



RESEARCH ARTICLE

Weather-based predictive assessment of Sigatoka leaf spot in banana cultivars

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Abstract

Sigatoka leaf spot, a major fungal disease of banana, causes significant yield losses. Although its development is strongly influenced by weather, the specific relationships between meteorological factors and disease severity in key Indian cultivars require quantification for effective forecasting and management. Weekly disease assessments (percent disease index; PDI) and meteorological data were collected for three banana cultivars (Grand Naine, Ney Poovan and Nendran) during the 2024–25 cropping season. The relationships between meteorological variables and PDI were evaluated through Pearson's correlation and multiple linear regression analysis. Correlation analysis identified wind speed as having the strongest negative correlation with PDI across all cultivars ($r = -0.42$ to -0.45), while rainfall showed a positive correlation ($r = 0.27$ to 0.31). Multiple regression confirmed wind speed and rainfall as the most significant predictors ($p < 0.05$), with relative humidity and temperature showing minimal independent effects. The findings demonstrate that managing the microclimate to reduce leaf wetness from rainfall and enhance airflow is critical. These insights form a scientific basis for prioritising management strategies such as increased plant spacing and canopy pruning to achieve sustainable control.

Keywords: banana; cultivars; prediction; Sigatoka leaf spot; weather

Introduction

Banana (*Musa* spp.), of the family Musaceae among the world's most important and historically significant fruit crop. Its widespread production in tropical and subtropical regions plays a vital role for supporting food security, enhancing essential nutrition and sustaining an economic livelihood of rural communities (1). Global fruit production has expanded remarkably, increasing by nearly 30 % between 2010 and 2023, with bananas contributing significantly to this growth. During this period, banana production rose by about 27 %, reaching an estimated 139 million tonnes and underscoring the crop's vital role in global agriculture (2). India ranks among the world's top banana producers, where the crop plays a vital role in supporting rural livelihoods across various regions. The fruit has been cultivated in different parts of India, which grown in the southern states of Tamil Nadu and Kerala to the western plains of Gujarat and Maharashtra. Optimal condition for growth required warm, humid zones of tropical and subtropical regions, grown up to 2000 m above mean sea level where temperatures maintained between 20 °C and 30 °C. The crop is highly sensitive to temperature declined below 12 °C, which substantially reduce plant growth,

vigour and yield (3). This strong dependence on specific weather variable highlights the importance of stable environmental conditions, particularly temperature, for sustainable production.

As a fundamental component of tropical agriculture, banana cultivation is persistently challenged by a range of pests and diseases that suppress yields and restrict the commercial use of popular cultivars. Among these, Sigatoka leaf spot, caused by *Mycosphaerella* species, stands as a major contributor to annual losses (4, 5). The principal pathogens include *Mycosphaerella fijiensis*, *M. musicola* and *M. eumusae*, which are the causal agents of black, yellow and eumusae leaf spot disease respectively (6–8). Pathogenic activity is characterised by the formation and expansion of necrotic lesions on leaf tissue, severely diminishes photosynthetic function, induces premature senescence and leads to 11 to 80 % of yield reduction (9, 10). An extensive distribution of these pathogens poses a severe and persistent economic challenge to global banana cultivation.

Weather variables strongly influence the epidemiology of Sigatoka leaf spot. Optimal conditions for infection and disease development consist of warm temperatures around 25–28 °C, elevated humidity, frequent heavy rainfall and sustained periods of

leaf wetness (11, 12). Wind velocity directly influences both the period of leaf wetness and the dispersal of fungal spores (13). Therefore, developing statistically significant models between disease severity and weather patterns is essential for predicting outbreaks and site-specific management strategies (14).

Although the general influence of weather on Sigatoka is recognised, the precise, quantitative relationships between key meteorological factors and disease severity for specific, commercially important banana cultivars in India remain poorly defined. This knowledge gap limits the development of accurate, cultivar-specific forecasting models needed for precise and sustainable disease management.

The findings of this study demonstrate significant implications for banana cultivation, aimed to quantify the relationship between key weather variables and Sigatoka leaf spot severity in three commercially important banana cultivars and develop cultivar-specific predictive models to inform targeted management strategies.

Materials and Methods

Experimental site and plant material

The field experiment was conducted during the 2024–25 cropping season at the fruit orchard of Horticultural College and Research Institute, Tamil Nadu Agricultural University, Coimbatore, India (Latitude 11.03°N, Longitude 76.93°E). The site is characterised by a semi-arid tropical climate with an average annual rainfall of 600–700 mm. The soil at the experimental plot is a well-drained clay loam, with a pH of 7.2–7.8 and low to medium organic carbon content. Sigatoka leaf spot susceptible cultivars such as Grand Naine, Ney Poovan and Nendran were selected. The planting material were sourced as tissue culture plantlets from the Southern Petrochemical Industries Corporation- Agro Biotech centre tissue culture. The experiment was laid out in a randomised complete block design (RCBD) with 3 replications. The plot size of 9.0 m × 3.6 m was determined by the 1.8 m × 1.8 m spacing between plants and rows.

Disease assessment of sigatoka leaf spot severity

The first symptoms of Sigatoka leaf spot were observed 12–14 weeks after planting. Subsequently, disease severity was evaluated weekly throughout the 2024–25 cropping period. Final disease severity was recorded when the most susceptible cultivars reached 70–80 % infection. Weekly severity data for each cultivar were utilised to develop predictive models, whereas the final severity % served to compare resistance levels among the tested cultivars.

Percent disease index (PDI)

Disease severity of banana plants was evaluated using a 0–6 scale adapted from Gauhl's modification of Stover's Sigatoka scoring system (15). Ten plants per plot were selected at random and 5 leaves from each plant were examined. The scale ranged from 0 (no symptoms) to 6 (51–100 % of lamina affected), with intermediate values representing increasing proportions of leaf area affected. Percent disease index was determined in following equation (16).

$$PDI = \frac{\text{Sum of all numerical ratings}}{\text{Total number of leaves observed}} \times \frac{100}{\text{Maximum disease grade in the score chart}} \quad (\text{Eq. 1})$$

Meteorological data

An automated weather station at the experimental site was used to record daily meteorological data. The system specifically recorded parameters including maximum and minimum temperatures (X_1 , X_2), relative humidity (X_3), wind speed (X_4) and rainfall (X_5). Daily measurements were combined into weekly mean values for disease assessments.

Statistical analysis

Correlation analysis

Correlation analysis was conducted using Pearson's correlation coefficient (r) to measure the strength and direction of the linear relationship between weather variables and disease severity (17).

$$r = \frac{[\sum (x_i - \bar{x})(y_i - \bar{y})]}{[\sqrt{\sum (x_i - \bar{x})^2} \times \sqrt{\sum (y_i - \bar{y})^2}]} \quad (\text{Eq. 2})$$

Where, x_i and y_i represent individual weather parameter and disease severity values and $\bar{x}$ and $\bar{y}$ are their respective means.

Multiple linear regression

The influence of meteorological variables on Sigatoka leaf spot severity was quantified using multiple regression analysis as described by the following model (18):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n + \epsilon \quad (\text{Eq. 3})$$

Where, the dependent variable Y represents disease severity, independent variable X_1 to X_n correspond to meteorological factors; β_0 to β_n are regression coefficients; and ϵ is the error term.

Coefficient of determination (R^2)

The performance of the regression model was evaluated through the coefficient of determination (R^2), representing the proportion of total variation in disease severity explained by the independent variables (19).

$$R^2 = 1 - \frac{SS_{\text{res}}}{SS_{\text{tot}}} \quad (\text{Eq. 4})$$

Where, SS_{res} (sum of squares of residuals) = $\sum (y_i - \hat{y}_i)^2$, SS_{tot} (total sum of squares) = $\sum (y_i - \bar{y})^2$, y_i = observed values, $\hat{y}_i$ = predicted values, $\bar{y}$ = mean of observed values. The value of R^2 ranges from 0 to 1.

Results

Based on the weekly observations, the present study examined the influence of five key weather parameters maximum temperature, minimum temperature, relative humidity, wind speed and rainfall on the severity of Sigatoka leaf spot, expressed as PDI, across three banana cultivars: Grand Naine, Ney Poovan and Nendran.

Correlation between weather variables and percent disease index of Sigatoka leaf spot

The analysis of correlations between weather variables and PDI

demonstrated that wind speed had the strongest effect, showing strong negative correlations across all 3 cultivars (Grand Naine: $r = -0.4227$; Ney Poovan: $r = -0.4155$; Nendran: $r = -0.4476$). This relationship explained 17–20 % of the variation, indicating that higher wind speeds were consistently associated with reduced

Table 1. Correlation between weather variables and contribution of Sigatoka leaf spot disease index on 3 banana cultivars

Weather variables		Grand Naine	Ney poovan	Nendran
Maximum temperature (°C) (X1)	r	-0.2174	-0.2305	-0.2268
	R^2	4.73	5.31	5.15
Minimum temperature (°C) (X2)	r	0.2047	0.1559	0.2138
	R^2	4.19	2.43	4.57
Relative humidity (%) (X3)	r	0.3436	0.3263	0.3541
	R^2	11.81	10.65	12.54
Wind (m / s) (X4)	r	-0.4227	-0.4155	-0.4476
	R^2	17.87	17.27	20.04
Rainfall (mm / day) (X5)	r	0.2980	0.3076	0.2711
	R^2	8.88	9.46	7.35

disease severity. Relative humidity, on the other hand, was positively correlated with PDI ($r = 0.3263$ – 0.3541), explaining 11–13 % of the variation, which reinforces the role of moist conditions in favouring disease progression. Rainfall also contributed positively ($r = 0.27$ – 0.31), accounting for 7–9 % of the variation. Temperature parameters exhibited relatively weak associations; maximum temperature was negatively correlated (approximately -0.22), whereas minimum temperature displayed a weak positive relationship (0.16–0.21) (Table 1).

Multiple regression models for predicting percent disease index of Sigatoka leaf spot

The severity of Sigatoka leaf spot in the Grand Naine cultivar was found to be governed by specific meteorological mechanisms. A significant inhibitory effect of wind speed on disease development was identified (Coefficient: -14.84, $p = 0.039$), which is attributed to the disruption of pathogen establishment and reduced spore retention on leaves. Conversely, rainfall demonstrated a significant positive effect on disease progression (Coefficient: 16.80, $p = 0.020$), which prolongs leaf wetness duration and increasing infection efficiency. Relative humidity exhibited a positive yet statistically non-significant relationship with disease severity (Coefficient: 1.37, $p = 0.402$), indicating its role may be complementary to rainfall rather than independent. Temperature variables, including maximum ($p = 0.576$) and minimum ($p = 0.265$) temperatures, were not significantly associated with disease expression, indicating that the epidemic was primarily influenced by moisture-related factors (Table 2). The visual representation through line fit plots corroborated these statistical findings, highlighted distinct relationships for wind and rainfall, while the relative humidity plot presented a positive yet scattered pattern, reflecting its borderline significance in the overall model (Fig. 1).

Multiple regression revealed distinct weather-disease relationships in Ney Poovan. Statistical analysis revealed a significant inhibitory effect of wind speed on pathological progression (coefficient: -15.63, $p = 0.025$). Conversely, rainfall intensity demonstrated a strong positive effect with disease severity

(coefficient: 17.10, $p = 0.014$). Relative humidity measurements indicated a positive yet statistically insignificant association with infection rates (coefficient: 0.97, $p = 0.521$), suggesting its pathological relevance may be contingent upon concurrent rainfall events. A temperature conditions exhibited negligible influence on disease dynamics, with both maximum ($p = 0.737$) and minimum ($p = 0.280$) temperature measurements showed insignificant effects. The regression model intercepts demonstrated statistical non-significance ($p = 0.999$). These results emphasise rainfall's critical role in driving disease progression and wind's natural suppressive effect in this cultivar (Table 3). The visual inspection via Line Fit Plots reinforced the regression findings, highlighting distinct inhibitory effects of wind speed and strong promotive effects of rainfall, whereas the relative humidity plot displayed a scattered positive trend and the temperature plots remained minimal variation, reflecting the key influence of local microclimatic conditions on disease severity (Fig. 2).

In the Nendran cultivar, multiple regression analysis revealed wind speed (coefficient: -14.81, $p = 0.037$) and rainfall (coefficient: 15.47, $p = 0.026$) as the principal climatic determinants of Sigatoka leaf spot severity. The significant negative coefficient for wind speed confirms its protective role through physical disruption of spore settlement on leaf surfaces. Rainfall emerged as the dominant contributed factor for disease progression, with its coefficient indicated substantial enhancement of pathogen development through prolonged periods of leaf wetness. Relative humidity demonstrated a positive but statistically non-significant association with disease severity (coefficient: 1.09, $p = 0.491$), implying its pathogen influence its condition upon interaction with other weather variables. A temperature condition proved minimally influential, with both upper ($p = 0.685$) and lower ($p = 0.341$) temperature extremes demonstrated non-significant relationship with disease development. The non-significant model intercept ($p = 0.887$) indicated no substantial baseline disease pressure independent of the measured weather variables (Table 4). Line fit plots visually confirmed the statistical relationships, showed a clear inverse trend for wind speed and a strong positive correlation with rainfall. Relative humidity displayed scattered positive associations, while temperature profiles remained flat. These patterns underscore that moisture factors, not temperature, were the primary drivers of disease progression (Fig. 3).

The regression model derived predictive equations for all three banana cultivars (Table 5). A comparative analysis positioned Nendran with intermediate climatic susceptibility. Its wind

Table 2. Multiple linear regression analysis of weather parameters and Sigatoka leaf spot in banana cv. Grand Naine

Predictor	Coefficients	Standard error	t Stat	p-value
Intercept	-61.9	211.6993	-0.2924	0.77846
Maximum temperature (°C) (X1)	3.028499	5.162788	0.586602	0.575892
Minimum temperature (°C) (X2)	-4.72433	3.899873	-1.21141	0.265043
Relative humidity (%) (X3)	1.367326	1.531604	0.892741	0.401642
Wind (m / s) (X4)	-14.8411	5.874682	-2.52628	0.039447
Rainfall (mm / day) (X5)	16.79529	5.618946	2.989047	0.020254

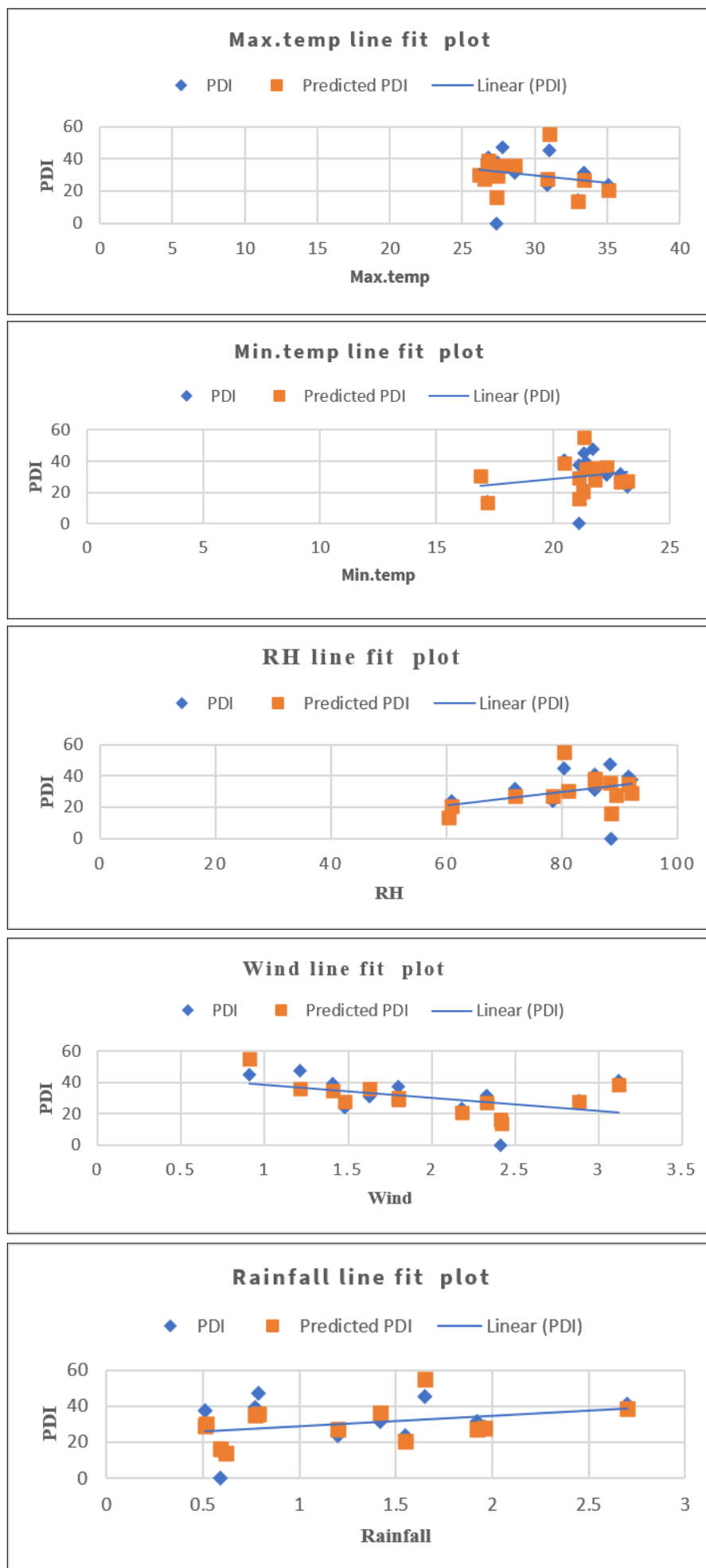


Fig. 1. Prediction of weather variables and percent disease index of Sigatoka leaf spot in cv. Grand Naine.

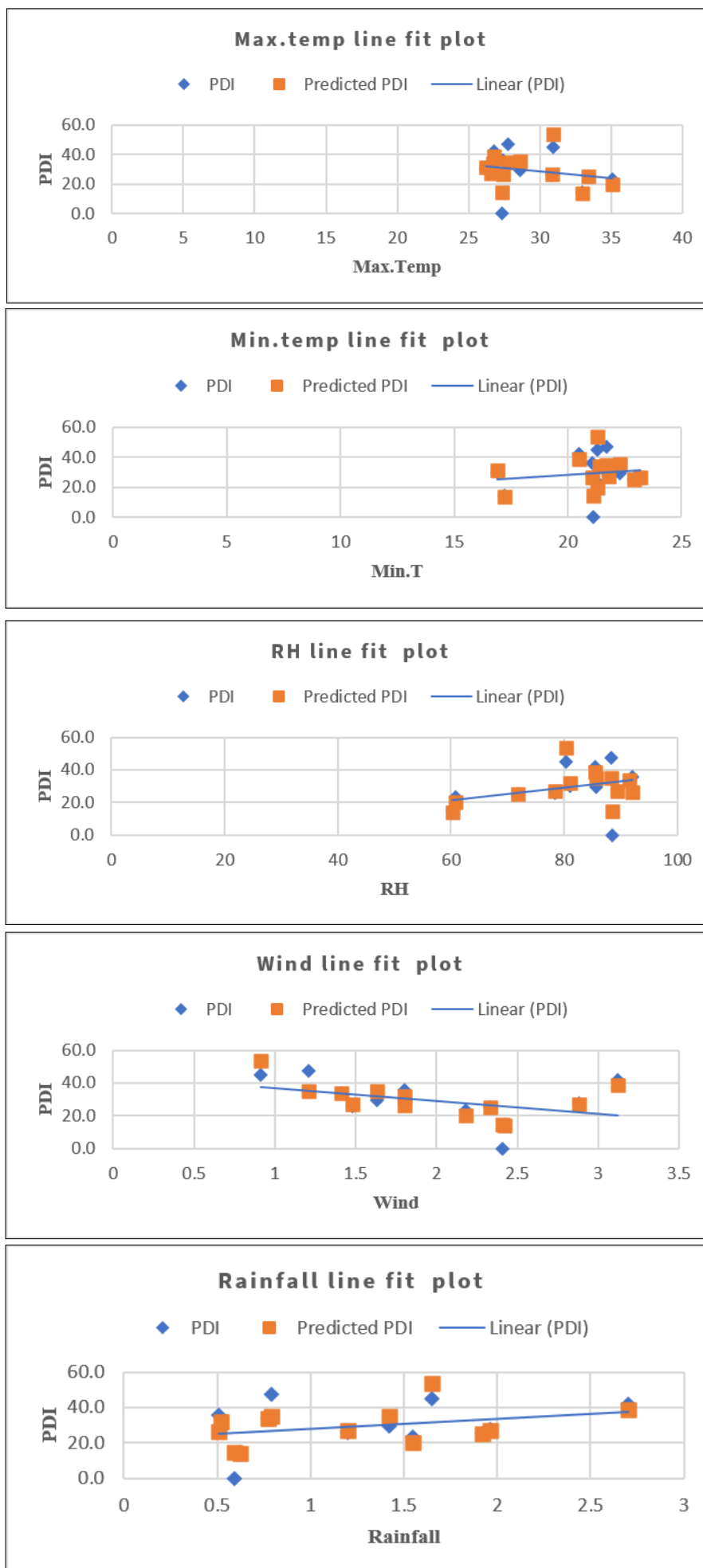


Fig. 2. Prediction of weather variables and percent disease index of Sigatoka leaf spot in cv. Ney poovan.

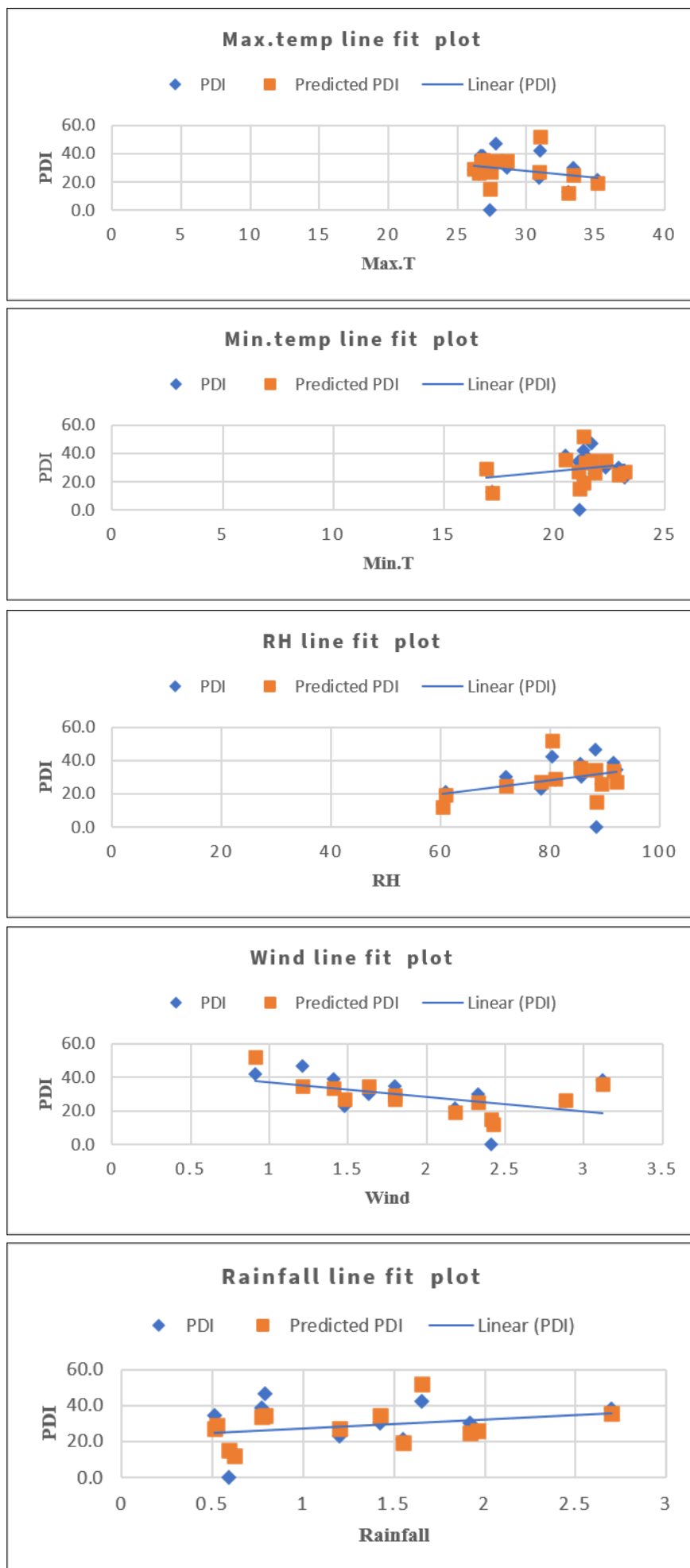


Fig. 3. Prediction of weather variables and percent disease index of Sigatoka leaf spot in cv. Nendran.

Table 3. Multiple linear regression analysis of weather parameters and Sigatoka leaf spot in banana cv. Ney Poovan

Predictor	Coefficients	Standard error	t Stat	p-value
Intercept	0.182899	198.7424	0.00092	0.999291
Maximum temperature (°C) (X1)	1.696009	4.846803	0.349923	0.736688
Minimum temperature (°C) (X2)	-4.28394	3.661184	-1.1701	0.280253
Relative humidity (%) (X3)	0.971388	1.437863	0.675578	0.520994
Wind (m / s) (X4)	-15.6323	5.515127	-2.83444	0.025245
Rainfall (mm / day) (X5)	17.10059	5.275043	3.241791	0.014218

Table 5. Model prediction

Cultivars	Equation	R ²
Grand Naine	$Y = -61.90 + 3.03(X1) - 4.72(X2) + 1.37(X3) - 14.84(X4) + 16.80(X5)$	67.49
Ney poovan	$Y = 0.18 + 1.70(X1) - 4.28(X2) + 0.97(X3) - 15.63(X4) + 17.10(X5)$	69.77
Nendran	$Y = -30.51 + 2.14(X1) - 3.90(X2) + 1.09(X3) - 14.81(X4) + 15.47(X5)$	66.45

coefficient (-14.81) fell between Ney Poovan (-15.63) and Grand Naine, while its rainfall response (15.47) exceeded Grand Naine's but remained below Ney Poovan's. These values confirm meteorological factors exert moderate but distinct influence on disease progression in this cultivar.

The findings indicate that rainfall and wind speed are the primary weather variables influencing Sigatoka leaf spot development in Nendran bananas, whereas relative humidity exerted a limited influence. These insights provide a basis for developing targeted, cultivar-specific management approaches.

Discussion

The present findings demonstrate that rainfall and wind speed are the dominant meteorological factors influencing Sigatoka leaf spot severity across three banana cultivars. Multiple regression models accounted for a substantial proportion of disease variance, with R² values of 0.6749 for Grand Naine, 0.6977 for Ney Poovan and 0.6645 for Nendran. These high R² values indicate that weather-based models as an effective approach for predicting disease outbreaks in these cultivars.

Rainfall consistently showed significant positive relationships with disease severity across all cultivars, with regression coefficients of 16.80 for Grand Naine ($p = 0.020$), 17.10 for Ney Poovan ($p = 0.014$) and 15.47 for Nendran ($p = 0.026$). The stronger rainfall coefficient in Ney Poovan suggests vulnerability to moisture-driven infection processes. This aligns with established understanding that rainfall facilitates conidial dispersal and maintains leaf wetness essential for infection (11, 20). The cultivar-specific differences in rainfall response may reflect distinct canopy architectures that influence moisture retention, as leaf orientation and density are known to affect microclimate conditions (21, 22).

Wind speed exhibited significant negative relationships with disease severity, with coefficients of -14.84 for Grand Naine ($p = 0.039$), -15.63 for Ney Poovan ($p = 0.025$) and -14.81 for Nendran ($p = 0.037$). Nendran showed the strongest correlation with wind speed ($r = -0.4476$), indicating sensitivity to airflow effects. These results support the mechanism whereby wind reduces disease by accelerating leaf drying and dispersing spores from infection sites (23, 24). The cultivar variation in wind response may relate to

Table 4. Multiple linear regression analysis of weather parameters and Sigatoka leaf spot in banana cv. Nendran

Predictor	Coefficients	Standard error	t Stat	p-value
Intercept	-30.5106	207.3535	-0.14714	0.887167
Maximum temperature (°C) (X1)	2.135613	5.056807	0.422324	0.685457
Minimum temperature (°C) (X2)	-3.90484	3.819817	-1.02226	0.340682
Relative humidity (%) (X3)	1.090629	1.500164	0.727007	0.490814
Wind (m / s) (X4)	-14.8132	5.754088	-2.57438	0.036772
Rainfall (mm / day) (X5)	15.46935	5.503602	2.810768	0.026117

differences in leaf surface properties or canopy density that modify wind penetration and drying efficiency (25).

Temperature parameters showed minimal influence on disease development, with non-significant p -values across all cultivars ($p = 0.265$ – 0.737 for minimum temperature; $p = 0.576$ – 0.737 for maximum temperature). This finding is consistent with previous reports that *Pseudocercospora musae* has a broad temperature optimum (20–30 °C) and is relatively insensitive to temperature fluctuations within this range (26). The results confirm that temperature plays a secondary role to moisture availability in disease progression (27).

The statistical models derived from this study provide cultivar-specific predictive equations that explain approximately two-third of disease severity variation. This represents a significant advancement in developing practical forecasting tools for banana growers. The distinct climatic sensitivities identified for each cultivar enable targeted management strategies, such as prioritising canopy management in Ney Poovan during high-rainfall periods and emphasising plant spacing in Nendran to maximise wind benefits. These approaches support sustainable disease management through microclimate modification rather than a primary dependence on chemical controls.

Conclusion

The research findings consistently indicate that wind speed acts as a suppressive factor, whereas rainfall serves as the principal driver of Sigatoka leaf spot severity across Grand Naine, Ney Poovan and Nendran. Relative humidity exhibited a minor effect, largely mediated by rainfall. Temperature within the observed range did not appear to limit disease development, aligning with earlier epidemiological findings. The results highlight rainfall as the key factor influencing Sigatoka outbreaks and underscore the need for effective microclimate management. Implementing cultural practices such as increased plant spacing, canopy pruning and better ventilation can help minimise leaf wetness and reduce disease pressure. Integrating of these practices with resistant cultivars and targeted fungicide use ensures sustainable and effective control of Sigatoka leaf spot.

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Authors' contributions

SD carried out the methodology and was responsible for writing the original research draft, as well as review, editing, visualisation and validation. KPS handled conceptualisation, methodology, supervision and validation of the experiments. SP contributed to methodology, supervision and visualisation. MI contributed to conceptualisation, methodology and supervision. SA contributed to review, editing and validation. KS, VG and AJ contributed to supervision and visualisation. All authors read and approved the final manuscript.

Compliance with ethical standards

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Ethical issues: None

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

During the preparation of this work the authors used ChatGPT in order to verify grammar. After using this tool / service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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