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Seasonal Population Dynamics of Sucking Insect Pests and Pink Bollworm on Cotton and Their Correlation with Meteorological Parameters

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ABSTRACT

A two-year field investigation was conducted at the Cotton Research Station, Multan during Kharif seasons of 2024 and 2025 to study the seasonal population dynamics of major sucking insect pests jassid (*Amrasca biguttula biguttula* Dist), whitefly (*Bemisia tabaci* Genn.), aphid (*Aphis gossypii* Glov.) and thrips (*Thrips tabaci* Lind.), along with pink bollworm (*Pectinophora gossypiella* Saund.) on cotton variety MNH-1020. Pest counts were recorded on a weekly basis from June to October using standard sampling methods. Simultaneously, meteorological data including maximum temperature, minimum temperature, relative humidity and rainfall were recorded from the nearest agro meteorological observatory. The results revealed that all sucking pests reached their peak population during the second week of August in both years, with whitefly (*Bemisia tabaci*) recording the highest count of 23.0 ± 1.77 adults/leaf in 2024 (and 20.4 ± 1.57 adults/leaf in 2025). Jassid (*Amrasca biguttula biguttula*) peaked at 7.1 ± 0.55 nymphs/leaf in 2024 and 6.4 ± 0.49 nymphs/leaf in 2025. Aphid (*Aphis gossypii*) attained maximum populations of 15.8 ± 1.21 individuals/leaf in 2024 and 13.1 ± 1.01 individuals/leaf in 2025, while thrips (*Thrips tabaci*) reached 25.7 ± 1.97 individuals/plant in 2024 and 22.3 ± 1.72 individuals/plant in 2025. Pink bollworm (*Pectinophora gossypiella*) attained maximum larval infestation of 22.5 ± 1.73 larvae/100 bolls in 2025 and 17.5 ± 1.34 larvae/100 bolls in 2024. Statistical analysis showed highly significant positive correlations of jassid, whitefly and aphid populations with temperature ($r = 0.847-0.876$) and relative humidity ($r = 0.741-0.858$). Pink bollworm showed significant positive correlation with both temperature ($r = 0.684-0.712$) and humidity ($r = 0.698$). Rainfall exhibited a negative relationship with sucking pests but a positive relationship with pink bollworm larval populations. Simple linear regression models explained up to 76.7% of the variance in pest populations attributable to meteorological factors. These findings provide a scientific basis for forecasting pest outbreaks and planning timely integrated pest management interventions in the cotton agro-ecosystem of Southern Punjab.

KEYWORDS: Population dynamics, sucking pests, pink bollworm, meteorological correlation, regression analysis, cotton

INTRODUCTION

Cotton (*Gossypium hirsutum* L.) is the most significant cash crop of Pakistan, contributing approximately 4.2% to the national GDP and accounting for nearly 60% of total export earnings through the textile sector (Government of Pakistan, 2026). Pakistan ranks among the top cotton-producing countries globally, with the crop being cultivated on approximately 2.5 million hectares annually (Iqbal *et al.*, 2022; Sarfraz *et al.*, 2018). However, the productivity potential of cotton remains severely limited by insect pest infestations that can cause yield losses ranging from 20 to 80% under unmanaged conditions (Rajendran *et al.*, 2018; Shera *et al.*, 2020).

Among the most economically destructive pests of cotton in Pakistan, sucking insects occupy a prominent position (Waseem *et al.* 2025). The cotton jassid (*Amrasca biguttula biguttula* Dist.), whitefly (*Bemisia tabaci* Gennadius), cotton aphid (*Aphis gossypii* Glover) and thrips (*Thrips tabaci* Lindeman) damage the crop by extracting plant sap, injecting toxic saliva, causing hopper burn and transmitting viral diseases such as cotton leaf curl virus (CLCuV), which is endemic to the Indo-Pakistan subcontinent (Rajendran *et al.*, 2018; Shera *et al.*, 2020; Manzoor *et al.*, 2022). The compounding effects of these pests, particularly under changing climatic conditions, have been identified as major constraints to cotton productivity in

South Asia (Ahmad *et al.*, 2020; Farooq *et al.*, 2023). Pink bollworm (*Pectinophora gossypiella* Saunders) is equally devastating as a boll-feeding internal pest that directly reduces lint yield and deteriorates fiber quality (Farooq *et al.*, 2023).

Insect pest populations in agro-ecosystems do not exist in isolation but are profoundly influenced by abiotic environmental factors, particularly temperature, relative humidity and precipitation (Raza 2025). Understanding the physiological responses of insects to abiotic stressors such as temperature and humidity fluctuations is fundamental to predicting population dynamics, as these factors directly influence metabolic rates, development times, and reproductive output (Ramniwas, *et al.* 2023, Nath 2025). In cotton, abiotic stress tolerance mechanisms involving osmotic adjustment, antioxidant defense systems, and heat shock proteins have been extensively characterized (Mahmood *et al.*, 2022; Zafar *et al.*, 2024; Zafar *et al.*, 2022). Moreover, knowledge of the quantitative relationship between pest incidence and meteorological variables is a prerequisite for the development of accurate pest forecasting models, which are essential tools for evidence-based integrated pest management (IPM) decision-making (Ali and Zhuo 2025). Threshold-based spray advisories, when calibrated against weather data, can reduce unnecessary pesticide applications, lower production costs and minimize environmental contamination (Riaz *et al.*, 2022; Khan *et al.*, 2022).

Although scattered studies on the seasonal fluctuation of cotton pests have been reported from various regions of Pakistan (Ahmad *et al.*, 2020; Hafeez *et al.*, 2021; Zafar *et al.*, 2023), systematic two-year investigations that simultaneously document sucking pest and bollworm dynamics and rigorously correlate them with meteorological parameters using regression analysis are limited from the Multan agro-ecosystem. Furthermore, while extensive research has been conducted on cotton yield stability and fiber quality genetics (Iqbal *et al.*, 2021; Sarfraz *et al.*, 2021; Geng *et al.*, 2020), the integration of pest-weather correlation models with genetic improvement strategies remains poorly explored. The present study was therefore undertaken to (i) monitor weekly population fluctuations of major sucking pests and pink bollworm on cotton over two consecutive Kharif seasons (2024 and 2025), (ii) record prevailing meteorological conditions during the cropping period, (iii) establish correlation and regression relationships between pest populations and weather variables, and (iv) identify critical meteorological thresholds that trigger pest outbreak conditions.

MATERIALS AND METHODS

Experimental Site and Crop Management: The field experiments were conducted at the experimental farm of Latitude 30.18° N (30°10'48" N), Longitude 71.43° E (71°25'48" E), and an altitude of 122 m above sea level (a.s.l.). For precise geo-referencing, the site falls

within UTM Zone 42N (Easting: 738,000; Northing: 3,340,000, WGS 84) during consecutive Kharif seasons of 2024 and 2025. The improved cotton variety MNH-1020, recommended for Southern Punjab, was sown in both years following the standard agronomic package of practices prescribed by the Punjab Department of Agriculture. A plot area of 0.4 hectares was maintained each year with row-to-row spacing of 75 cm and plant-to-plant spacing of 30 cm. No chemical insecticides were applied throughout the cropping season to allow undisturbed natural pest build-up and population expression.

Pest Sampling Methodology: Pest populations were monitored on a weekly basis from the first week of June to the fourth week of October (20 observation periods per season). Sampling was conducted between 7:00–9:00 AM on each observation date to minimize temperature-related pest behavior bias. A total of 10 plants were randomly selected from the experimental plot for each weekly observation. From each plant, 10 leaves were sampled (upper, middle, and lower canopy positions), giving a sampling unit of 100 leaves per week. These leaves were used to monitor jassid nymphs, whitefly adults, and aphid individuals, as these pests are leaf-associated. Thrips were monitored separately using the tray-tapping method, while pink bollworm infestation was assessed from bolls. Pink bollworm larval infestation was assessed by collecting and dissecting 100 freshly formed bolls from 10 randomly selected plants per observation week. Each boll was carefully dissected using a sterile scalpel under a stereomicroscope (Nikon SMZ745T, magnification 10–45×) with incident light illumination (LED ring light, 6,500 K) to detect and count larvae.

Different counting methods were employed for each pest species based on their distinct behavioral and ecological characteristics, following standard entomological protocols. Jassid nymphs were dislodged and counted per leaf from these sampling units. Jassid nymphs cause the primary damage (hopper burn) through sap-feeding, while adults are highly mobile and difficult to count accurately. Jassid nymphs were counted per leaf as they are sessile and remain on leaf undersides. Whitefly adults were dislodged and counted per leaf from these sampling units. Whitefly adults are the primary dispersive stage responsible for virus transmission and direct feeding damage; nymphs are scale-like and attached to leaf undersides, making them difficult to count in routine field monitoring. Whitefly adults were counted per leaf as they are the primary damaging stage. Aphid colonies were counted per leaf. Aphid and thrips populations are counted as individuals including both nymphs and adults. Aphids were counted as individuals per leaf including both nymphs and adults. Thrips were counted per plant using the standard white tray method (30 × 40 cm tray): each plant was gently tapped three times over the tray, and all dislodged thrips were counted. Thrips were counted per plant using the tray-tapping method because they are highly mobile and leaf counts

significantly underestimate actual populations. While this method does not capture the absolute population, it provides a reliable relative index of thrips abundance that is standard in cotton pest monitoring (Zafar *et al.*, 2023). Similar standardized monitoring protocols for cotton pests have been employed in previous studies across Punjab (Shahid *et al.*, 2013, 2014).

Data were expressed as nymphs/leaf (jassid), adults/leaf (whitefly), individuals/leaf (aphid), individuals/plant (thrips) and larvae/100 bolls (PBW). Mean $\pm$ Standard Error (SE) was calculated for each observation period. The 10 plants served as sub-samples (technical replicates) from which the mean $\pm$ SE was calculated for each observation week.

Meteorological Data Recording: Weekly meteorological data maximum temperature ($^{\circ}\text{C}$), minimum temperature ($^{\circ}\text{C}$), relative humidity (%) and rainfall (mm) were obtained from the Agro meteorological Observatory co-located with Cotton Research Station, Multan. These data were collected over both crop seasons (June–October 2024 and 2025) and were used in all subsequent statistical analyses.

Statistical Analysis: All data were subjected to statistical analysis using SPSS v.26.0 (IBM Corp.) and Microsoft Excel 2019. Prior to parametric analyses, data were checked for normality using the Shapiro-Wilk test and for homogeneity of variances using Levene's test. Where necessary, data were transformed using square root or logarithmic transformations to meet the assumptions of analysis of variance and linear regression. Weekly population data were analyzed using one-way ANOVA with a Completely Randomized Design (CRD) model, where 'week' was the main factor (20 levels, $n = 20$ weeks per year) and pest population counts (nymphs/leaf, adults/leaf, individuals/leaf, individuals/plant, and larvae/100 bolls) were the response variables. ANOVA was performed separately for each pest species and each year, and Fisher's Least Significant Difference (LSD) test was used for mean separation at $p \leq 0.05$. In addition, independent samples t-tests were applied to compare mean pest populations between the two study years (2024 vs. 2025), ensuring consistency between year-to-year comparisons and weekly analysis of variance results. The complete summary of mean comparisons, including F-values, degrees of freedom, and LSD values for all species and years, is presented in Table 4. For correlation and regression analyses, data from both years were pooled ($n = 40$ weekly observations: 20 weeks $\times$ 2 years) to increase statistical power. However, weekly population dynamics are presented separately for each year (Figure 1) to allow year-to-year comparisons. Although Table 5 summarizes meteorological data as monthly means for ease of presentation, the correlation and regression analyses were performed using weekly meteorological records (temperature, relative humidity, rainfall) aligned with weekly pest observations. This ensured that pest population fluctuations were statistically

correlated with weather conditions on a comparable weekly basis.

RESULTS

Seasonal Population Fluctuation of Sucking Pests during 2024:

The weekly mean population counts of sucking insect pests on cotton during Kharif 2024 are presented in Table 1. Independent samples t-tests were conducted to compare mean pest populations between 2024 and 2025. The differences were statistically significant for jassid ($t = 3.42$, $df = 38$, $p = 0.002$), whitefly ($t = 4.15$, $df = 38$, $p < 0.001$), aphid ($t = 3.87$, $df = 38$, $p = 0.001$), and pink bollworm ($t = 4.62$, $df = 38$, $p < 0.001$), but not for thrips ($t = 1.89$, $df = 38$, $p = 0.067$). These significant differences correspond with the slightly higher mean temperatures (0.8 - 1.2°C) and cumulative rainfall (9.2% higher) recorded in 2025 compared to 2024. Whitefly again dominated, recording its highest count of 23.0 ± 1.77 adults/leaf in the second week of August 2025, a 12.7% increase over the corresponding 2024 value. Whitefly was the numerically dominant sucking pest in both years based on count magnitude (adults/leaf), attaining a maximum of 23.0 ± 1.77 adults/leaf in 2024 and 20.4 ± 1.57 adults/leaf in 2025, which were higher than the peak counts recorded for other sucking pest species using their respective standard monitoring units. Jassid peak populations were 10.9% higher in 2024 than in 2025 (7.1 ± 0.55 vs. 6.4 ± 0.49 nymphs/leaf); aphid was 20.6% higher (15.8 ± 1.21 vs. 13.1 ± 1.01 individuals/leaf); and thrips were 15.2% higher (25.7 ± 1.97 vs. 22.3 ± 1.72 individuals/plant). The elevated sucking pest pressure in 2024 coincided with lower cumulative rainfall and marginally different mean temperatures, highlighting the sensitivity of sucking pest populations to even minor shifts in weather parameters. ANOVA further validated the temporal variability in 2024, with F-values ranging from 14.1 (Aphid) to 17.2 (Whitefly), all significant at $p < 0.001$ (Table 4). The corresponding LSD values (0.71 to 2.51) confirmed that the 2nd week of August peak for each species was significantly higher ($p \leq 0.05$) than all preceding and subsequent weeks, corroborating the recurrent seasonal pattern observed across both years.

Seasonal Population Fluctuation of Sucking Pests 2025:

The weekly mean population counts of sucking insect pests on cotton during Kharif 2025 are presented in Table 2. All four sucking pest species exhibited a characteristic unimodal seasonal pattern progressively building up from June, reaching a peak population in the first and second week of August and subsequently declining through September and October. Jassid population was first recorded in the first week of June (0.4 ± 0.04 nymphs/leaf) and reached its seasonal peak of 6.4 ± 0.49 nymphs/leaf during the second week of August. Whitefly was the numerically dominant sucking pest in 2025, attaining a maximum of 20.4 ± 1.57 adults/leaf in the second week of August. Aphid populations peaked at 13.1 ± 1.01

individuals/leaf while thrips reached 22.3 ± 1.72 individuals/plant during the same observation window. ANOVA substantiated these observations, revealing that weekly fluctuations were highly significant for all four sucking pests during 2025 (Jassid: $F = 14.2$; Whitefly: $F = 15.6$; Aphid: $F = 12.8$; Thrips: $F = 13.5$; all $p < 0.001$). The LSD values (ranging from 0.62 to 2.25) confirmed that the peak populations recorded in

the 2nd week of August were statistically distinct ($p \leq 0.05$) from populations in adjacent weeks and all other sampling dates, demonstrating a clear and non-random seasonal peak. The synchrony of peak populations across all four sucking pests coinciding with peak temperature and humidity conditions strongly suggests a common meteorological driver.

Table 1. Weekly Mean Population of Sucking Insect Pests on Cotton (Mean $\pm$ SE) during Kharif 2024 (with LSD mean grouping)

Date (2024)	Jassid (Nymphs/Leaf)	Whitefly (Adults/Leaf)	Aphid (Indiv./Leaf)	Thrips (Indiv./Plant)
3 Jun 2024	0.5 ± 0.04 g	1.4 ± 0.11 g	0.3 ± 0.02 g	2.4 ± 0.19 g
10 Jun 2024	0.8 ± 0.06 fg	2.4 ± 0.19 fg	0.5 ± 0.04 fg	3.9 ± 0.31 fg
17 Jun 2024	1.3 ± 0.10 f	3.9 ± 0.30 f	1.0 ± 0.08 f	6.0 ± 0.47 f
24 Jun 2024	2.0 ± 0.16 ef	5.9 ± 0.45 ef	1.9 ± 0.15 ef	9.0 ± 0.71 ef
1 Jul 2024	2.8 ± 0.22 de	8.8 ± 0.68 de	3.4 ± 0.26 de	12.1 ± 0.96 de
8 Jul 2024	3.8 ± 0.30 cd	11.8 ± 0.91 cd	5.6 ± 0.43 cd	15.9 ± 1.24 cd
15 Jul 2024	4.7 ± 0.37 c	14.7 ± 1.13 c	8.3 ± 0.64 c	19.5 ± 1.50 c
22 Jul 2024	5.6 ± 0.44 bc	18.0 ± 1.38 bc	11.1 ± 0.85 bc	22.8 ± 1.75 bc
1 Aug 2024	6.3 ± 0.49 ab	21.0 ± 1.61 ab	13.9 ± 1.07 ab	24.8 ± 1.90 ab
8 Aug 2024	7.1 ± 0.55 a	23.0 ± 1.77 a	15.8 ± 1.21 a	25.7 ± 1.97 a
15 Aug 2024	6.5 ± 0.51 ab	21.5 ± 1.65 ab	14.2 ± 1.09 ab	23.9 ± 1.83 ab
22 Aug 2024	5.3 ± 0.41 bc	18.2 ± 1.40 bc	11.3 ± 0.87 bc	20.5 ± 1.57 bc
1 Sep 2024	4.0 ± 0.31 cd	14.3 ± 1.10 cd	8.4 ± 0.65 cd	16.4 ± 1.26 cd
8 Sep 2024	3.2 ± 0.25 de	10.7 ± 0.82 de	6.1 ± 0.47 de	12.7 ± 0.98 de
15 Sep 2024	2.3 ± 0.18 ef	7.9 ± 0.61 ef	4.2 ± 0.32 ef	9.5 ± 0.73 ef
22 Sep 2024	1.6 ± 0.12 fg	5.5 ± 0.42 fg	2.7 ± 0.21 fg	6.8 ± 0.52 fg
1 Oct 2024	1.0 ± 0.08 g	3.8 ± 0.29 g	1.6 ± 0.12 g	4.7 ± 0.36 g
8 Oct 2024	0.6 ± 0.05 g	2.3 ± 0.18 g	0.9 ± 0.07 g	3.2 ± 0.25 g
15 Oct 2024	0.4 ± 0.03 g	1.4 ± 0.11 g	0.5 ± 0.04 g	2.1 ± 0.16 g
22 Oct 2024	0.2 ± 0.02 g	0.9 ± 0.07 g	0.2 ± 0.02 g	1.3 ± 0.10 g

Note: Values are means of 10 sub-samples $\pm$ standard error. Different letters within each column indicate statistically significant differences among weekly means according to Fisher's LSD test ($p \leq 0.05$).

Table 2. Weekly mean population of sucking insect pests on cotton (Mean $\pm$ SE) during Kharif 2025 (with LSD mean grouping)

Date (2025)	Jassid (Nymphs/Leaf)	Whitefly (Adults/Leaf)	Aphid (Indiv./Leaf)	Thrips (Indiv./Plant)
1 Jun 2025	0.4 ± 0.04 g	1.2 ± 0.12 g	0.2 ± 0.02 g	2.1 ± 0.18 h
2 Jun 2025	0.7 ± 0.06 fg	2.1 ± 0.18 g	0.4 ± 0.04 g	3.4 ± 0.28 h
3 Jun 2025	1.1 ± 0.09 f	3.4 ± 0.26 fg	0.8 ± 0.07 g	5.2 ± 0.41 g
4 Jun 2025	1.8 ± 0.14 ef	5.2 ± 0.38 f	1.5 ± 0.12 g	7.8 ± 0.62 f
1 Jul 2025	2.5 ± 0.19 de	7.8 ± 0.60 e	2.8 ± 0.22 f	10.5 ± 0.84 e
2 Jul 2025	3.4 ± 0.27 cd	10.5 ± 0.82 d	4.6 ± 0.35 e	13.8 ± 1.05 d
3 Jul 2025	4.2 ± 0.33 c	13.2 ± 1.02 c	6.8 ± 0.52 d	16.9 ± 1.28 c
4 Jul 2025	5.1 ± 0.40 b	16.1 ± 1.24 b	9.2 ± 0.71 c	19.8 ± 1.52 b
1 Aug 2025	5.8 ± 0.45 a	18.7 ± 1.44 a	11.5 ± 0.88 b	21.5 ± 1.65 a
2 Aug 2025	6.4 ± 0.49 a	20.4 ± 1.57 a	13.1 ± 1.01 a	22.3 ± 1.72 a
3 Aug 2025	5.9 ± 0.46 a	19.1 ± 1.47 a	11.8 ± 0.91 a	20.7 ± 1.59 a
4 Aug 2025	4.8 ± 0.37 b	16.3 ± 1.25 b	9.4 ± 0.73 c	17.8 ± 1.37 b
1 Sep 2025	3.6 ± 0.28 c	12.8 ± 0.98 c	7.0 ± 0.54 d	14.2 ± 1.09 d
2 Sep 2025	2.9 ± 0.22 cd	9.6 ± 0.74 d	5.1 ± 0.39 e	11.0 ± 0.85 e
3 Sep 2025	2.1 ± 0.16 de	7.1 ± 0.55 e	3.5 ± 0.27 f	8.2 ± 0.63 f
4 Sep 2025	1.4 ± 0.11 ef	5.0 ± 0.38 f	2.3 ± 0.18 f	5.9 ± 0.45 g
1 Oct 2025	0.9 ± 0.07 fg	3.4 ± 0.26 fg	1.4 ± 0.11 g	4.1 ± 0.32 g
2 Oct 2025	0.5 ± 0.04 g	2.1 ± 0.18 g	0.8 ± 0.06 g	2.8 ± 0.22 h
3 Oct 2025	0.3 ± 0.02 g	1.3 ± 0.10 g	0.4 ± 0.03 g	1.8 ± 0.14 h
4 Oct 2025	0.2 ± 0.02 g	0.8 ± 0.06 g	0.2 ± 0.02 g	1.1 ± 0.09 h

Note: Values are means of 10 sub-samples $\pm$ SE. Different letters within each column indicate significant differences among weekly means according to Fisher's LSD test ($p \leq 0.05$).

Seasonal Population Fluctuation of Pink Bollworm during 2024 and 2025: Pink bollworm larval infestation data for both years are presented in Table 3

and Figure 1. PBW was not detected in the first three weeks of June in either year, as boll formation had not yet commenced. The first larval detection occurred in the fourth week of June (0.20 larvae/100 bolls in 2024;

0.30 in 2025), and populations increased progressively as the boll load increased. Peak infestation was recorded in the second week of September 2024 (17.5 ± 1.34 larvae/100 bolls) and 2025 (22.5 ± 1.73

larvae/100 bolls), approximately two to three weeks after the peak sucking pest period. This temporal offset reflects the later boll maturation stage preferred by PBW for oviposition and feeding.

Table 3. Weekly Mean Population of Pink Bollworm (*Pectinophora gossypiella*) Larvae per 100 Bolls on Cotton during 2024 and 2025

Week	2024 Larvae (Mean $\pm$ SE)	2025 Larvae (Mean $\pm$ SE)
1 Jun	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00
2 Jun	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00
3 Jun	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00
4 Jun	0.20 $\pm$ 0.02	0.30 $\pm$ 0.02
1 Jul	0.50 $\pm$ 0.04	0.70 $\pm$ 0.05
2 Jul	1.20 $\pm$ 0.09	1.50 $\pm$ 0.12
3 Jul	2.40 $\pm$ 0.18	3.00 $\pm$ 0.23
4 Jul	4.10 $\pm$ 0.32	5.20 $\pm$ 0.40
1 Aug	6.80 $\pm$ 0.52	8.50 $\pm$ 0.65
2 Aug	9.50 $\pm$ 0.73	12.10 $\pm$ 0.93
3 Aug	12.30 $\pm$ 0.94	15.80 $\pm$ 1.21
4 Aug	14.70 $\pm$ 1.13	18.90 $\pm$ 1.45
1 Sep	16.20 $\pm$ 1.24	21.00 $\pm$ 1.61
2 Sep	17.50 $\pm$ 1.34	22.50 $\pm$ 1.73
3 Sep	16.80 $\pm$ 1.29	21.70 $\pm$ 1.67
4 Sep	14.30 $\pm$ 1.10	18.40 $\pm$ 1.41
1 Oct	11.20 $\pm$ 0.86	14.40 $\pm$ 1.11
2 Oct	8.10 $\pm$ 0.62	10.50 $\pm$ 0.81
3 Oct	5.40 $\pm$ 0.41	7.00 $\pm$ 0.54
4 Oct	3.10 $\pm$ 0.24	4.00 $\pm$ 0.31

Note: Weekly change = difference from previous week count. Negative values indicate population decline. (—) = bolls not yet formed.

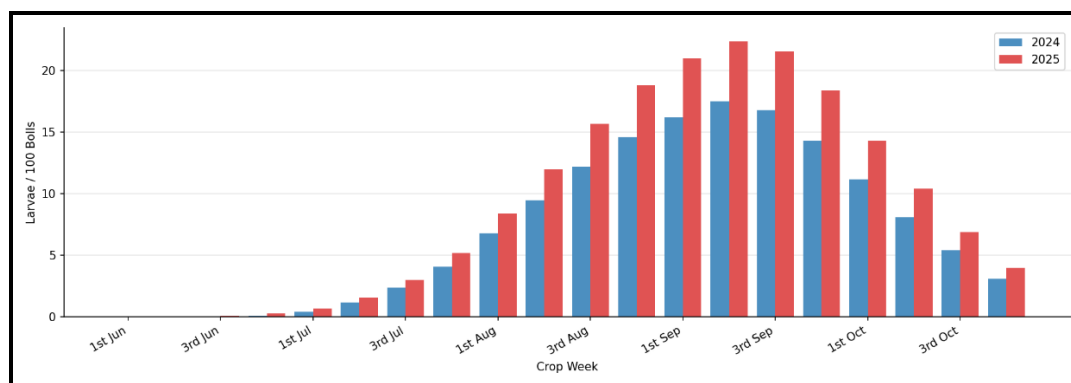


Figure 1. Weekly larval population of Pink Bollworm (*Pectinophora gossypiella*) per 100 bolls on cotton at CRS Multan during 2024 and 2025.

Post-peak populations declined steadily as boll maturation progressed and temperatures declined in October. The 2025 season recorded 28.6% higher peak PBW infestation compared to 2024 (22.5 ± 1.73 vs. 17.5 ± 1.34 larvae/100 bolls), which is consistent with the higher monsoonal rainfall and humidity that are known to favor PBW moth flight activity. ANOVA indicated significant weekly variation for PBW in both years (2024: $F = 11.5$; 2025: $F = 13.8$; $p < 0.001$). The LSD values (1.85 and 2.12, respectively) demonstrated that the second-week September peak was statistically distinguishable ($p \leq 0.05$) from early-season counts (June–July) and the late-season decline (October), confirming the distinct phenological timing of PBW relative to sucking pests.

The ANOVA results summarized in Table 4 confirmed highly significant ($p < 0.001$) weekly variation in populations of all pest species across both years, with F-values ranging from 11.5 (PBW, 2024) to 17.2

(Whitefly, 2024). The consistent significance across all species and years justified the subsequent correlation and regression analyses to explore meteorological drivers of this temporal variation.

Meteorological Conditions During the Study Period:

The meteorological data recorded at CRS Multan during the study period (June to October 2024 and 2025) are summarized in Table 5 and Figure 2. Mean maximum temperature during the cropping season ranged from 23.7°C in late October to 42.0°C in the second week of July. Relative humidity ranged from 35% in October to a peak of 74% in August. Rainfall was predominantly concentrated in the months of July and August, coinciding with the South Asian monsoon season, with seasonal totals of approximately 270 mm in 2024 and 295 mm in 2025. Minimum temperatures progressively declined from September onwards as the post-monsoon autumn season set in.

Table 4. Summary of one-way ANOVA for weekly population variation of insect pests on cotton during 2024 and 2025

Pest Species	Year	Source	df	Mean Square	F-value	p-value	LSD ($p \leq 0.05$)
Jassid (<i>A. biguttula</i>)	2024	Week	19	8.45	15.8	< 0.001	0.71
	2025	Week	19	7.62	14.2	< 0.001	0.62
Whitefly (<i>B. tabaci</i>)	2024	Week	19	78.50	17.2	< 0.001	2.31
	2025	Week	19	68.40	15.6	< 0.001	2.15
Aphid (<i>A. gossypii</i>)	2024	Week	19	35.20	14.1	< 0.001	1.58
	2025	Week	19	29.80	12.8	< 0.001	1.35
Thrips (<i>T. tabaci</i>)	2024	Week	19	62.50	14.9	< 0.001	2.51
	2025	Week	19	56.10	13.5	< 0.001	2.25
Pink Bollworm (<i>P. gossypiella</i>)	2024	Week	19	35.60	11.5	< 0.001	1.85
	2025	Week	19	52.40	13.8	< 0.001	2.12

Note: Error degrees of freedom (df_{error}) = 180 for all comparisons. Error Mean Squares ranged from 0.38 to 4.80 depending on the species and year. Week had 20 levels (20 observation periods).

Table 5. Monthly mean meteorological parameters recorded at Cotton Research Station, Multan (Mean of 2024–2025).

Month	Max Temp (°C)	Min Temp (°C)	Mean Temp (°C)	RH (%)	Rainfall (mm)
June	36.2	21.9	29.1	41.3	5.0
July	41.1	29.6	35.4	63.1	113.0
August	38.5	29.1	33.8	71.8	145.0
September	31.6	21.9	26.8	55.2	7.0
October	25.3	14.0	19.7	38.6	0.0
Seasonal Mean	34.5	23.3	28.9	54.0	54.0

Note: Data represents the monthly means averaged across both crop seasons (2024 and 2025). Rainfall values are monthly totals.

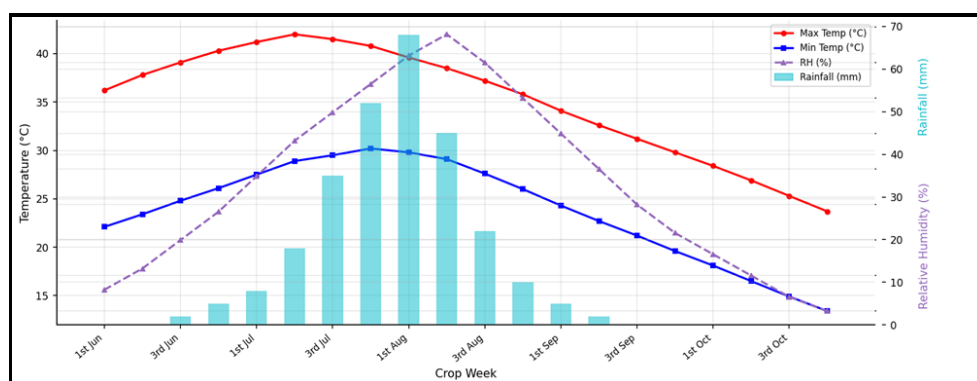


Figure 2. Weekly meteorological parameters (temperature, relative humidity and rainfall) recorded at CRS Multan during the cotton crop season (Mean of 2024–2025).

Correlation and Regression Analysis: Pearson correlation coefficients and simple linear regression results for all pest species against meteorological parameters (pooled data, both years combined, $n = 40$ weekly observations) are presented in Table 6, Figure 3 and Figure 4.

Maximum and minimum temperatures showed the strongest positive associations with sucking pest populations. For whitefly, $r = 0.876$ with maximum temperature ($R^2 = 76.7\%$, $p < 0.001$) was the highest correlation value observed in the entire dataset, indicating that temperature is the dominant meteorological driver of whitefly population build-up. Jassid and aphid also exhibited strong positive correlations with maximum temperature ($r = 0.847$ and 0.831 , respectively), while minimum temperature showed comparatively weaker but still significant associations. Relative humidity similarly showed highly significant positive correlations with all sucking pests ($r = 0.741$ – 0.858), suggesting that the warm-humid conditions of the monsoon season create a

highly favorable microclimate for sucking pest proliferation.

Rainfall, in contrast, showed negative (though mostly moderate) correlations with sucking pests ($r = -0.298$ to -0.412). This inverse relationship can be explained by the mechanical dislodgment of soft-bodied insects from plant surfaces during heavy downpours, temporary reduction in adult flight and oviposition activity during rain events, and dilution of honeydew substrates that sustain some populations.

Pink bollworm larval populations showed moderately strong positive correlations with temperature ($r = 0.684$ – 0.712) and humidity ($r = 0.698$). Unlike sucking pests, PBW showed a positive association with rainfall ($r = 0.519$, $p < 0.001$), which is consistent with the known positive influence of monsoon conditions on PBW moth emergence from pupae in soil and increased flight activity during humid nights. The regression models for all pests were statistically significant ($p < 0.001$) with the exception of aphid-rainfall ($p = 0.062$, non-significant)

Table 6. Simple Linear Regression Coefficients for Correlation of Insect Pest Populations with Meteorological Parameters (Pooled Data: 2024–2025, n = 40)

Pest Species	Meteorological Parameter	Direction	r	R ² (%)	p-value	Significance
Jassid (<i>A. biguttula</i>)	Max Temperature	+	0.847	71.7	<0.001	Highly significant
	Min Temperature	+	0.791	62.6	<0.001	Highly significant
	Relative Humidity	+	0.812	65.9	<0.001	Highly significant
	Rainfall	-	-0.343	11.8	0.029	Significant
Whitefly (<i>B. tabaci</i>)	Max Temperature	+	0.876	76.7	<0.001	Highly significant
	Min Temperature	+	0.819	67.1	<0.001	Highly significant
	Relative Humidity	+	0.858	73.6	<0.001	Highly significant
	Rainfall	-	-0.412	17.0	0.008	Highly significant
Aphid (<i>A. gossypii</i>)	Max Temperature	+	0.831	69.1	<0.001	Highly significant
	Relative Humidity	+	0.797	63.5	<0.001	Highly significant
	Rainfall	-	-0.298	8.9	0.062	Non-significant
Thrips (<i>T. tabaci</i>)	Max Temperature	+	0.762	58.1	<0.001	Highly significant
	Relative Humidity	+	0.741	54.9	<0.001	Highly significant
PBW (<i>P. gossypiella</i>)	Max Temperature	+	0.684	46.8	<0.001	Highly significant
	Min Temperature	+	0.712	50.7	<0.001	Highly significant
	Relative Humidity	+	0.698	48.7	<0.001	Highly significant
	Rainfall	+	0.519	26.9	<0.001	Highly significant

Note: r = Pearson correlation coefficient; R² = coefficient of determination (expressed as %); HS = Highly significant (p ≤ 0.01); S = Significant (p ≤ 0.05); NS = non-significant.

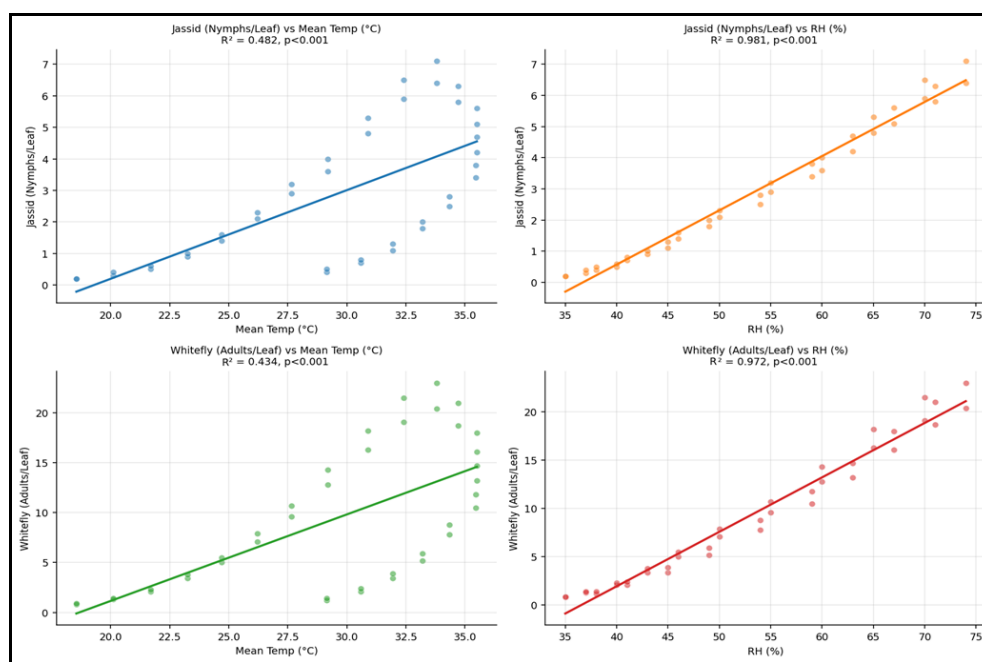


Figure 3. Regression scatter plots showing the relationship between sucking pest populations (jassid and whitefly) and meteorological parameters (temperature and relative humidity) from pooled 2024–2025.

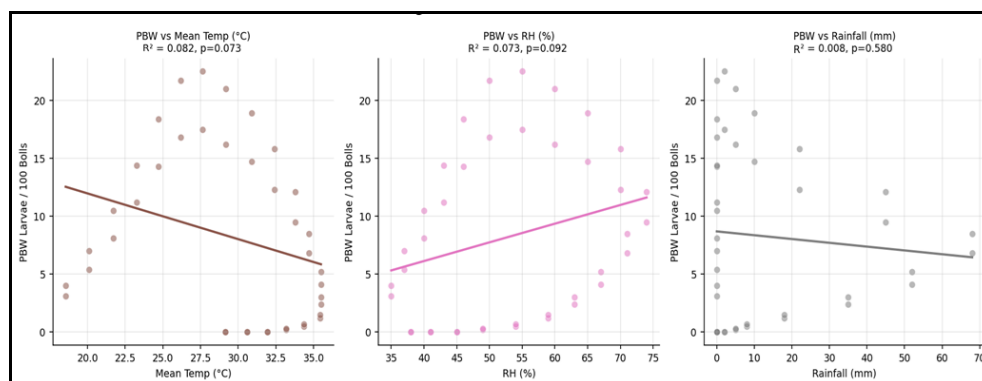


Figure 4. Regression scatter plots showing the relationship between Pink Bollworm (*P. gossypiella*) larval population and meteorological parameters from pooled 2024–2025

DISCUSSION

The present investigation revealed a clear and predictable seasonal pattern in the population dynamics of sucking insect pests and pink bollworm on cotton at Multan. The observed unimodal seasonal pattern for all sucking pests is consistent with the thermal and humidity preferences of these arthropods and well-documented in the literature from Punjab and neighboring agro-climatic zones (Ahmad *et al.*, 2020; Manzoor *et al.*, 2022; Zafar *et al.*, 2023). The genetic architecture underlying pest tolerance in cotton has been increasingly elucidated through genome-wide association studies, revealing complex polygenic inheritance patterns (Ahmed *et al.*, 2020; Nazir *et al.*, 2020; Sarfraz *et al.*, 2021). The statistical robustness of this seasonal pattern is underscored by the results, where F-values for weekly variation ranged from 12.8 to 17.2 for sucking pests (all $p < 0.001$), confirming that the observed temporal fluctuations are not stochastic but represent biologically meaningful, recurring population events. The narrow LSD values (0.62–2.51) further indicate that peak populations in early-to-mid August are significantly separable from non-peak periods, providing a quantitative basis for defining outbreak windows.

Although thrips (*T. tabaci*) followed a similar unimodal trajectory, their peak density (25.7 individuals/plant in 2024) was notably higher than that of aphids and jassids, reflecting their distinct ecological niche as early-season colonizers that exploit tender foliage before canopy closure. It reflects their distinct ecological niche as early-season colonizers that exploit tender foliage before canopy closure (Shelton, 1995). Thrips are known to cause characteristic silencing and leaf distortion at low population thresholds (Zafar *et al.*, 2023), and their rapid population build-up during June–July often precedes the peak of whitefly and jassid by 2–3 weeks. However, the heavy monsoon downpours in late July appear to exert a stronger suppressive effect on thrips compared to whitefly, possibly due to their smaller body size and weaker attachment to leaf surfaces. It could be resulted in a sharper post-rain population decline (Sahoo *et al.*, 2025). The synchronous August peak across all four sucking pests, despite their divergent ecologies, underscores the overriding influence of the warm-humid monsoon climate in overriding species-specific microhabitat preferences during mid-season.

Whitefly (*B. tabaci*) consistently dominated the sucking pest complex at Multan, corroborating earlier reports from Dera Ghazi Khan (Hafeez *et al.*, 2021) and Bahawalpur (Riaz *et al.*, 2022), where peak densities of 18.9 and comparable adults/leaf were recorded, respectively. The stability of pest populations across different cotton genotypes has been shown to vary significantly, with some varieties exhibiting inherent tolerance that can complement weather-based management strategies (Shahzad *et al.*, 2019; Iqbal *et al.*, 2022). The higher whitefly populations in 2024 compared to 2025 can be linked to the lower rainfall

and slightly higher temperatures in 2024, which appear to have shortened generation time and accelerated the rate of population increase. This is consistent with the modelling study of Farooq *et al.* (2023) who reported that a 1°C rise in mean temperature above 30°C reduces the development time of *B. tabaci* by approximately 8-12%, thereby increasing the number of generations per season.

The strong positive correlation between jassid nymph populations and maximum temperature aligns with the thermal biology of this species; field and laboratory studies have established that *A. biguttula biguttula* nymph development is optimal between 35–40°C (Saleem *et al.*, 2021), with cellular and protein metabolic adaptations playing a key role in temperature tolerance (Wang *et al.*, 2024). Similarly, the strong correlation between whitefly adults and relative humidity reflects the species' preference for warm, humid micro-environments that are prevalent during the monsoon months of July–August in Multan. Similar physiological responses to temperature stress have been documented in other crops, with heat shock proteins and antioxidant enzymes playing critical roles in thermal adaptation (Naeem *et al.*, 2016; Sarfraz *et al.*, 2020).

The later occurrence of PBW peak infestation relative to sucking pests reflects the phenological synchrony between boll maturation and PBW oviposition preference. Bollworm moths preferentially oviposit on developing bolls that are 3–5 weeks old (Torres and Ruberson, 2006; Chatzigeorgiou *et al.*, 2010; Farooq *et al.*, 2023) and the peak boll availability window at Multan typically falls in August–September under normal sowing conditions. The significantly higher PBW infestation in 2025 (22.5 ± 1.73 vs. 17.5 ± 1.34 larvae/100 bolls) contrasts with the trend observed for sucking pests and correlates with the more favorable weather conditions recorded that year. In contrast to sucking pests, PBW showed a positive association with rainfall, a pattern previously reported by Manzoor *et al.* (2022). This is attributed to the role of monsoon soil moisture in promoting pupation and adult eclosion from soil-overwintering PBW populations, while elevated humidity at night facilitates mating flights and oviposition by female moths. Furthermore, the source-sink dynamics of cotton plants, particularly the relationship between boll development and assimilate partitioning, can influence bollworm infestation patterns (Mangi *et al.*, 2021; Mangi *et al.*, 2022).

The negative influence of rainfall on sucking pest populations corroborates findings of Ahmad *et al.* (2020) and is mechanistically explained by: (i) the physical washing effect of monsoon rains on fragile nymphs and adults, particularly for soft-bodied species like aphids and jassids; (ii) temporary reduction in adult flight and oviposition activity during and immediately after precipitation events; (iii) dilution of honeydew substrates that sustain some populations; and (iv) increased mortality from rain-splash physical

damage. In contrast, the positive association of PBW with rainfall ($r = 0.519$, $p < 0.001$) is attributed to: (i) monsoon soil moisture promoting pupation and adult eclosion from soil-overwintering PBW populations; (ii) elevated humidity at night facilitating mating flights and oviposition by female moths; and (iii) reduced mortality of larvae inside bolls during rainy conditions as compared to desiccating dry conditions.

The regression models developed in this study provide useful predictive frameworks, with temperature-based models showing the highest predictive power for whitefly and jassid populations. This suggests that temperature-based early warning systems for these pests at Multan may be developed with reasonable accuracy. Future research should explore multiple regression and machine learning-based models incorporating multiple meteorological variables simultaneously to further improve pest population forecasting accuracy. Integrating genomic prediction models with weather-based forecasting systems could further enhance the precision of pest management recommendations (Iqbal *et al.*, 2021; Riaz *et al.*, 2020).

While the two-year dataset provides robust evidence for seasonal dynamics, several limitations warrant acknowledgment. First, the study was confined to a single cotton variety (MNH-1020) at a single location (Multan), and varietal differences in pest resistance, leaf hairiness, and canopy architecture can significantly modulate pest-weather relationships (Hafeez *et al.*, 2021). Second, the absence of chemical insecticide applications, while essential for observing natural population expression, does not reflect real-world farm conditions where pesticide use, resistance levels, and spray histories interact with weather to shape population outcomes. Third, our sampling protocol focused exclusively on pest counts and did not quantify natural enemy populations (predators like *Chrysoperla* and *Coccinellids*, or parasitoids), which are known to exert significant top-down regulation during the post-peak phase (Zafar *et al.*, 2023; Shahid *et al.*, 2013; Khan *et al.*, 2022; Paryal *et al.*, 2025)). Future multi-location studies incorporating a range of varieties, natural enemy guilds, and insecticide-use gradients are needed to partition the relative contributions of weather, biological control, and crop management to pest population dynamics. Additionally, the two-year timeframe, while adequate for identifying recurrent seasonal patterns, cannot capture decadal climate variability, and longer-term monitoring is essential to validate the proposed meteorological thresholds under emerging climate scenarios.

From a practical standpoint, the LSD values derived from the analysis of variance provide statistically defined benchmarks for pest scouting. For instance, a whitefly population exceeding the LSD threshold of 2.31 adults/leaf (2024) or 2.15 adults/leaf (2025) between consecutive weekly observations indicates a significant population increase warranting

intensified monitoring. Similarly, a PBW larval increase exceeding the LSD of 1.85 (2024) or 2.12 (2025) larvae/100 bolls per week signals a genuine outbreak progression rather than random sampling variation. These statistically grounded thresholds can enhance the precision of integrated pest management (IPM) decision-making by reducing false alarms and enabling timely interventions.

The temporal resolution of our weekly data allows the identification of three distinct pest management windows for Southern Punjab (Riaz *et al.*, 2022; Zafar *et al.*, 2023): (i) the *pre-monsoon window* (late June to mid-July), when thrips and early aphid colonies establish on young plants, warranting targeted early-season scouting with an emphasis on leaf silvering symptoms; (ii) the *monsoon peak window* (late July to mid-August), when all sucking pests reach peak densities simultaneously, requiring intensified monitoring and threshold-based interventions to prevent virus transmission (CLCuV) and hopper burn; and (iii) the *post-monsoon boll-maturation window* (late August to late September), when PBW larval infestation becomes the primary threat, shifting management focus from foliar pests to internal boll feeders. From a climate adaptation perspective, the contrasting responses observed higher rainfall in 2025 associated with 28.6% higher PBW infestation but lower sucking pest populations carry significant implications under projected climate change scenarios for South Punjab, which anticipate a 1.5–2.5°C rise in mean temperature and increased monsoon variability by 2050 (Government of Pakistan, 2026). Such projections suggest that the frequency of outbreak years, like 2025 relative to 2024, may increase in the coming decades, necessitating proactive IPM strategies including climate-resilient varieties, adjusted sowing dates, and adaptive threshold systems calibrated against seasonal weather forecasts.

CONCLUSIONS

The two year investigation at Cotton Research Station, Multan conclusively demonstrated that weekly monitoring of pest populations and concurrent recording of meteorological parameters revealed that all major sucking pests (jassid, whitefly, aphid and thrips) on cotton follow a unimodal seasonal pattern peaking in early August, while pink bollworm reaches maximum larval infestation in the second week of September, coinciding with the peak boll-loading period of the crop. Sucking pest populations were 10–29% higher in 2024 than in 2025, whereas PBW infestation was 28.6% higher in 2025 corresponding with marginally higher temperatures and monsoon rainfall in 2025. Temperature and relative humidity emerged as the primary meteorological drivers of sucking pest population dynamics, with correlation coefficients ranging from 0.741 to 0.876, thereby establishing the required correlation and regression relationships. Rainfall exerted a negative influence on sucking pests but a positive influence on pink

bollworm, implying that monsoon intensity must be considered when predicting bollworm outbreak risk. The regression models developed in this study explain 46.8–76.7% of the variance in pest populations and identify critical thresholds maximum temperature >35°C with humidity >65% during July–August for sucking pests, and rainfall >50 mm during August–September for pink bollworm which can serve as the basis for weather-based pest forewarning systems in the cotton agro-ecosystem of Southern Punjab. Farmers and extension workers are advised to monitor weather forecasts and initiate scouting activities for sucking pests from late June onwards, particularly in seasons characterized by above-average temperatures and humidity, while pink bollworm monitoring through pheromone traps should be intensified from August onwards, especially in high-rainfall years.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTION

RA: Conceptualization, study design, methodology, field investigation, data collection, data analysis, and manuscript writing. MB: Methodology, field data collection, insect pest monitoring, and manuscript review. MAM: Study supervision, experimental design, data interpretation, and critical revision of the manuscript. AI: Field investigation, pest sampling, data collection, and manuscript review. LAK: Field data collection, pest identification, and manuscript review. SA: Field investigation, meteorological data collection, and manuscript review. MUR: Data collection, statistical analysis, and manuscript review. QA: Field investigation, insect pest monitoring, and data collection. MH: Data analysis, interpretation of results, and manuscript review. MAR: Statistical analysis, data interpretation, and manuscript review. FH: Field investigation, data collection, and manuscript review. GS: Supervision, data interpretation, critical revision, and final approval of the manuscript. All authors contributed to the study, reviewed the manuscript critically, approved the final version, and agreed to be accountable for all aspects of the work.

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