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Influence of weather parameters on cotton leaf curl disease development and white fly population dynamics in S. W. haryana

N. K. Yadav[1], Deepak Kumari[2] and Preeti Vashisht*[2]

[1]CCS HAU, Regional Research Station, Bawal, India
[2]CCSHAU, College of Agriculture, Bawal, India

ABSTRACT

Cotton leaf curl disease is a major devastating disease of cotton causing significant reduction in yield in the northern region of India where around 17.96 lakh hectare areas exists in the states of Punjab, Haryana and Rajasthan. Present study was under taken to evaluate the relationship between weather parameters and whitefly population in the CLCuD development of cotton under consideration in south west zone of Haryana over a period of four years i.e. Kharif, 2021 -2024. The maximum disease intensity was recorded as 33.62 % (45th SMW) in the year 2021 and the lowest (0.1%) during 30th SMW during all the years of experimentation. It was inferred that across all years, T_{max} and T_{min} exhibited consistently negative correlations with both CLCuD PDI and incidence, suggesting that lower temperatures favoured increased disease expression. Notably, T_{min} showed stronger negative correlations than T_{max}, indicating that cooler night temperatures play a critical role in promoting virus development. In contrast, morning relative humidity (RH_m) displayed a positive correlation with CLCuD severity and incidence supporting the notion that high morning humidity favours both whitefly activity and virus infection. Evening relative humidity (RH_e) showed weak and inconsistent correlations. Rainfall showed variable and generally weak correlations. Among all parameters, whitefly population consistently showed significant positive correlations with both PDI and disease incidence. This clearly highlights the central role of whitefly as the vector of cotton leaf curl virus (CLCuV). Furthermore, whitefly population was negatively correlated with T_{max} and evaporation and positively with RH_m indicating that cooler, more humid environments support vector proliferation and subsequent virus spread. The regression analysis clearly identifies low minimum temperature, high morning humidity, and increased sunshine hours as the most important weather parameters influencing CLCuD epidemics and vector build-up in cotton.The highest model fits were recorded for CLCuD PDI ($R^2 = 0.9238$) and incidence ($R^2 = 0.9143$), underscoring the reliability of these models for long-term disease forecasting.

Keywords: *CLCuD, correlation, devastating, exhibited, forecasting, influencing, proliferation, regression, whitefly.*

INTRODUCTION

Cotton is the most important fiber crop of Indian farming community and plays an important role in rural economy of India. Although cotton is primarily a fibre crop, it is also used as source of oil and its seed are utilized as feed for ruminant livestock (1). Cotton waste, trash and other residues can be converted into ethanol with no environmental pollution (2). Dried cotton sticks are an important source of fuel for domestic use. All four cultivable species viz., *Gossypium arboreum*, *G. herbaceum*, *G. barbadense* and *G. hirsutum* are grown in India, occupying largest area in the world (113.6 lakh ha). India is the second largest producer of cotton in the world accounting for about 20.7 per cent of the world cotton production. However, India ranked second with a production of 371 lakh bales but productivity is very low i.e., 448 kg/ha as compared to world average of 854 kg/ha during the year 2024-25 (3). Though occupying largest acreage in the world, the productivity of cotton is very low in India. Among the several reasons for low productivity of cotton; high incidence of insect pests and diseases caused by fungal, bacterial and viral pathogens are the major constraints. Among the diseases, Cotton leaf curl disease is one of the most serious diseases of cotton particularly in the northern region of India where around 17.96 lakh hectare areas exists in the states of Punjab, Haryana and Rajasthan. It is characterized by typical disease symptoms like vein thickening, stunted growth, leaf curling and leaf like enations on the underside leaf under extreme conditions (4). Cotton leaf curl disease (CLCuD) causing enormous loss to the crop (5,6). noted The loses in yield up to 54 per cent due to CLCuD was noted by Monga (7). Depending on the cultivars used, yield losses are 68-79 per cent posing serious threat to cotton production (8) and even up to 90 per cent in severe cases (9, 10). Cotton leaf curl virus belongs to the genus Begomovirus and is transmitted by its exclusive vector whitefly (*Bemisia tabaci* gem) in a circulative and persistent manner (11). Epidemiology is the study of the variable incidence of diseases in populations (12). The important populations are those of the host and the pathogen. Diseases are however not independent entities but the result of a complex interaction among host plants, pathogens and the environment. This is embodied in the basic concept of the disease triangle. As the same way of ecology, epidemiology includes the biotic environment (alternate sources of infection, vectors, and even the activity of man such as in pathogen dissemination) and the abiotic environment *i.e.* climate, soil nutrition, etc. (13, 14). Temporal and spatial variance of meteorological conditions can affect soil conditions, water availability, agricultural yields and susceptibility to pest and

*Corresponding Author: ***Preeti Vashisht***

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pathogen infestations. However, weather has a very crucial role in CLCuD spread and development and also affects vector whitefly. Therefore, the present study was conducted over a period of four years *i.e. Kharif,* 2021 -2024 to evaluate the relationship between weather parameters and whitefly population in the CLCuD development of cotton under consideration in south west zone of Haryana. The ultimate aim was to develop prediction equation with better accuracy and reliability for disease incidence through regression which ultimately can help the timely application of management decisions in the prevailing climatic conditions.

MATERIALS AND METHODS

Experiment details

The experiment was done from *Kharif*, 2021 to 2024 to investigate the effect of weather factors on the development of CLCuD at CCS HAU, Regional Research station, Bawal (Rewari) on susceptible cotton cultivar HS-6. Every year, the sowing was done by the dibbling method during first fortnight of May, at a depth of 4-5 cm keeping row to row and plant to plant spacing of 67.5 cm X 30 cm, respectively. To ensure an optimal plant population per plot, gap filling was carried out five days after germination. Additionally, thinning was performed after the first irrigation to maintain single plant per hill. The crop was raised by following standard package and practices as recommended by CCHSAU, Hisar for cotton crop (15).

Observations recorded

Percent disease intensity (%)

Percent disease intensity (PDI) was recorded with appearance of initial disease symptoms of CLCuD as per disease scale (0-6) proposed by AICCIP (2016) on weekly basis and PDI was calculated as per following formula:

$$PDI = \frac{\text{Total of all the numerical ratings of plants observed}}{\text{Total number of plants observed} \times \text{Maximum grading}} \times 100$$

Disease incidence (%)

The observations on disease progress were recorded at each standard meteorological week (SMW) from the initiation of disease symptoms. Disease incidence (%) was computed using the formula:

$$\text{Disease incidence (\%)} = \frac{\text{No. of diseased plants}}{\text{Total no. of plants examined}} \text{ X } 100$$

Whitefly population:

Whitefly population was noted by observing the number of whiteflies on lower, middle and upper leaves of five randomly selected cotton plants on weekly basis during early morning hours.

Meteorological data:

The meteorological data during the course of study were recorded and used to assess the impact of weather parameters on CLCuD development and whitefly population. The meteorological data were obtained from the meteorological laboratory of Regional Research Station, Bawal.

Statistical analysis

Data collected during the course of investigation was statistically analysed using standard procedures by software OPSTAT (Sheoran *et al.*, 1998), SPSSv23 (IBM Corp, 2015). Correlation among various parameters was found out by computing Karl Pearson coefficient of correlation. Step-wise regression analysis was performed and linear models were designed to quantify the effect exerted by weather factors on white rust disease development. OriginPro® graphing and R statistical analysis software (R Core Team, 2025) was used to prepare the correlograms.

Results

However, diseases are not independent entities; instead, they are the outcome of complex relationships between pathogens, plants, and the weather variables. Variability in weather conditions over time and space can impact various aspects of agricultural production, including soil health, water availability and vulnerability to infections by pathogens and insects. To understand the influence of weather conditions on CLCuD development in cotton, correlation coefficients were calculated between PDI (percent disease intensity and key weather parameters *i.e.* maximum temperature (T_{max}), minimum temperature (T_{min}), morning relative humidity (RH_m), evening relative humidity (RH_e), rainfall, sunshine, and evaporation across different *kharif* seasons of 2021 to 2024. A pooled analysis was also conducted to assess the overall trends. Maximum CLCuD incidence was recorded as 33.62%, 11.7%, 21.66% and 21.26% during *kharif,* 2021, 2022, 2023 and 2024 respectively in 45th SMW. Whereas, minimum CLCuD incidence was recorded as 1.2%, 0.67%, 0.56% and 0.46% during 2021, 2022, 2023 and 2024 respectively in 30th SMW. Maximum PDI of CLCuD was observed as 6.34, 2.3, 4.22 and 4.58 during *kharif,* 2021, 2022, 2023 and 2024 respectively in 45th SMW, whereas, the lowest PDI (0.1) was recorded in 30th SMW of all the year of Experimentation.

Influence of sowing dates on PDI, disease incidence and white fly population of CLCuD in cotton and its correlation with weather variables

To understand the influence of weather conditions on Cotton Leaf Curl disease (CLCuD) development in cotton, correlation coefficients were calculated between percent disease intensity (PDI), disease incidence and key weather parameters—maximum temperature (T_{max}), minimum temperature (T_{min}), morning relative humidity (RH_m), evening relative humidity (RH_e), rainfall, sunshine, evaporation and whitefly population—across different years from 2021 to 2024. A pooled analysis was also performed to assess overall trends and the findings are summarized in Table 1, Fig 1-5. It was inferred that across all years, T_{max} and T_{min} exhibited consistently negative correlations with both CLCuD PDI and incidence, suggesting that lower temperatures favoured increased disease expression. Notably, T_{min} showed stronger negative correlations than T_{max}, particularly during the year 2022 (r = –0.765**) and in pooled data (r = -0.802** for PDI), indicating that cooler night temperatures play a critical role in promoting virus development. In contrast, morning relative humidity (RH_m) displayed a positive correlation with CLCuD severity and incidence. The highest correlation was observed in pooled data (r = 0.489** for incidence), supporting the notion that high morning humidity favours both whitefly activity and virus infection. Evening relative humidity (RH_e) showed weak and inconsistent correlations, suggesting a less direct influence. Rainfall showed variable and generally weak correlations, with some negative associations noted in 2023 and 2024. These findings suggest that rainfall may play an indirect role, potentially influencing whitefly dynamics or plant susceptibility, rather than directly affecting disease development.

Among all parameters, whitefly population consistently showed significant positive correlations with both PDI and disease incidence across all seasons, with the strongest association in the year, 2024 (r = 0.868** for incidence). This clearly highlights the central role of whitefly as the vector of cotton leaf curl virus (CLCuV). Furthermore, whitefly population was negatively correlated with T_{max} and evaporation (r = -0.673** and –0.601**, respectively) and positively with RH_m (r = 0.604), indicating that cooler, more humid environments support vector proliferation and subsequent virus spread. The pooled correlation analysis confirmed that low temperature, high morning humidity and high whitefly population are the most critical drivers of CLCuD epidemics under cotton-growing conditions. Thus, these results underscore the importance of adjusting sowing windows and monitoring whitefly populations in relation to local weather patterns to mitigate CLCuD outbreaks in cotton. These results are in line with the findings of Monga who analyzed data from 1999–2009 (27^{th}–37^{th} SMWs), found the highest disease incidence (98%) in 2001 and lowest (2.7%) in 2008 (16). Peak whitefly populations aligned with high disease years, with weather parameters significantly influencing both disease progression and vector abundance. Similarly, negative correlations between disease intensity and several parameters including temperature, wind speed, vapour pressure, and evapotranspiration (17). In contrast, morning relative humidity, cumulative rainfall, and solar radiation had positive correlations. The optimum temperature range for disease development at Hisar was 33-37 °C, with rainfall above 100 mm sharply accelerating disease progression. A negative correlation between CLCuD severity and maximum/minimum temperature, rainfall, and wind speed was reported, while relative humidity showed a positive association across sowing times (18). Disease development was favoured in the first sowing at 35-38 °C (max temp), 23-24 °C (min temp), 65-75% RH, and 1-2 mm rainfall. Similar trends were observed in the second sowing under slightly lower temperatures and higher humidity. The impact of weather on CLCuD using correlation and regression analysis was demonstrated, showing that temperature had a negative, and relative humidity a positive effect on disease and vector dynamics (19).

Table 1: Correlation matrix of CLCuD and white fly population in cotton with weather parameters

Year		Weather parameters							
		T_{max} (ºC)	T_{min} (ºC)	RH_m (%)	RH_e (%)	Rainfall (mm)	Sunshine	Evaporation	White fly/ 3 leaves
Kharif, 2021	CLCuD PDI	-0.679**	-0.646*	0.560**	0.219	-0.155	-0.096	-0.676**	0.483*
	CLCuD Incidence	-0.685**	-0.608*	0.585**	0.267	-0.123	-0.132	0.703**	0.496*
	White fly/3 leaves	-0.342	-0.018	0.495**	0.525**	0.182	-0.361	-0.501**	-
Kharif, 2022	CLCuD PDI	-0.511**	-0.765**	0.352	-0.008	-0.013	0.237	-0.590**	0.220
	CLCuD Incidence	-0.564**	-0.692**	0.414*	0.074	-0.052	0.226	-0.627**	0.379*
	White fly/3 leaves	-0.478*	0.118	0.555**	0.569**	0.107	-0.189	-0.439*	-
Kharif, 2023	CLCuD PDI	-0.314*	-0.667**	0.203	-0.342	-0.397*	0.100	0.073	0.284
	CLCuD Incidence	-0.282	-0.624**	0.196	-0.328	-0.416*	0.115	0.056	0.339
	White fly/3 leaves	0.000	0.277	0.200	0.185	-0.107	-0.020	-0.172	-
Kharif, 2024	CLCuD PDI	-0.285	0.828**	0.366	-0.226	-0.325	0.098	-0.469*	0.838**
	CLCuD Incidence	-0.363	-0.785**	0.436	-0.123	-0.277	0.039	-0.523**	0.868**
	White fly/3 leaves	-0.439*	-0.692**	0.498**	0.043	-0.112	-0.063	-0.586**	-
Pooled	CLCuD PDI	-0.615**	-0.802**	0.445*	-0.095	-0.372	0.082	-0.498**	0.652**
	CLCuD Incidence	-0.644**	-0.738**	0.489**	-0.019	-0.345	0.048	-0.541**	0.714**
	White fly/3 leaves	-0.673**	-0.260	0.604	0.393*	-0.024	-0.181	-0.601**	-

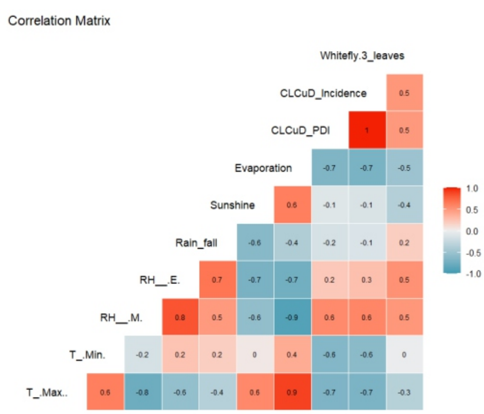

Fig 1. Correlation heatmap 2021

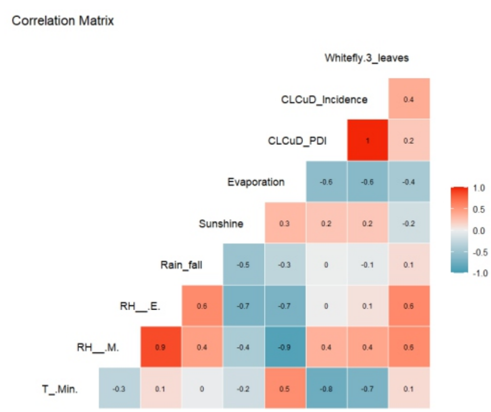

Fig 2. Correlation heatmap 2022

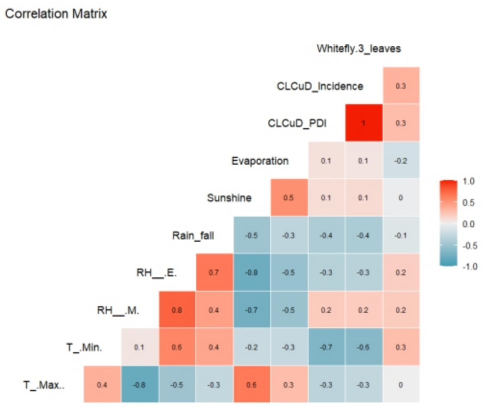

Fig 3. Correlation heatmap 2023

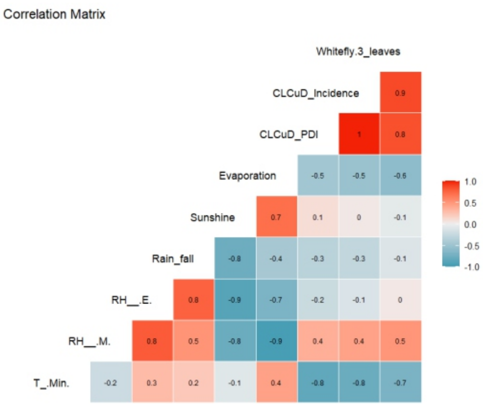

Fig 4. Correlation heatmap 2024

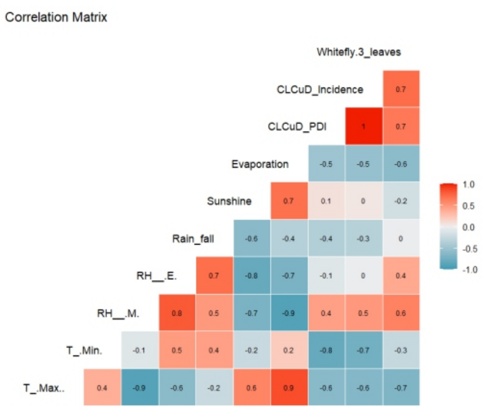

Fig 5. Correlation heatmap (pooled)

Regression Analysis of CLCuD PDI, disease incidence and white fly population in Relation to Weather Parameters and Sowing Time in Cotton

To further understand the influence of weather variables on Cotton Leaf Curl disease (CLCuD) development and its primary vector, whitefly, a multiple linear regression analysis was conducted using data of four years (2021–2024). Regression coefficients were derived to quantify the direction and strength of influence of individual weather parameters on CLCuD PDI, disease incidence and whitefly population. The pooled results and seasonal breakdowns are presented in Table 2. Across all years, minimum temperature (T_{min}) consistently exhibited negative regression coefficients, particularly for CLCuD incidence, indicating a strong inverse relationship. This implies that lower night temperatures significantly favour disease progression. Likewise, T_{max} had a variable but generally weak influence, with both positive and negative coefficients across years, suggesting that maximum temperature plays a less consistent role in CLCuD dynamics. Morning relative humidity (RH_m) showed positive regression coefficients in most seasons, with the strongest influence in 2024, reinforcing the earlier correlation results that higher morning humidity favours virus development, possibly by supporting vector survival and viral transmission. However, its overall magnitude remained moderate compared to temperature variables. Evening RH (RH_e) generally had negative or weak positive effects, indicating a limited and inconsistent role in influencing disease parameters. Rainfall exhibited small and largely negative coefficients, especially in the pooled data, suggesting a minimal or suppressive role in CLCuD development. This may be due to the washing-off effect on whiteflies, or because excessive moisture interferes with their activity. However, due to its generally low magnitude and inconsistent direction across years, rainfall appears to have no major direct influence on disease pressure. Sunshine hours showed consistently positive coefficients for CLCuD incidence and PDI, with the highest values in pooled data (1.673 for incidence). This suggests that increased solar radiation promotes whitefly activity, which in turn enhances virus spread. On the contrary, evaporation had variable effects, being negatively associated with disease incidence in 2021 and 2022, but showing weak or slightly positive values in 2024. The overall pooled result (–0.783 for incidence) points to a moderate suppressive effect, likely due to drier conditions reducing vector activity and virus viability.

When examining the regression for whitefly population, sunshine emerged as the most influential positive predictor, especially in 2024 (0.439) and in the pooled analysis (0.410), reaffirming its role in enhancing vector proliferation. T_{min} again had a negative effect in most years, particularly in 2024 (–0.312), highlighting that cooler nights may suppress vector build-up. RH_m occasionally showed a weak positive relationship with whitefly population (0.102 in 2024), but overall, the regression strength remained low, suggesting indirect or secondary influence. The pooled regression further confirmed that T_{min} (–0.900), RH_m (0.472) and sunshine (1.673) are key drivers of CLCuD incidence. In conclusion, the regression analysis clearly identifies low minimum temperature, high morning humidity, and increased sunshine hours as the most important weather parameters influencing CLCuD epidemics and vector build-up in cotton. These insights emphasize the need for adjusting sowing windows and strategic vector management, especially under climate-resilient agricultural planning. Similarly, the multiple regression analysis was evaluated of CLCuD and identified minimum temperature and sunshine hours as having significant negative correlations with disease incidence, whereas morning relative humidity and rainfall were positively correlated (16). also observed that the temperature is the most frequent factor influencing the development and prediction of CLCuD (20).

Table 2: Regression coefficients of weather parameters influencing CLCuD PDI, disease incidence and white fly population in cotton

Year		Weather parameters							
		T_{max} (ºC)	T_{min} (ºC)	RH_m (%)	RH_e (%)	Rainfall (mm)	Sunshine hrs.	Evaporation	White fly/ 3 leaves
Kharif, 2021	CLCuD PDI	0.013	-0.283	0.038	0.018	-0.015	0.396	-0.400	0.850
	CLCuD Incidence	0.267	-1.446	0.149	0.120	-0.080	2.131	-2.918	4.425
	White fly/3 leaves	0.230	-0.145	-0.003	0.056	-0.005	-0.010	-0.087	-
Kharif, 2022	CLCuD PDI	-0.349	-0.142	-0.048	-0.124	0.013	0.080	-0.592	1.166
	CLCuD Incidence	-1.852	-0.542	-0.259	-0.475	0.032	0.864	-2.321	7.109
	White fly/3 leaves	-0.031	0.059	0.015	0.021	-0.004	0.171	0.018	-
Kharif, 2023	CLCuD PDI	0.285	-0.380	0.097	-0.034	-0.003	0.160	0.035	1.097
	CLCuD Incidence	1.552	-1.896	0.466	-0.124	-0.020	-0.623	0.140	5.886
	White fly/3 leaves	-0.122	0.185	0.035	-0.024	-0.004	0.167	-0.017	-
Kharif, 2024	CLCuD PDI	-0.030	-0.117	0.109	-0.066	-0.002	0.040	0.161	0.318
	CLCuD Incidence	-0.226	-0.850	0.541	-0.147	-0.024	0.638	1.376	1.824
	White fly/3 leaves	-0.035	-0.312	0.102	0.012	-0.003	0.439	0.244	-
Pooled	CLCuD PDI	0.012	-0.220	0.107	-0.049	-0.015	0.273	-0.108	0.671
	CLCuD Incidence	0.053	-0.900	0.472	-0.184	-0.082	1.673	-0.783	4.091
	White fly/3 leaves	-0.083	-0.090	-0.012	0.058	-0.008	0.410	-0.078	-

Regression models and predictive strength of weather parameters on CLCuD and whitefly Population

To better understand the influence of weather variables on the dynamics of cotton leaf curl disease (CLCuD) and its vector, whitefly, multiple regression models were constructed using CLCuD Per cent Disease intensity (PDI), disease incidence, and whitefly population as dependent variables, and eight meteorological factors—maximum temperature (X_1), minimum temperature (X_2), morning relative humidity (X_3), evening relative humidity (X_4), rainfall (X_5), sunshine hours (X_6), evaporation (X_7) and wind speed (X_8)—as independent predictors, as detailed in Table 3. The models, analysed across four consecutive years (2021–2024) with pooled data, revealed consistent and robust associations between specific climatic parameters and CLCuD progression. During the 2021 season, moderate-to-strong model fits were observed for both CLCuD PDI (R^2 = 0.8349) and incidence (R^2 = 0.8153), indicating that weather variables explained a substantial portion of disease variability. Sunshine hours (X_6) and evaporation (X_7) exerted the strongest positive and negative influences, respectively, while minimum temperature (X_2) showed a prominent negative impact across all disease metrics. Whitefly population models in this season had moderate predictability (R^2 = 0.4082), with maximum temperature and sunshine emerging as notable contributors. The 2022 season exhibited similarly high model performance for CLCuD parameters (R^2 = 0.8068 for PDI; R^2 = 0.8281 for incidence), with minimum temperature again acting as a strong suppressor of disease, while sunshine hours and evaporation continued to be critical positive and negative drivers, respectively. Interestingly, in 2022, the whitefly population was moderately predicted (R^2 = 0.4642), with sunshine and morning humidity (X_3) showing positive contributions. In 2023, the regression models remained strong for CLCuD PDI and incidence (R^2 = 0.7709 and 0.7597, respectively), though whitefly prediction accuracy slightly declined (R^2 = 0.3311). Here, maximum temperature (X_1) had a consistently positive relationship with CLCuD, whereas minimum temperature continued to exert a negative effect. Morning relative humidity (X_3) gained prominence in disease expression, while sunshine and wind (X_8) appeared influential, likely due to their roles in enhancing vector movement. By 2024, the regression strength reached its peak, with CLCuD PDI and incidence models achieving R^2 values of 0.9333 and 0.9107, respectively. Maximum temperature, morning humidity, sunshine, and evaporation were highly influential, whereas minimum temperature retained its inhibitory effect. Notably, whitefly population predictions were strongest in 2024 (R^2 = 0.7100), indicating favourable climatic alignment with vector proliferation, especially under high sunshine and humidity. Pooled regression analysis across all four years reinforced these findings. The highest model fits were recorded for CLCuD PDI (R^2 = 0.9238) and incidence (R^2 = 0.9143), underscoring the reliability of these models for long-term disease forecasting. Sunshine hours (X_6) consistently emerged as a dominant positive predictor across both disease and whitefly models, while minimum temperature (X_2) was the most stable negative factor, reaffirming the suppressive role of lower night temperatures in both disease development and vector dynamics. Morning relative humidity (X_3) and evaporation (X_7) also played key roles in modulating disease intensity and white fly activity. These results are in correlation with the study, which showed that that the coefficient of determination (R^2) for CLCuD development ranged from 0.19 to 0.90, indicating year-to-year variability. Predictive regression models were developed for disease incidence ($Y = -12.913T_{max} + 2.489T_{min} + 0.242RHm - 0.197RH_e - 0.890Rf + 459.368$) and percent disease intensity (PDI) ($Y = -8.962T_{max} + 2.608T_{min} + 0.232RHm - 0.567RHe - 0.570Rf + 306.433$) (19). A strong positive correlation was found between whitefly population and CLCuD incidence/PDI. Whitefly abundance was significantly influenced by weather, particularly relative humidity, with 25–62% variability explained by climatic factors through the regression model: $Y = -0.194T_{max} - 1.610T_{min} - 0.439RH_m + 0.911RH_e + 0.020Rf + 44.733$. Similarly, a multiple regression model was developed with a high R^2 value (0.82) for the 27^{th}–31^{st} SMW, indicating strong predictive power for disease progression: $Y10 = 199.50 - 6.26X2120 - 3.33X121 + 0.68X133 + 0.55X140 + 0.40X144 - 4.33X153 + 0.43X181 + 0.44X162$ (16).

Table 3: Multiple regression equations depicting the influence of weather parameters on CLCuD and whitefly population in cotton

Year		Weather parameters		
		R	R^2	Regression Equation
Kharif, 2021	CLCuD PDI	0.9137	0.8349	$4.555 + 0.013X_1 - 0.283X_2 + 0.038X_3 + 0.018X_4 - 0.015X_5 + 0.396X_6 - 0.400X_7 + 0.850X_8$
	CLCuD Incidence	0.9030	0.8153	$23.692 + 0.267X_1 - 1.446X_2 + 0.149X_3 + 0.120X_4 - 0.080X_5 + 2.134X_6 - 2.918X_7 + 4.428X_8$
	White fly/3 leaves	0.6389	0.4082	$-6.088 + 0.230X_1 - 0.145X_2 - 0.003X_3 + 0.056X_4 - 0.005X_5 - 0.010X_6 - 0.087X_7$
Kharif, 2022	CLCuD PDI	0.8982	0.8068	$29.468 - 0.349X_1 - 0.142X_2 - 0.048X_3 - 0.124X_4 + 0.013X_5 + 0.080X_6 - 0.592X_7 + 1.166X_8$
	CLCuD Incidence	0.9100	0.8281	$135.4293 - 1.854X_1 - 0.542X_2 - 0.259X_3 - 0.475X_4 + 0.032X_5 + 0.864X_6 - 2.321X_7 + 7.109X_8$
	White fly/3 leaves	0.6813	0.4642	$-2.391 - 0.031X_1 + 0.059X_2 + 0.015X_3 + 0.021X_4 - 0.004X_5 + 0.171X_6 + 0.018X_7$
Kharif, 2023	CLCuD PDI	0.8780	0.7709	$-5.220 + 0.285X_1 - 0.380X_2 + 0.097X_3 - 0.034X_4 - 0.003X_5 + 0.160X_6 + 0.035X_7 + 1.097X_8$
	CLCuD Incidence	0.8718	0.7597	$-32.285 + 1.552X_1 - 1.896X_2 + 0.466X_3 - 0.124X_4 - 0.020X_5 - 0.623X_6 + 0.140X_7 + 5.886X_8$
	White fly/3 leaves	0.5754	0.3311	$-1.672 - 0.122X_1 + 0.185X_2 + 0.035X_3 - 0.024X_4 - 0.004X_5 + 0.167X_6 - 0.017X_7$
Kharif, 2024	CLCuD PDI	0.9661	0.9333	$-1.487 - 0.030X_1 - 0.117X_2 + 0.109X_3 - 0.066X_4 - 0.002X_5 + 0.040X_6 + 0.161X_7 + 0.318X_8$
	CLCuD Incidence	0.9543	0.9107	$-11.804 - 0.226X_1 - 0.850X_2 + 0.541X_3 - 0.147X_4 - 0.024X_5 + 1.439X_6 + 1.376X_7 + 1.824X_8$
	White fly/3 leaves	0.8426	0.7100	$-1.947 - 0.035X_1 - 0.312X_2 + 0.102X_3 + 0.021X_4 - 0.003X_5 + 0.439X_6 + 0.244X_7$
Pooled	CLCuD PDI	0.9611	0.9238	$-0.119 + 0.012X_1 - 0.220X_2 + 0.107X_3 - 0.049X_4 - 0.015X_5 + 0.273X_6 - 0.108X_7 + 0.671X_8$
	CLCuD Incidence	0.9562	0.9143	$-3.409 + 0.053X_1 - 0.900X_2 + 0.472X_3 - 0.184X_4 - 0.082X_5 + 31.673X_6 - 0.783X_7 + 4.090X_8$
	White fly/3 leaves	0.7996	0.6394	$2.532 - 0.083X_1 - 0.099X_2 - 0.012X_3 + 0.058X_4 - 0.008X_5 + 0.410X_6 - 0.078X_7$

Conclusion

The regression analyses highlight the pivotal roles of maximum temperature, morning humidity, and sunshine hours as positive drivers of CLCuD progression, with minimum temperature acting as a key inhibitory factor. The consistency of these effects across years and their prominence in pooled models make them valuable for predictive modelling and integrated disease management strategies and monitoring key weather variables to mitigate CLCuD outbreaks under changing climatic scenarios.

Author Contributions

The authors are entirely responsible for their contributions to the entire article. The final draft was read by all authors and got their approval.

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Ethics Statement

The article contains the ethical approval and consent to participation.

Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request

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