vegetable crops cultivated globally. India is the largest producer, consumer and exporter of dry chilli in the world, cultivated on approximately 852,000 hectares and producing 1,578,000 MT during 2021-22 (Muralimohan et al., 2023; Srinivasnaik et al., 2025). The crop belongs to the Solanaceae family and is valued for its pungency, colour, flavour and nutritional properties as, a rich source of vitamins A, B, C and the alkaloid capsaicin with medicinal properties (Gill, 1989; Samotaa and Jat, 2017; Dekebo, 2022). Telangana ranks second in chilli area, production and productivity of Indian states with, 1.13 lakh ha, 5.07 lakh tonnes and 4.50 tonnes ha<sup>-1</sup>, respectively, accounting for 13.38% of area and 22.24% of production (Srinivasnaik et al., 2025; Indiatat, 2024). Chilli production faces significant challenges from various biotic stresses, with insect pests being the most critical. The crop is encountered by 57 insect and non-insect pests (Reddy and Puttaswamy, 1984; Venugopal et al., 2019; Srinivasnaik et al., 2025). Over 35 species of insects and mites have been reported as pests on chilli, among which thrips and mites are considered major constraints for successful production (Muralimohan et al., 2023). Normally, *Scirtothrips dorsalis* is the regular pest infesting chilli, however in recent years, the invasive thrips species *Thrips parvispinus* (Karny), also known as Southeast Asian thrips, has emerged as a significant threat to chilli cultivation in India causing devastating outbreaks in chilli-growing regions of southern states including Andhra Pradesh, Karnataka, and Telangana, causing yield losses of 60-80% (Sridhar et al., 2021; Srinivasnaik et al., 2025; Veeranna

et al., 2022). Originally native to Southeast Asia, this species was first recorded in India on papaya in Bangalore, Karnataka in 2015 (Tyagi et al., 2015; Srinivasnaik et al., 2025).

Population dynamics of thrips are significantly influenced by weather parameters, with temperature, relative humidity, rainfall, and sunshine hours playing crucial roles. Several studies were documented on the influence of abiotic factors on thrips populations. Lokare et al. (2024) reported positive correlation with maximum temperature (0.478) and negative correlations with morning relative humidity (-0.497) for *T. parvispinus*. Raval et al. (2025) observed highly negative correlations with morning vapour pressure ( $r = -0.67^{**}$ ) and minimum temperature ( $r = -0.51$ ). Sadafale et al. (2025) found significant positive correlations with maximum temperature ( $r = 0.61$ ) and negative correlations with minimum temperature ( $r = -0.68$ ) during rabi. Shaik Rizwana et al. (2024) reported significant negative correlation with morning relative humidity (-0.673) and evening relative humidity (-0.372). Gopal et al. (2018) found significant negative correlation with maximum temperature (-0.54), minimum temperature (-0.76), rainfall (-0.49), and evaporation (-0.49\*). The development of weather-based pest prediction models can help in taking timely and targeted actions so that pesticide applications could be minimized and yield losses due to the pests could be reduced. Multiple regression, correlation and multivariate data analysis methods such as PCA and cluster analysis can provide effective solutions.

## Objectives

Following are the objectives of the present study:

1. To study the population fluctuation of thrips on leaf and flower of chilli during four Kharif seasons (2022-2025)
2. The influence of weather parameters on thrips population by stepwise multiple regression analysis
3. The correlation between thrips population and each weather parameter.
4. Characterization of weather regimes using Principal component analysis (PCA) and K-Means clustering.
5. To develop predictive models for predicting outbreaks of thrips

## MATERIAL AND METHODS

The present experiment was conducted at the Vegetable Research Station, Sri Konda Laxman Telangana Horticultural University, Mulugu, Siddipet District, Telangana, India during four consecutive Kharif seasons (2022-2025). The experimental site is located at an altitude of about 300 m above mean sea level, with a semi-arid climate, characterized by hot summers and mild winters. The meteorological data was collected on a standard meteorological week (SMW) basis throughout the crop growing period. The observations were made from SMW 32 to SMW 52 (August to December) for the Kharif season and continued up to SMW 1 to SMW 5 (January to February) to capture the extended crop duration. The following weather parameters were recorded:

**Table 1. Weather Parameters and their Abbreviations.**

| Parameter                        | Abbreviation | Unit   |
|----------------------------------|--------------|--------|
| Maximum Temperature              | Temp Max     | °C     |
| Minimum Temperature              | Temp Min     | °C     |
| Relative Humidity I (Morning)    | RH I         | %      |
| Relative Humidity II (Afternoon) | RH II        | %      |
| Rainfall                         | Rainfall     | mm     |
| Rainy Days                       | RainyDays    | Days   |
| Sunshine Hours                   | Sunshine     | hr/day |
| Wind Speed                       | WindSpeed    | km/hr  |
| Evaporation                      | Evaporation  | mm/day |

The crop was cultivated under standard recommended package of practices for the Kharif season chilli and uniform agronomic management was maintained for all four experimental year to ensure the consistency in data collection. The present experiment was conducted for four consecutive Kharif seasons (August-February) i.e., 2021–22, 2022–23, 2023–24 and 2024–25 under chilli variety Teja at Vegetable Research Station, Rajendranagar, Sri Konda Laxman Telangana Horticultural University using the standard package of practices. Seeds of chilli were raised in the nursery bed for 60 days followed by transplanting them to main field with a plant spacing of 60×40 cm. The crop was raised by following the recommended package of practices, while the plant protection measures were not employed throughout the crop growth period. The thrips population counts were recorded weekly on both leaves and flowers from SMW 32 (August) to SMW 5 (February) for the four Kharif Seasons (2022-2025). The thrip counts were recorded from the leaves and flowers as Thrips\_leaf: Number of thrips per leaf (average of 5 leaves per plant, 10 plants per replication) and Thrips\_flower: Number of thrips per flower (average of 5 flowers per plant, 10 plants per replication). The daily meteorological data was collected from the automatic weather station (AWS) installed at the Vegetable Research Station. The weekly means/sums were calculated for each standard meteorological week i.e., for SMW 32-52 and SMW 1-5.

## Statistical Analysis

The stepwise multiple regression was used to identify the most significant weather predictors for thrips infestation. The model equation is:  $Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \dots + \beta_nX_n + \varepsilon$  where Y is the thrips count,  $\beta_0$  is the intercept,  $\beta_i$  are the regression coefficients,  $X_i$  are the weather variables and  $\varepsilon$  is the error term, while the variables were entered and removed based on the statistical significance ( $p < 0.05$ ). Pearson's correlation coefficient (r) was calculated to measure the linear relationship between each pair of variables, and it was tested for significance at  $p < 0.05$ ,  $p < 0.01$ , and  $p < 0.001$  levels. The PCA was conducted

on the standardized weather variables to reduce the dimensionality and identify the underlying weather regimes. The analysis was done separately for each year (2022-2025) and the pooled dataset. The component loadings (correlation loadings = eigenvector  $\times \sqrt{\text{eigenvalue}}$ ) were calculated, with  $|\text{loading}| \geq 0.50$  being significant. K-Means clustering was applied on the PCA scores to group the weekly observations into distinct weather patterns. The optimal number of clusters (k) was determined using the silhouette score, which measures how close the observations are to one another. The higher the value of the silhouette score ( $>0.5$ ), the better the clustering. The statistical analysis was performed using the R programming language (Version 4.3.0) with packages: stats, factoextra, cluster, and ggplot2.

## RESULTS

Stepwise multiple regression analysis was conducted to identify the most significant weather predictors for thrips infestation on leaves and flowers.

**Table 2.** Stepwise Regression Equations for Thrips Infestation (Kharif Seasons 2022-2025).

| Year   | Target Variable | R <sup>2</sup> | Adjusted R <sup>2</sup> | Significant Predictors                  | Regression Equation                                                                              |
|--------|-----------------|----------------|-------------------------|-----------------------------------------|--------------------------------------------------------------------------------------------------|
| 2022   | Thrips_leaf     | 0.181          | 0.147                   | Evaporation                             | Thrips_leaf = 107.79 – 27.53·Evaporation*                                                        |
| 2022   | Thrips_flower   | 0.726          | 0.689                   | WindSpeed, Temp_Max, RainyDays          | Thrips_flower = 108.32 – 1.92·WindSpeed** – 2.96·Temp_Max*** – 2.34·RainyDays**                  |
| 2023   | Thrips_leaf     | 0.791          | 0.772                   | Temp_Min, Evaporation                   | Thrips_leaf = 46.56 – 1.23·Temp_Min*** – 4.14·Evaporation**                                      |
| 2023   | Thrips_flower   | 0.873          | 0.849                   | Evaporation, RainyDays, WindSpeed, RH_I | Thrips_flower = –2.23 – 6.62·Evaporation*** – 2.15·RainyDays*** + 0.78·WindSpeed** + 0.47·RH_I** |
| 2024   | Thrips_leaf     | 0.766          | 0.734                   | Temp_Min, Evaporation, Rainfall         | Thrips_leaf = 42.51 – 0.97·Temp_Min*** – 4.21·Evaporation** – 0.052·Rainfall*                    |
| 2024   | Thrips_flower   | 0.917          | 0.905                   | Temp_Min, Evaporation, Rainfall         | Thrips_flower = 58.99 – 1.26·Temp_Min*** – 6.20·Evaporation*** – 0.077·Rainfall***               |
| 2025   | Thrips_leaf     | 0.875          | 0.851                   | Temp_Min, Evaporation, Rainfall, RH_II  | Thrips_leaf = 55.86 – 3.14·Temp_Min*** – 3.42·Evaporation* – 0.104·Rainfall*** + 0.581·RH_II**   |
| 2025   | Thrips_flower   | 0.848          | 0.827                   | Temp_Min, Rainfall, Sunshine            | Thrips_flower = 68.39 – 1.99·Temp_Min*** – 0.107·Rainfall*** – 2.64·Sunshine***                  |
| Pooled | Thrips_leaf     | 0.574          | 0.537                   | Temp_Min, Evaporation                   | Thrips_leaf = 80.32 – 1.55·Temp_Min** – 10.88·Evaporation**                                      |
| Pooled | Thrips_flower   | 0.951          | 0.945                   | Temp_Min, Evaporation, Rainfall         | Thrips_flower = 60.42 – 1.29·Temp_Min*** – 6.59·Evaporation*** – 0.064·Rainfall**                |

Note: \* $p < 0.001$ ,  $p < 0.01$ ,  $p < 0.05$

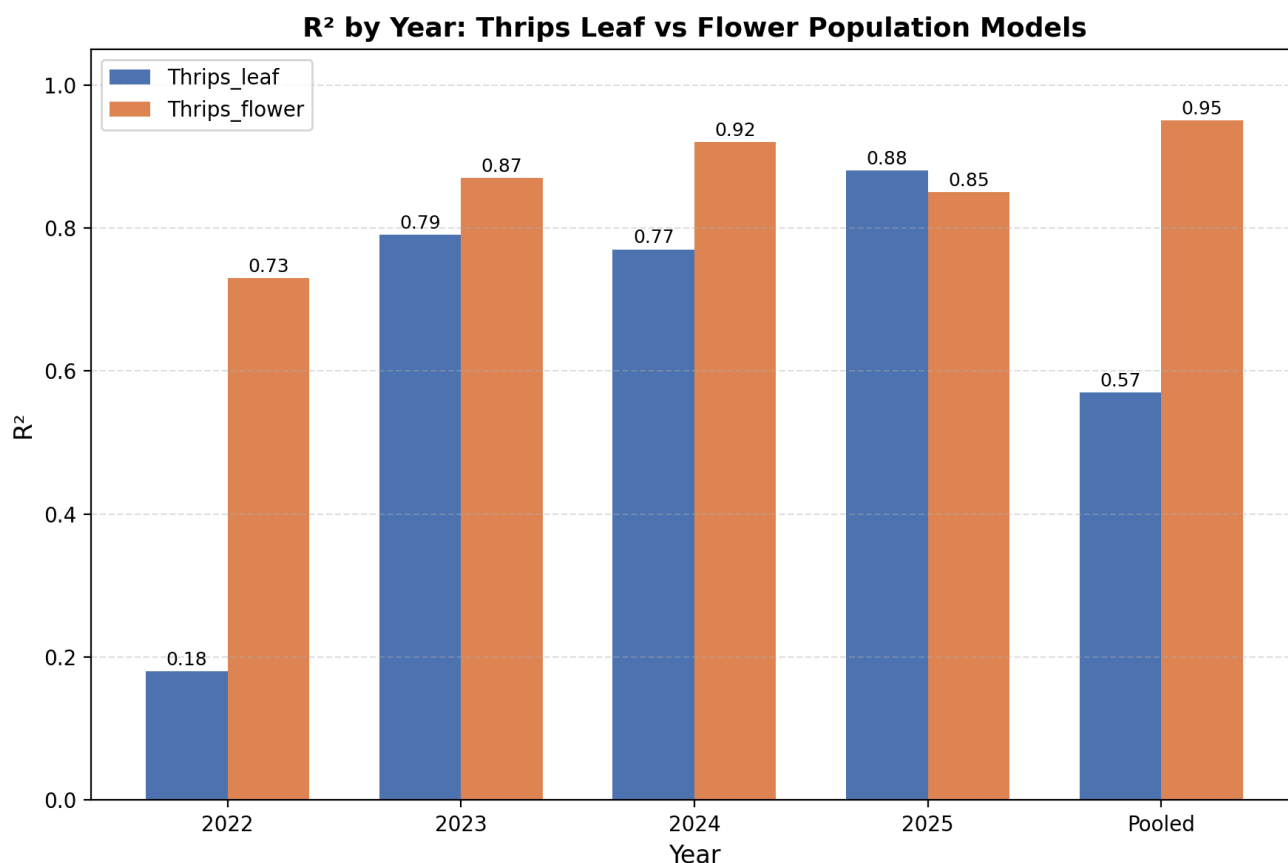


**Figure 1.** Bar chart showing  $R^2$  values for different years and target variables

### Multiple Linear Regression of weather parameters and population dynamics of chilli thrips (*Thrips parvispinus*)

The Thrips\_flower models consistently outperformed Thrips\_leaf models, with the Pooled flower model achieving an excellent  $R^2 = 0.951$  (adjusted  $R^2 = 0.945$ ). The 2024 flower model ( $R^2 = 0.917$ ) and 2023 flower model ( $R^2 = 0.873$ ) also showed high predictive power. The recurring negative predictors from the results are, Evaporation was a strong negative predictor across almost all years for both leaf and flower thrips. The coefficient ranged from -0.97 (2024 leaf) to -6.62 (2023 flower). Temp\_Min became a dominant negative predictor from 2023 onwards, with coefficients ranging from -0.97 (2024 leaf) to -3.14 (2025 leaf). Rainfall emerged as a significant negative predictor in 2024 and 2025, with coefficients of -0.052 to -0.107. The yearly variations indicating that in the year 2022, the leaf model was weak ( $R^2 = 0.181$ ), with only Evaporation as a significant predictor. The flower model was stronger ( $R^2 = 0.726$ ), with WindSpeed, Temp\_Max, and RainyDays as predictors. In the year 2023, both leaf ( $R^2 = 0.791$ ) and flower ( $R^2 = 0.873$ ) models improved substantially. Temp\_Min and Evaporation were the key predictors for leaves. In the year 2024, the flower model was exceptionally strong ( $R^2 = 0.917$ ), with Temp\_Min, Evaporation, and Rainfall as significant predictors and in the year 2025, both models showed high  $R^2$  values (0.875 for leaf, 0.848 for flower). Temp\_Min, Evaporation, Rainfall, and RH\_II were predictors for leaf thrips. In the pooled model, Thrips\_flower:  $R^2 = 0.951$ , with Temp\_Min ( $\beta = -1.29$ ,  $p < 0.001$ ), Evaporation ( $\beta = -6.59$ ,  $p < 0.001$ ), and Rainfall ( $\beta = -0.064$ ,  $p < 0.01$ ) were found as significant negative predictors. Thrips\_leaf:  $R^2 = 0.574$ , with Temp\_Min ( $\beta = -1.55$ ,  $p < 0.01$ ) and Evaporation ( $\beta = -10.88$ ,  $p < 0.01$ ) as predictors.

### Pearson Correlation Analysis of weather parameters and population dynamics of chilli thrips (*Thrips parvispinus*)

Pearson correlation coefficients were calculated to assess the linear relationship between individual weather variables and thrips populations.

**Table 3.** Correlation Matrix for Thrips Leaf.

| Variable    | 2022   | 2023     | 2024     | 2025     | Pooled   |
|-------------|--------|----------|----------|----------|----------|
| Temp_Max    | -0.36  | -0.02    | -0.51**  | -0.60**  | -0.63*** |
| Temp_Min    | -0.13  | -0.84*** | -0.79*** | -0.75*** | -0.64*** |
| RH_I        | 0.10   | -0.30    | -0.18    | -0.33    | -0.35    |
| RH_II       | -0.02  | -0.74*** | -0.53**  | -0.56**  | -0.49*   |
| Rainfall    | -0.16  | -0.56**  | -0.35    | -0.53**  | -0.48*   |
| RainyDays   | -0.06  | -0.70*** | -0.47*   | -0.63*** | -0.51**  |
| Sunshine    | -0.18  | 0.47*    | 0.15     | 0.17     | 0.17     |
| WindSpeed   | -0.25  | -0.58**  | -0.53**  | -0.51**  | -0.53**  |
| Evaporation | -0.43* | -0.70*** | -0.58**  | -0.40*   | -0.63*** |

Note: \*\*\* $p < 0.001$ , \*\* $p < 0.01$ , \* $p < 0.05$

**Table 4.** Correlation Matrix for Thrips Flower.

| Variable    | 2022     | 2023     | 2024     | 2025     | Pooled        |
|-------------|----------|----------|----------|----------|---------------|
| Temp Max    | -0.42*   | -0.16    | -0.55**  | -0.45*   | -0.60**       |
| Temp Min    | -0.63*** | -0.68*** | -0.85*** | -0.82*** | <b>-0.90*</b> |
| RH I        | -0.44*   | -0.09    | -0.23    | -0.27    | -0.49*        |
| RH II       | -0.58**  | -0.53**  | -0.61*** | -0.68*** | -0.77***      |
| Rainfall    | -0.50**  | -0.39*   | -0.39    | -0.60**  | -0.67***      |
| RainyDays   | -0.57**  | -0.55**  | -0.52**  | -0.72*** | -0.77***      |
| Sunshine    | 0.23     | 0.25     | 0.17     | 0.30     | 0.47*         |
| WindSpeed   | -0.64*** | -0.64*** | -0.62*** | -0.58**  | -0.77***      |
| Evaporation | -0.47*   | -0.77*** | -0.65*** | -0.27    | -0.68***      |

*Note:* \*\*\*p<0.001, \*\*p<0.01, \*p<0.05

### Visual Representations (Correlation Heatmaps)

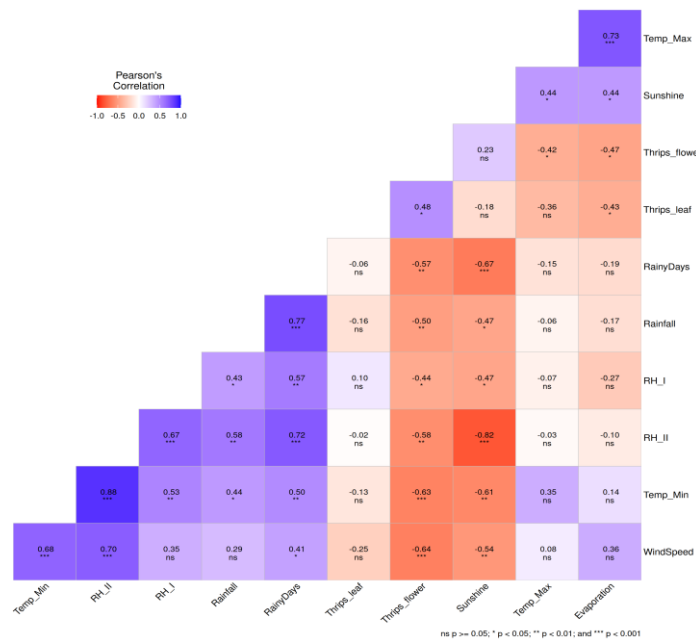


**Figure 2.** Pearson correlation heatmap illustrating the relationship between weather parameters and chilli thrips (*Thrips parvispinus*) population dynamics during 2022.

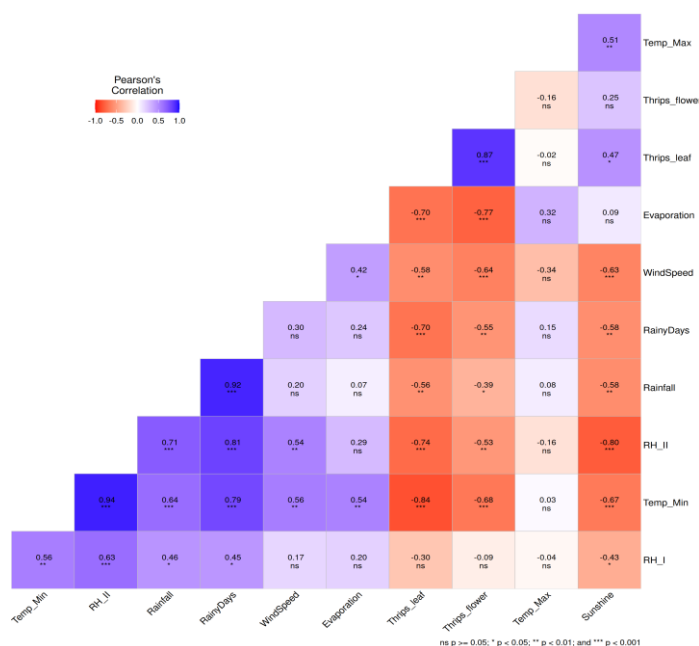


**Figure 3.** Pearson correlation heatmap illustrating the relationship between weather parameters and chilli thrips (*Thrips parvispinus*) population dynamics during 2023.



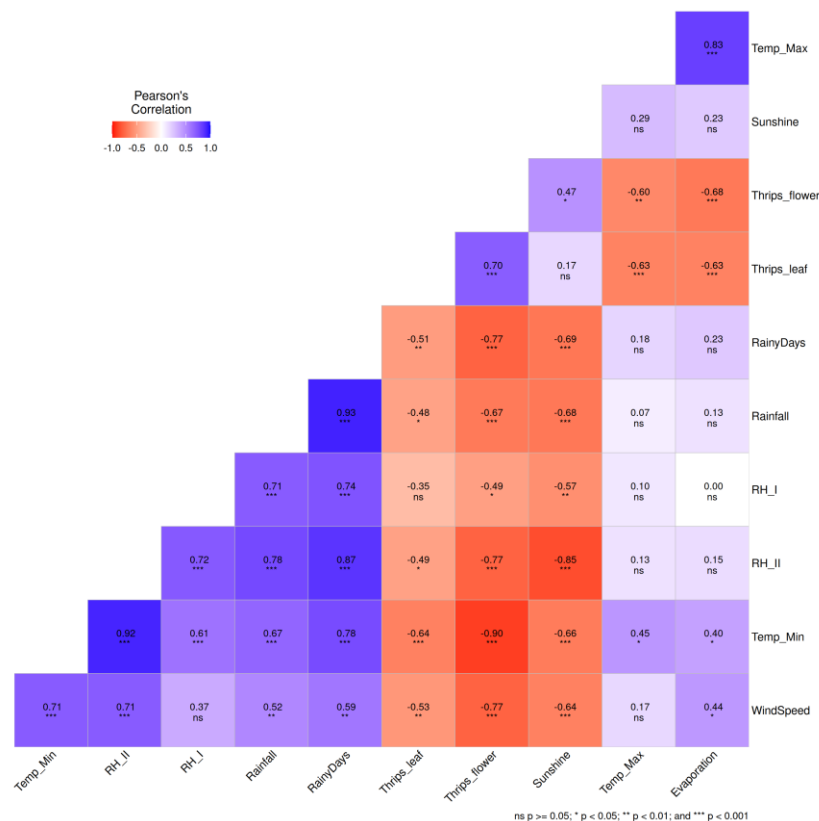


**Figure 6.** Pearson correlation heatmap illustrating the relationship between weather parameters and chilli thrips (*Thrips parvispinus*) population dynamics of pooled data (2022-2025).

#### Correlation Analysis of weather parameters and population dynamics of chilli thrips (*Thrips parvispinus*)

Temp\_Min was the strongest negative correlation for Thrips\_flower in the pooled dataset ( $r = -0.90$ ,  $p < 0.001$ ). For individual years, Temp\_Min showed correlations ranging from -0.63 (2022) to -0.85 (2024) for flower thrips. The Moisture Variables, RH\_II consistently showed strong negative correlations with both leaf and flower thrips across all years (pooled:  $r = -0.49$  for leaf,  $r = -0.77$  for flower). The RainyDays showed negative correlations ranging from -0.47 to -0.72 for flower thrips (pooled:  $r = -0.77$ ). Windspeed showed strong negative correlations for flower thrips (pooled:  $r = -0.77$ ). Evaporation showed significant negative correlations, particularly in 2023 ( $r = -0.70$  for leaf,  $r = -0.77$  for flower) and pooled data ( $r = -0.63$  for leaf,  $r = -0.68$  for flower). Sunshine showed weak positive correlations, becoming significant only in the pooled flower dataset ( $r = 0.47$ ,  $p < 0.05$ ). In 2023, sunshine showed a positive correlation with leaf thrips ( $r = 0.47$ ,  $p < 0.05$ ). The yearly variations indicating that in, In the year 2022, flower thrips showed significant negative correlations with Temp\_Min ( $r = -0.63$ ), RH\_II ( $r = -0.58$ ), RainyDays ( $r = -0.57$ ), WindSpeed ( $r = -0.64$ ), Rainfall ( $r = -0.50$ ), and Evaporation ( $r = -0.47$ ). In the year 2023, leaf thrips showed strong negative correlations with Temp\_Min ( $r = -0.84$ ), RH\_II ( $r = -0.74$ ), RainyDays ( $r = -0.70$ ), and Evaporation ( $r = -0.70$ ). In the year 2024, both leaf and flower thrips showed strong negative correlations with Temp\_Min ( $r = -0.79$  for leaf,  $r = -0.85$  for flower) and in the year 2025, flower thrips showed strong negative correlations with Temp\_Min ( $r = -0.82$ ) and RainyDays ( $r = -0.72$ ).

#### Principal Component Analysis (PCA) of weather parameters and population dynamics of chilli thrips (*Thrips parvispinus*)

PCA was conducted on standardized weather variables (9 variables) to reduce dimensionality and identify underlying weather regimes.

**Table 5.** PCA Summary – Eigenvalues and Variance Explained.

| Dataset       | PC1 %        | PC2 %        | PC3 %       | PC1+2 %      | PC1+2+3 %    | Kaiser ( $\lambda > 1$ ) | PCs 80%  |
|---------------|--------------|--------------|-------------|--------------|--------------|--------------------------|----------|
| data 22       | 50.39        | 23.93        | 9.69        | 74.32        | 84.01        | 2                        | 3        |
| data 23       | 52.92        | 18.63        | 14.05       | 71.55        | 85.60        | 3                        | 3        |
| data 24       | 49.28        | 25.90        | 10.55       | 75.18        | 85.73        | 2                        | 3        |
| data 25       | 53.55        | 21.22        | 10.43       | 74.77        | 85.20        | 2                        | 3        |
| <b>Pooled</b> | <b>59.12</b> | <b>23.11</b> | <b>8.50</b> | <b>82.23</b> | <b>90.72</b> | <b>2</b>                 | <b>2</b> |

**Table 6.** Component Loadings – data 22 (Kharif 2022). Highlighted values indicate  $|loading| \geq 0.50$ .

| Variable | PC1          | PC2          | PC3          | PC4          | PC5    |
|----------|--------------|--------------|--------------|--------------|--------|
| Temp_Max | -0.122       | <b>0.907</b> | <b>0.319</b> | 0.201        | -0.204 |
| Temp_Min | <b>0.827</b> | 0.449        | -0.098       | 0.204        | -0.298 |
| RH_I     | <b>0.735</b> | -0.089       | 0.179        | <b>0.562</b> | 0.374  |
| RH_II    | <b>0.982</b> | 0.116        | -0.121       | 0.078        | -0.093 |

|             |               |              |              |        |        |
|-------------|---------------|--------------|--------------|--------|--------|
| Rainfall    | <b>0.721</b>  | -0.083       | <b>0.565</b> | -0.342 | -0.037 |
| RainyDays   | <b>0.852</b>  | -0.124       | 0.341        | -0.234 | 0.113  |
| Sunshine    | <b>-0.867</b> | 0.315        | 0.325        | 0.098  | 0.195  |
| WindSpeed   | <b>0.691</b>  | 0.451        | -0.455       | -0.219 | 0.259  |
| Evaporation | -0.196        | <b>0.932</b> | -0.026       | -0.239 | 0.209  |

**Table 7.** Component Loadings – data 23 (Kharif 2023). *Highlighted values indicate  $|loading| \geq 0.50$ .*

| Variable    | PC1           | PC2          | PC3          | PC4          | PC5    |
|-------------|---------------|--------------|--------------|--------------|--------|
| Temp_Max    | -0.125        | <b>0.936</b> | -0.127       | -0.115       | 0.337  |
| Temp_Min    | <b>0.954</b>  | 0.180        | 0.175        | 0.006        | -0.048 |
| RH_I        | <b>0.655</b>  | 0.084        | -0.165       | <b>0.740</b> | 0.102  |
| RH_II       | <b>0.987</b>  | -0.042       | -0.014       | 0.055        | -0.024 |
| Rainfall    | <b>0.810</b>  | 0.153        | -0.478       | -0.220       | -0.088 |
| RainyDays   | <b>0.883</b>  | 0.256        | -0.310       | -0.246       | -0.082 |
| Sunshine    | <b>-0.824</b> | <b>0.541</b> | 0.062        | 0.084        | -0.135 |
| WindSpeed   | <b>0.617</b>  | -0.303       | <b>0.649</b> | -0.193       | 0.253  |
| Evaporation | 0.358         | <b>0.595</b> | <b>0.701</b> | 0.066        | -0.222 |

**Table 8.** Component Loadings – data 24 (Kharif 2024). *Highlighted values indicate  $|loading| \geq 0.50$ .*

| Variable    | PC1           | PC2          | PC3          | PC4    | PC5    |
|-------------|---------------|--------------|--------------|--------|--------|
| Temp_Max    | -0.228        | <b>0.933</b> | 0.220        | -0.158 | -0.107 |
| Temp_Min    | <b>0.680</b>  | <b>0.665</b> | -0.135       | -0.316 | -0.019 |
| RH_I        | <b>0.567</b>  | 0.099        | <b>0.789</b> | -0.064 | 0.277  |
| RH_II       | <b>0.944</b>  | 0.115        | -0.207       | -0.116 | -0.039 |
| Rainfall    | <b>0.873</b>  | -0.145       | 0.144        | 0.325  | -0.095 |
| RainyDays   | <b>0.878</b>  | 0.040        | 0.172        | 0.297  | -0.275 |
| Sunshine    | <b>-0.834</b> | 0.344        | 0.074        | 0.383  | 0.110  |
| WindSpeed   | <b>0.779</b>  | 0.236        | -0.440       | 0.198  | 0.354  |
| Evaporation | -0.221        | <b>0.945</b> | -0.082       | 0.247  | -0.036 |

**Table 9.** Component Loadings – data 25 (Kharif 2025). *Highlighted values indicate  $|loading| \geq 0.50$ .*

| Variable    | PC1           | PC2          | PC3           | PC4          | PC5    |
|-------------|---------------|--------------|---------------|--------------|--------|
| Temp_Max    | -0.178        | <b>0.931</b> | 0.228         | -0.077       | -0.208 |
| Temp_Min    | <b>0.809</b>  | 0.416        | 0.226         | -0.375       | 0.108  |
| RH_I        | <b>0.633</b>  | 0.057        | <b>0.580</b>  | <b>0.495</b> | 0.230  |
| RH_II       | <b>0.958</b>  | 0.101        | 0.119         | -0.245       | 0.102  |
| Rainfall    | <b>0.842</b>  | 0.092        | -0.334        | 0.242        | -0.309 |
| RainyDays   | <b>0.888</b>  | 0.252        | -0.104        | 0.142        | -0.233 |
| Sunshine    | <b>-0.893</b> | 0.364        | -0.082        | 0.080        | 0.095  |
| WindSpeed   | <b>0.773</b>  | 0.013        | <b>-0.550</b> | 0.010        | 0.328  |
| Evaporation | -0.339        | <b>0.854</b> | -0.301        | 0.160        | 0.203  |

**Table 10.** Component Loadings – Pooled Data. *Highlighted values indicate  $|loading| \geq 0.50$ .*

| Variable    | PC1           | PC2          | PC3          | PC4    | PC5    |
|-------------|---------------|--------------|--------------|--------|--------|
| Temp_Max    | 0.228         | <b>0.936</b> | -0.221       | -0.182 | -0.091 |
| Temp_Min    | <b>0.930</b>  | 0.235        | 0.077        | -0.281 | -0.156 |
| RH_I        | <b>0.783</b>  | -0.182       | -0.471       | -0.159 | 0.382  |
| RH_II       | <b>0.985</b>  | -0.105       | 0.070        | -0.162 | -0.090 |
| Rainfall    | <b>0.888</b>  | -0.145       | -0.248       | 0.360  | -0.123 |
| RainyDays   | <b>0.951</b>  | -0.038       | -0.201       | 0.232  | -0.092 |
| Sunshine    | <b>-0.814</b> | <b>0.505</b> | -0.264       | 0.112  | 0.075  |
| WindSpeed   | <b>0.775</b>  | 0.166        | <b>0.574</b> | 0.109  | 0.243  |
| Evaporation | 0.278         | <b>0.940</b> | 0.112        | 0.188  | 0.087  |

Weather Pattern Clusters (K-means) – Projected on PCA Axes

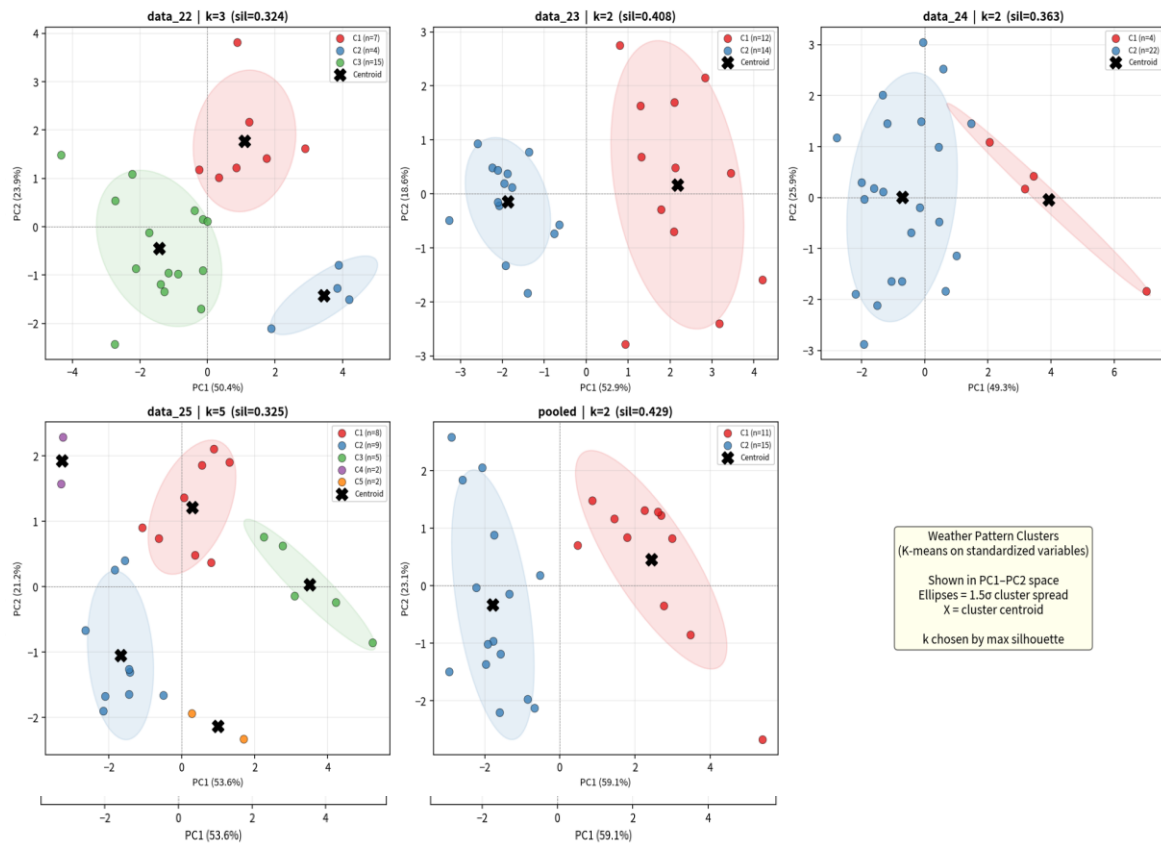


**Figure 7.** Year-wise & Pooled PCA biplots of weather parameters and population dynamics of chilli thrips (*Thrips parvispinus*) (Red arrows = variable loadings; Blue dots = observations).

**PCA Factor Loadings of weather parameters and population dynamics of chilli thrips (*Thrips parvispinus*)**  
PC1 (wet/humidity axis): explained the largest proportion of variance for all years (49-59%). This component had high positive loadings for RH\_II, RainyDays, Temp\_Min, Rainfall, and WindSpeed, and a high negative loading for Sunshine. PC2 (thermal/evaporation axis) explained 19-26% of variance, which was also considerable. It had high positive loadings for Temp\_Max and Evaporation. Overall, the two components captured the two types of weather found: wet/humid/cool and hot/dry/evaporative. Consistency: The loadings were largely similar for different years, which suggests that the same two types of weather dominated the regional climate throughout the period. The pooled data, PC1+PC2 = 82.23% variance (with PC1 explaining 59.12%), which was the best performance among all options considered. Moreover, using two components was sufficient to reach 80% variance reduction.

**K-Means Clustering of weather parameters and population dynamics of chilli thrips (*Thrips parvispinus*)**  
The K-Means clustering procedure was applied to the scores from the PCA analysis to identify clusters of weeks with similar weather patterns. The results are shown below.

**Table 11.** K-Means Clustering Summary for Weather Patterns.

| Dataset | Optimal k | Silhouette Score | Main Pattern                                 |
|---------|-----------|------------------|----------------------------------------------|
| data_22 | 3         | 0.32             | Wet / Warm-humid / Dry-cool                  |
| data_23 | 2         | 0.41             | Wet-humid vs Dry-sunny                       |
| data_24 | 2         | 0.36             | Wet vs Dry-warm                              |
| data_25 | 5         | 0.33             | Fragmented (wet, dry, hot-dry)               |
| Pooled  | 2         | 0.43             | Wet-humid vs Dry-sunny (Clearest separation) |

**Figure 8.** Weather Pattern Clusters – Projected on PCA Axes (Ellipses represent  $1.5\sigma$  cluster spread; X = centroid).

## Weather Cluster Profiles (Standardized Means)

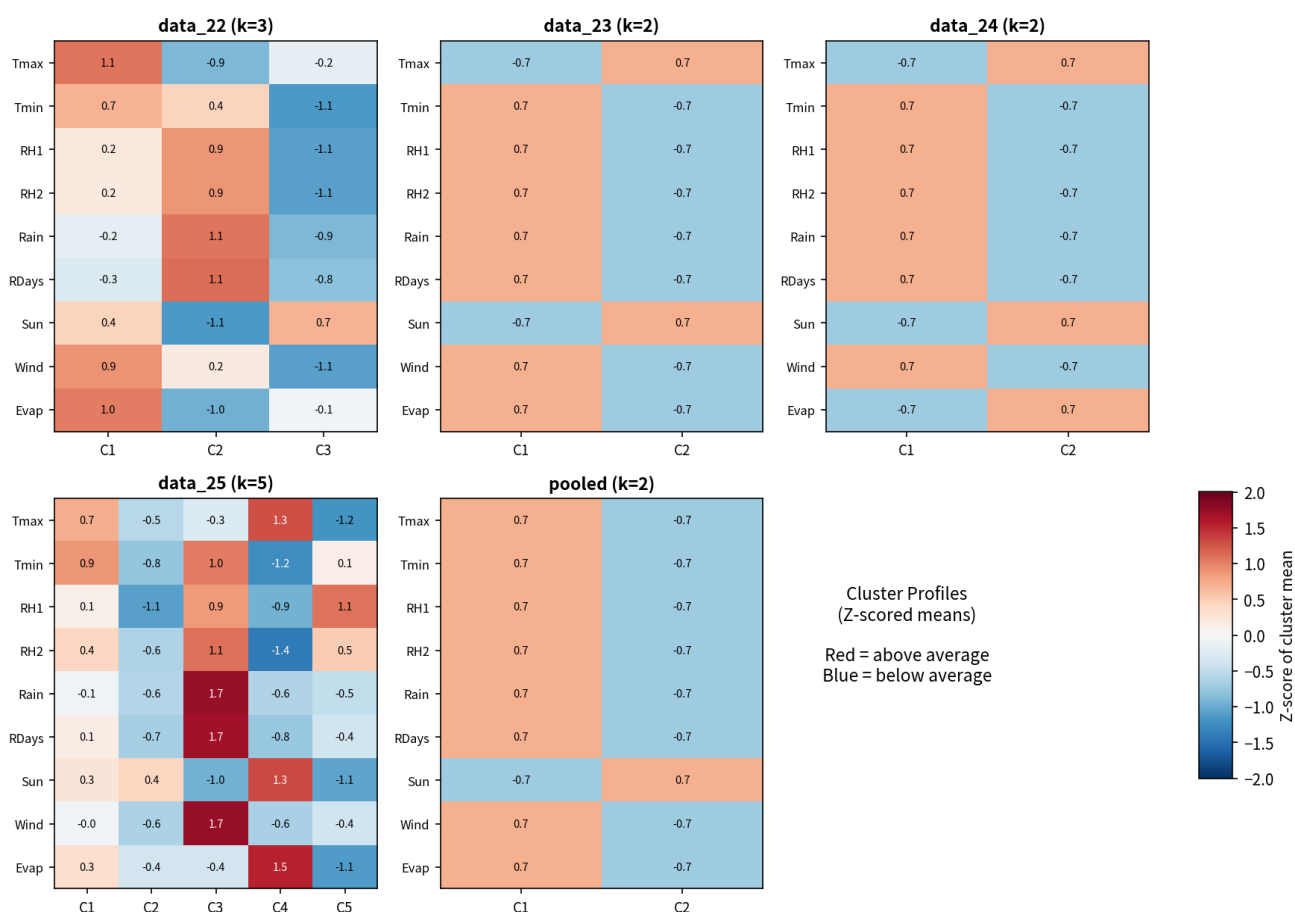


**Figure 9.** Weather Cluster Profiles (Standardized Means) – Heatmap showing Z-scores

for each variable per cluster.

In pooled data, the clearest separation was observed with  $k=2$  (Silhouette = 0.43), splitting into Cluster 1 (Wet-Humid): High RH\_I, RH\_II, Rainfall, RainyDays, WindSpeed; Low Temp\_Max, Sunshine, Evaporation and Cluster 2 (Dry-Sunny): High Temp\_Max, Sunshine, Evaporation; Low RH\_I, RH\_II, Rainfall, RainyDays. The yearly variability across the years 2023 and 2024 showed stable 2-cluster splits (Wet vs Dry). The year 2022, required 3 clusters (Wet / Warm-humid / Dry-cool), indicating more transitional weather patterns. The year 2025, highly fragmented ( $k=5$ ) with lower silhouette score (0.33), indicate more complex or unstable weather regime. The cluster profiles, the heatmap (Figure 9) confirmed that Wet-Humid clusters have positive Z-scores for RH, Rainfall, RainyDays, and WindSpeed, but negative Z-scores for Temp\_Max, Sunshine, and Evaporation and Dry-Sunny clusters show the opposite pattern

## DISCUSSION

### Weather-Thrips Relationships

The study revealed that thrips populations in chilli are significantly influenced by weather variables during the Kharif season (SMW 32-52 to SMW 1-5). The consistent negative correlation between thrips counts and moisture-related variables (Rainfall, RainyDays, RH\_II, WindSpeed) indicates that wet and humid conditions suppress thrips populations. This finding is consistent with previous studies as stated by Shaik Rizwana et al. (2024) who reported significant negative correlation of *T. parvispinus* with morning relative humidity (-0.673) and evening relative humidity (-0.372). Raval et al. (2025) observed highly negative correlations with morning vapour pressure ( $r = -0.67^{**}$ ) and minimum temperature ( $r = -0.51$ ). Gopal et al. (2018) found significant negative correlation of *S. dorsalis* with rainfall (-0.49) and evaporation (-0.49\*). The mechanism behind this suppression is likely multifactorial: rainfall physically dislodges thrips from plants, high humidity promotes fungal pathogens that attack thrips, and wet conditions may reduce thrips feeding and oviposition activity.

### Dominant Role of Minimum Temperature

Temp\_Min emerged as the most powerful negative driver of thrips infestation, particularly for flower thrips ( $r = -0.90$  pooled). This finding is particularly noteworthy and consistent with several earlier studies as reported by Sadafale et al. (2025) who found that thrips density during rabi was negatively correlated with minimum temperature ( $r = -0.68$ ) while Raval et al. (2025) observed negative correlation with minimum temperature ( $r = -0.51$ ). Gopal et al. (2018) reported significant negative correlation of *S. dorsalis* with minimum temperature (-0.76).

Lower night temperatures likely reduce metabolic rates, prolong their developmental periods, and reduce fecundity. The studies on biology by Priyanka et al. (2024) found that *T. parvispinus* completes its life cycle in

13-14 days at 25°C, while Kiran and Prakash (2026) reported 19-21 days at 25-30°C and Sridhar et al. (2025) found that the total pre-adult duration was longest at 15°C and shortest at 30°C, and fecundity was highest at 30°C. Our findings are in accordance with their studies.

### Evaporation as a Predictor

The consistent negative coefficient for Evaporation in the regression models is noteworthy. While evaporation is typically associated with dry conditions (which might favor thrips), the negative relationship suggests that high evaporation rates may cause desiccation stress to thrips or their host plants, resulting in reduced infestation. This finding contradicts some previous studies as reported by Lokare et al. (2024) who found positive correlation with maximum temperature (0.478) and bright sunshine hours (0.199) while Kotresh et al. (2020) reported negative correlation with evaporation for *S. dorsalis*. The discrepancy may be due to the specific environmental conditions at the study site, the species involved, or the interaction between evaporation and other variables. This finding highlights the complexity of weather-thrips interactions and requires further investigation.

### PCA and Weather Regimes

The PCA confirmed that two dominant weather axes characterize the Kharif season at the study location:

PC1 (Wet/Humid/Cool): High RH\_II, RainyDays, Rainfall, Temp\_Min, WindSpeed; Low Sunshine. This axis explained 59.12% of variance in pooled data and PC2 (Hot/Dry/Evaporative): High Temp\_Max, Evaporation. This axis explained 23.11% of variance in pooled data. The consistency of these loadings across all four years (2022-2025) indicates that these are fundamental weather regimes at the study location, not artifacts of a particular season.

### K-Means Clustering and Weather Regime Classification

The K-Means clustering identified these as "Wet-humid" and "Dry-sunny" clusters, with the pooled data showing the clearest separation (silhouette = 0.43). These clusters serve as effective descriptors of weather regimes that influence thrips dynamics. The year-wise analysis revealed that in, in the year 2023 and 2024, Stable 2-cluster splits, indicating predictable weather patterns. In 2022, required 3 clusters, suggesting more transitional weather whereas in 2025, highly fragmented (k=5), indicating more complex weather patterns. The fragmentation in 2025 may explain why the regression models for that year, while still strong ( $R^2 = 0.848-0.875$ ), required different predictor variables (e.g., RH\_II for leaf, Sunshine for flower).

### Predictive Modeling for IPM

The Pooled Thrips\_flower model ( $R^2 = 0.951$ ) is particularly robust and can be used for developing a weather-based early warning system for thrips management in chilli. The model predicts that:

$$\text{Thrips\_flower} = 60.42 - 1.29 \cdot \text{Temp\_Min} - 6.59 \cdot \text{Evaporation} - 0.064 \cdot \text{Rainfall}$$

This equation implies that increases in minimum temperature, evaporation, and rainfall will all lead to reduced flower thrips populations. This model aligns with the findings of Sahani et al. (2020), who reported that multiple regression analysis revealed that the combined effect of abiotic factors on population build-up of *S. dorsalis* was 89.8% ( $R^2 = 0.898$ ). Similarly, Kumar et al. (2021) found that weather factors contributed 77% ( $R^2 = 0.77$ ) influence on thrips population in chilli.

## CONCLUSIONS

The four-year (2022-2025) study at Vegetable Research Station, Sri Konda Laxman Telangana Horticultural University, Mulugu, Telangana provided conclusive evidence that the Wet humid and cool weather reduces thrips population on leaves and flowers of chilli. This was evident through K-Means clustering and PCA which identified that the weather regime of wet-humid reduces the incidence of thrips. Minimum Temperature (Temp\_Min) was the most negative predictor of thrips infestation, with a pooled correlation of  $r = -0.90$  for thrips on flower. This implies that the night temperature plays a significant role in thrips population dynamics. Rainfall and Evaporation were significant negative predictors in the pooled models. The pooled flower model indicated that an increase in these weather variables would lead to a decrease in thrips population. The Pooled Thrips\_flower model ( $R^2 = 0.951$ ) can be used as a predictive tool for thrips management. The model can be combined with weather forecasts to predict thrips outbreaks and take appropriate management measures. PCA and K-Means clustering were able to identify two dominant weather regimes (Wet-humid and Dry-sunny) that are consistent across years. This provides a framework for understanding the weather conditions that favor or suppress thrips outbreaks. Variability in yearly weather patterns (e.g., fragmentation in 2025) can influence the specific predictors and model strengths, highlighting the need for season-specific and pooled models for accurate prediction.

### Implications for IPM

The findings have important implications for integrated pest management (IPM) in chilli cultivation such as, the pooled flower model can be used to develop a system for predicting thrips outbreaks based on weekly weather forecasts. Predictive models can help reduce the use of pesticides by predicting outbreaks and allowing for more targeted applications. This would reduce costs and have a positive impact on the environment. The models can be used to determine the optimal timing for pesticide applications or biological control releases to maximize efficacy. The models were developed for the Telangana region but can be adapted to other regions with similar weather patterns by incorporating local weather data.

### Future Research Directions

Future research should focus on the validation of the predictive models across different regions and varieties of chilli. Incorporation of additional variables such as pest natural enemy populations and crop phenology into the models. Development of real-time monitoring systems using IoT sensors and automated weather stations. Long-term monitoring of *T. parvispinus* population dynamics to detect shifts in weather-thrips relationships and Integration of the models with IPM decision support systems for practical field applications.

**Supplementary Materials:** The following supporting information can be downloaded at: link will be added.

**Author Contributions:** Conceptualization, writing—original draft preparation and methodology, D.Anitha Kumai; software, validation, data analysis, visualization and investigation G. Sathish; resources, data curation V. Suresh ; review and data collection Bhagyashali Hudge; review and data collection B.S.K. Nikhil; Manuscript editing and revision P. Sudheer Kumar; All authors have read and agreed to the published version of the manuscript.

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