



Impact of weather parameters on the progression of bakanae disease (*Fusarium moniliforme* Sheldon) in aromatic rice (*Oryza sativa* L.) in the north-western region of Haryana, India

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Abstract

Various biotic constraints affect the cultivation of aromatic rice in India, especially in the North-West Plain Zone and bakanae disease is responsible for high economic losses ranging from 3.0–95.4 %. It occurs in Haryana and the adjoining states, particularly in early-transplanted rice crops. Weather influences all stages of the host and pathogen life cycle, as well as disease progression. To manage and forecast bakanae disease, it is important to understand the interaction between the host, pathogen and environment. Therefore, the present study was undertaken at Chaudhary Charan Singh Haryana Agricultural University, Rice Research Station, Kaul, Kaithal, during kharif 2021 and 2022 to study the effect of weather parameters viz., maximum and minimum temperatures ($^{\circ}\text{C}$; T_{max} and T_{min}), relative humidity in the morning and evening (%; RHM and RHE), rainfall (mm), wind velocity (km/hr) and bright sunshine (hr) on bakanae disease progression in basmati rice varieties PB 1121 and CSR 30. Accordingly, bakanae disease incidence across both seasons and pooled data progressively increased from the 28th to the 39th standard meteorological week (SMW), with PB 1121 showing higher susceptibility [19.1–34.6 % disease incidence (DI)] than CSR 30 (15.0–28.8 % DI). Peak disease incidence was observed under T_{max} of around 33.6–37.7 $^{\circ}\text{C}$, RHM of 94.9–97.6 % and low wind velocity of 2.0–2.5 km hr⁻¹. The RHM showed a significant positive correlation with disease incidence ($r = 0.754\text{--}0.851$), whereas minimum temperature ($r = -0.722$ to -0.857) and wind velocity ($r = -0.659$ to -0.789) exhibited significant negative correlations. Multiple regression analysis revealed high coefficients of determination ($R^2 = 0.85\text{--}0.99$), indicating a strong influence of weather parameters on bakanae disease progression. Ultimately, these results establish predictable weather thresholds that enable early warning systems to protect susceptible basmati rice varieties from economic losses.

Keywords: aromatic rice; bakanae; disease progression; *Fusarium moniliforme*; epidemiology; weather parameters

Received: 14 May 2026. **Accepted:** 03 August 2026. **Published:** 13 October 2026.

Cite this article: Vikram S, Ashwani K, Promil K, Mahaveer SB, Neha R. Impact of weather parameters on the progression of bakanae disease (*Fusarium moniliforme* Sheldon) in aromatic rice (*Oryza sativa* L.) in the north-western region of Haryana, India. Plant Science Today. 2026;13(sp9):01-16. <https://doi.org/10.14719/pst.15562>

1. Introduction

In India and worldwide, rice is one of the most important food grains. More than half of the world's population consumes rice, which is mostly consumed in Asia and Africa and cultivated in around 120 countries (1). An estimated 150.18 million tonnes of rice were produced globally in 2024–25. India has surpassed China to become the world's largest producer of rice (2). Rice is a host to more than 70 diseases in India. Of these, 15 diseases, including three bacterial (viz., bacterial leaf blight, bacterial foot rot and bacterial leaf streak), 12 fungal (viz., blast, foot rot and bakanae, false smut, sheath blight, stem rot, grain discolouration, sheath rot, brown spot, narrow

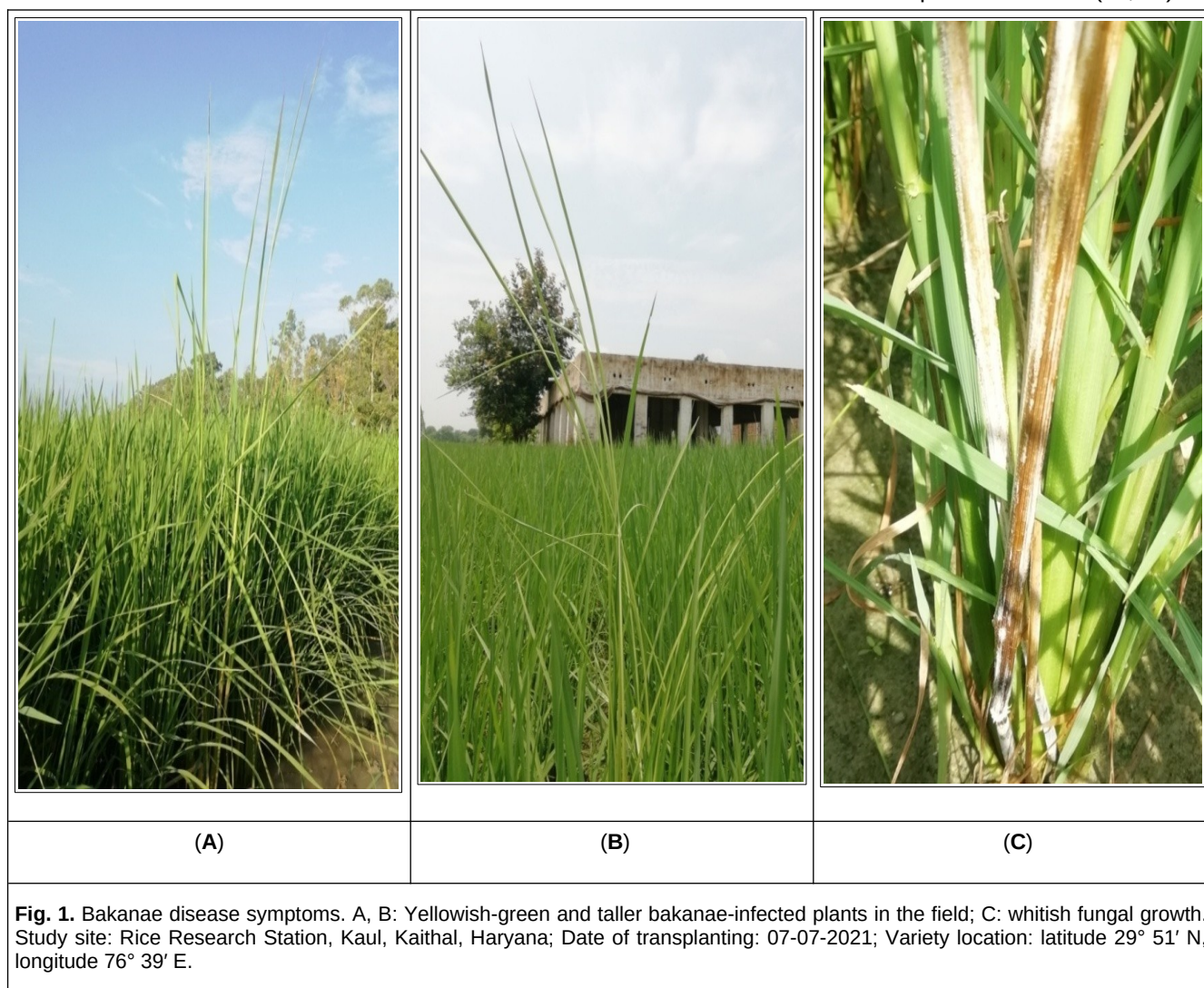
brown leaf spot, leaf smut, sheath blotch and kernel smut/bunt) and two nutritional disorders [viz., khaira (zinc deficiency) and chlorosis (iron deficiency)] are known to occur in Haryana (3). In Haryana, bakanae has attained the status of a major disease since its first record during kharif 1988, particularly in tall, scented rice varieties (4).

In Asia and other rice-growing countries worldwide, bakanae, caused by *Fusarium moniliforme* Sheldon, has recently emerged as one of the major diseases of aromatic rice (5). Bakanae disease, first identified in Japan in 1828 and subsequently documented in India (6) has a rich history of mycological and physiological discoveries. The

etiology of the disease was first demonstrated in 1898 through the identification of *Fusarium heterosporium* Nees as the causal agent of bakanae symptoms in rice plants (7). This pathogen was later reclassified under the genus *Gibberella* as *Gibberella fujikuroi* Sawada (8). By the 1930s, the taxonomic description was further refined by identifying the imperfect stage as *F. moniliforme* and the perfect stage as *G. fujikuroi* (9). The nomenclature of *G. fujikuroi* itself serves as a tribute to the distinguished Japanese plant pathologists Yosaburo Fujikuro and Kenkichi Sawada (10). The physiological understanding of the disease, often referred to as the “bakanae effect”, evolved through critical observations of fungal stimuli. The characteristic elongation of rice seedlings was first thought to be triggered by stimuli derived from fungal hyphae (11). This effect was experimentally confirmed in 1926 by demonstrating that culture filtrates from dried rice seedlings could induce hypertrophic elongation (12). Kurosawa concluded that the fungus secretes a specific chemical that encourages stem elongation while simultaneously suppressing root growth and chlorophyll formation. Building on these findings, the disease was formally designated as “Bakanae Byo”, confirming that isolated *Fusarium* species produced

the distinct hypertrophic elongation symptoms observed in previous culture filtration trials (13). Identification of *Fusarium* species associated with bakanae disease of basmati rice was performed using the Tef-1 gene molecular marker (14). The pathogen causes a variety of symptoms, including abnormal elongation of seedlings, whitish fungal growth (Fig. 1), seedling death, foot rot, light green/lanky seedlings and chaffy/infertile grains, depending on the type of toxin produced by the pathogen (either fusaric acid or gibberellic acid) and the prevailing environmental conditions.

Bakanae disease in basmati cultivars, particularly Pusa Basmati-1121, which is renowned for its long-cooked grain quality, is a major problem in the North Indian regions, particularly Punjab, Haryana and Western Uttar Pradesh (15, 16). Disease incidence in several aromatic rice cultivars ranged from 2.1–3.2 % in Uttarakhand, 1.2–11.7 % in Uttar Pradesh, 3–95 % in Haryana, 10.5–40.0 % in Punjab, 1.83–8.7 % in Bihar and 2.4–13.6 % in Rajasthan. Under optimal conditions, the disease is known to cause yield losses of 20–50 % in Japan, 70–80 % in Australia, 3.7–14.7 % in Thailand, 5–23 % in Spain, 3.0–95.4 % in India, 40 % in Nepal, 6.7–58 % in Pakistan and up to 75 % in Iran (17, 18).



Characterising the inherent variability of a pathogen is fundamental to developing effective disease management strategies. Molecular assessments utilising the β -tubulin gene have confirmed significant genetic diversity among *Fusarium* isolates, providing a high-resolution understanding of the pathogen population structure (19). Expanding on this genetic baseline, the cultural, morphological and molecular variability of *F. moniliforme* isolates was evaluated across 11 districts in Haryana, India (20). Their findings revealed substantial phenotypic plasticity, with significant variations in colony pigmentation and conidial morphology across major aromatic cultivars, including Pusa Basmati 1121 and Pusa Basmati 1509. Furthermore, the application of Vertf and FUM primers identified the presence of key toxin-producing genes in a majority of pathogen isolates, underscoring the physiological complexity of managing bakanae in the North-West Plain Zone (21). Collectively, these insights into pathogen diversity and toxigenic potential are critical for selecting broad-spectrum resistant donors and refining site-specific management interventions.

Bakanae is a monocyclic disease in which the pathogen produces conidia on infected plants, which are easily dispersed to healthy plants by water and wind. Conidia infect the inflorescence and contaminate seeds when the pathogen sporulates heavily throughout the flowering and ripening period (22). The term “disease triangle” refers to the three factors: susceptible host, virulent pathogen and environmental conditions that determine the incidence and establishment of the disease. Different weather parameters play a significant role in determining the incidence and geographical distribution of this emerging disease in rice (23).

Managing and forecasting bakanae disease requires an understanding of the interactions between the host, pathogen and environment. Temperature, relative humidity, rainfall, wind speed, evaporation, sunshine hours and other weather variables all have a significant impact on the occurrence, survival, reproduction and spread of diseases. However, limited research has been conducted on the effects of meteorological factors on bakanae disease. Temperature is another crucial factor influencing the development of bakanae during the seedling stage. While 35 °C is optimal for disease development and is also conducive to plant growth, 27–30 °C is the ideal temperature for pathogen infection. At 28–34 °C, a substantial positive correlation was observed between temperature and disease incidence (24). Disease incidence decreased with a decline in temperature (25, 26).

Bakanae disease progression is highly sensitive to environmental conditions, particularly during the critical flowering stage when conidia infect floral tissues are dispersed. While temperature and humidity influence fungal sporulation and germination, wind and rain accelerate conidial dissemination (27). To effectively manage this emerging disease, a thorough investigation of how the disease progresses under changing climatic conditions is required. Therefore, the present

investigation was carried out keeping in view the economic importance of bakanae and the role of weather parameters in disease progression.

2. Materials and Methods

Experimental site and design

The experiment was conducted during the kharif seasons of 2021 and 2022 at Chaudhary Charan Singh Haryana Agricultural University, Rice Research Station, Kaul, Kaithal, Haryana, India. The experimental site is located within the agro-climatically prominent North-West Plain Zone of India, a region known for the production of high-quality aromatic rice. Meteorological data were obtained from the on-site agrometeorological observatory located at the Rice Research Station, Kaul, Kaithal, Haryana, India. The Rice Research Station (RRS) is situated at latitude 29° 51' N, longitude 76° 39' E and an elevation of 230.7 m above mean sea level.

The experiment was laid out in a randomised block design (RBD) with 5 replications. Each treatment plot measured 5 × 3 m and seedlings were transplanted at a spacing of 20 × 15 cm. Two basmati rice varieties, Pusa Basmati 1121 and CSR 30, were used in the study.

Inoculum source and disease confirmation

The inoculum of *F. moniliforme* was isolated from infected rice plant tissues collected from the experimental trial fields and various regions of Haryana, India, during field surveys conducted in 2021 and 2022. Pure cultures were maintained on potato dextrose agar (PDA). To confirm pathogenicity and identity, Koch's postulates were fulfilled by inoculating healthy basmati rice plants, observing symptoms matching original field observations and consistently re-isolating the fungus from symptomatic tissues. Fungal identity was verified based on morphological characteristics and molecular confirmation was established using the translation elongation factor 1-alpha (TEF-1 α) gene marker, as described in our previous study (14). Disease development resulted from natural infection and no artificial inoculation was performed.

Disease assessment

Disease progression was measured on susceptible varieties at weekly intervals. Bakanae disease incidence was recorded visually as the percentage of infected plant based on a standardised high-throughput evaluation scale (15).

Percent disease incidence (PDI)=

Total number of infected plants/Total number of plants × 100

Sampling design and plant assessment

The progression of bakanae disease was evaluated using a whole-plot census approach across 10 experimental plots arranged systematically in an east-



to-west strip orientation. To maximise data reliability, all plants within each designated plot were comprehensively monitored, comprising 5 replicated plots per variety. The sampling intensity per experimental unit was robust, with individual plot populations ranging 364–495 plants. The total numbers of infected plants displaying diagnostic symptoms were recorded relative to the total plant population within each plot on the designated observation dates to calculate disease incidence.

Statistical analysis

Correlation coefficient, multiple regression analysis and area under disease progress curve (AUDPC) were computed between bakanae PDI and different weather parameters i.e., maximum and minimum temperatures ($^{\circ}\text{C}$; $T_{\text{max}}/T_{\text{min}}$), relative humidity morning and evening (%; RHM/RHE), bright sunshine hours (BSH) (hr), wind velocity (km/hr) and rainfall (mm) during kharif 2021, 2022 and pooled data for two basmati rice varieties (CSR 30 and PB 1121). Multicollinearity was monitored using variance inflation factor (VIF) diagnostics and all parameters met acceptable stability thresholds, reinforcing the validity of the high model fit ($R^2 = 0.85\text{--}0.99$). All experimental data were subjected to statistical analysis using the OPSTAT software package (28).

Calculation of the areas under the disease progress curve

The AUDPC was calculated using the standard epidemiological formula (29).

Table 1. Weather data from the 28th to 39th standard metrological week (SMW) during kharif 2021 growing season

Week No.	SMW	Temperature ($^{\circ}\text{C}$)		Rainfall (mm)	Relative humidity (%)		Wind velocity (km/hr)	BSH (hr)
		Max	Min		Morning	Evening		
28	09 July–15 July	34.1	26.0	8.7	88.3	75.0	6.9	6.9
29	16 July–22 July	32.9	26.1	204.2	91.7	78.0	4.3	4.1
30	23 July–29 July	33.8	24.2	151.6	92.9	79.9	4.0	3.4
31	30 July–05 August	34.4	25.3	27.3	93.3	69.7	2.9	2.5
32	06 August–12 August	34.1	26.7	0.0	90.9	72.3	2.6	4.8
33	13 August–19 August	34.7	26.1	0.0	90.9	68.9	3.1	9.0
34	20 August–26 August	32.5	25.5	74.5	92.9	78.4	3.6	3.3
35	27 August–2 September	32.6	24.6	8.3	94.7	78.0	2.9	5.8
36	03 September–09 September	32.7	24.4	34.7	94.9	77.4	2.5	4.6
37	10 September–16 September	36.5	23.8	35.0	94.6	83.1	3.0	4.0
38	17 September–23 September	37.0	24.9	28.7	94.6	78.1	2.4	6.1
39	24 September–30 September	37.7	23.2	37.5	94.9	67.7	2.0	3.8

SMW: standard meteorological weeks; BSH: bright sunshine hours.

$$\text{AUDPC} = \sum \frac{1}{2} (y_i + y_{i+1}) \times (t_{i+1} - t_i)$$

where k: number of successive evaluations; y_i : disease incidence at time t_i ; y_{i+1} : disease incidence at time t_{i+1} ; t_i : time when disease incidence was y_i ; t_{i+1} : time when disease incidence was y_{i+1} .

3. Results

The role of weather parameters in bakanae disease progression is presented. Two commonly grown aromatic rice varieties i.e., CSR 30 and PB 1121 and independent weather parameters viz., maximum and minimum temperatures ($^{\circ}\text{C}$; T_{max} and T_{min}), RHM and RHE (%), rainfall (mm), wind velocity (km/hr) and BSH (hr) were assessed during kharif 2021, 2022 and pooled.

Disease progression in CSR 30

The variety CSR 30 demonstrated greater resilience against bakanae disease, although it still showed a clear and steady progression of symptoms throughout the season. During the kharif 2021 season, disease incidence began at 15.0 % PDI and reached a maximum of 22.3 % by the end of the observation period. In the following year, kharif 2022, disease pressure was higher, starting at 18.0 % and increasing to 28.8 % PDI. On a pooled basis, the variety maintained a disease incidence range of 16.5 –25.5 % (Table 1–5, Fig. 2–5).



Table 2. Weather data from the 28th to 39th standard metrological week (SMW) during kharif 2022 growing season

Week No.	SMW	Temperature (°C)		Rainfall (mm)	Relative humidity (%)		Wind velocity (km/hr)	BSH (hr)
		Max	Min		Morning	Evening		
28	09 July–15 July	33.8	26.5	79.5	91.8	83.6	4.7	4.9
29	16 July–22 July	33.6	25.8	77.4	86.4	81.8	4.0	4.8
30	23 July–29 July	33.3	26.5	8.7	91.4	83.7	4.9	5.5
31	30 July–05 August	31.6	24.9	31.7	96.5	87.4	2.9	3.9
32	06 August–12 August	32.9	26.3	0.0	91.8	70.9	2.7	6.6
33	13 August–19 August	33.8	26.1	0.0	90.4	72.6	3.9	8.5
34	20 August–26 August	33.5	25.9	0.0	93.5	69.8	3.6	7.8
35	27 August–2 September	34.2	25.8	0.0	94.5	68.0	4.2	9.5
36	03 September–09 September	34.6	24.9	0.0	95.0	66.3	2.4	8.9
37	10 September–16 September	33.3	24.4	39.2	95.3	76.9	2.5	5.7
38	17 September–23 September	31.9	23.8	87.0	97.1	80.1	2.0	4.0
39	24 September–30 September	29.5	22.2	116.9	97.6	78.7	3.1	4.9

SMW: standard meteorological weeks; BSH: bright sunshine hours.

Table 3. Role of weather parameters on development of bakanae percent disease incidence (PDI) in basmati rice varieties CSR 30 and PB 1121 during kharif 2021

Week No.	PDI		SMW	Temperature (°C)		Rainfall (mm)	Relative humidity (%)		Wind velocity (km/hr)	BSH (hr)
	CSR 30	PB 1121		Max	Min		Morning	Evening		
28	15.0	19.1	09 July–15 July	34.1	26.0	8.7	88.3	75.0	6.9	6.9
29	15.2	19.2	16 July–22 July	32.9	26.1	204.2	91.7	78.0	4.3	4.1
30	16.4	20.5	23 July–29 July	33.8	24.2	151.6	92.9	79.9	4.0	3.4
31	16.6	20.7	30 July–05 August	34.4	25.3	27.3	93.3	69.7	2.9	2.5
32	17.1	21.3	06 August–12 August	34.1	26.7	0.0	90.9	72.3	2.6	4.8
33	17.1	21.3	13 August–19 August	34.7	26.1	0.0	90.9	68.9	3.1	9.0
34	18.3	22.5	20 August–26 August	32.5	25.5	74.5	92.9	78.4	3.6	3.3
35	18.6	22.7	27 August–2 September	32.6	24.6	8.3	94.7	78.0	2.9	5.8
36	19.3	23.4	03 September–09 September	32.7	24.4	34.7	94.9	77.4	2.5	4.6
37	19.5	23.8	10 September–16 September	36.5	23.8	35.0	94.6	83.1	3.0	4.0
38	20.2	24.3	17 September–23 September	37.0	24.9	28.7	94.6	78.1	2.4	6.1
39	22.3	26.4	24 September–30 September	37.7	23.2	37.5	94.9	67.7	2.0	3.8

SMW: standard meteorological weeks; BSH: bright sunshine hours; PDI: percent disease incidence.



Table 4. Role of weather parameters on development of bakanae percent disease incidence (PDI) in basmati rice varieties CSR 30 and PB 1121 during kharif 2022

Week No.	PDI		SMW	Temperature (°C)		Rainfall (mm)	Relative humidity (%)		Wind velocity (km/hr)	BSH (hr)
	CSR 30	PB 1121		Max	Min		Morning	Evening		
28	18.0	20.2	09 July–15 July	33.8	26.5	79.5	91.8	83.6	4.7	4.9
29	18.3	21.2	16 July–22 July	33.6	25.8	77.4	86.4	81.8	4.0	4.8
30	19.5	22.3	23 July–29 July	33.3	26.5	8.7	91.4	83.7	4.9	5.5
31	19.7	24.9	30 July–05 August	31.6	24.9	31.7	96.5	87.4	2.9	3.9
32	20.5	25.8	06 August–12 August	32.9	26.3	0.0	91.8	70.9	2.7	6.6
33	21.3	26.4	13 August–19 August	33.8	26.1	0.0	90.4	72.6	3.9	8.5
34	22.4	27.5	20 August–26 August	33.5	25.9	0.0	93.5	69.8	3.6	7.8
35	23.8	28.9	27 August–2 September	34.2	25.8	0.0	94.5	68.0	4.2	9.5
36	25.7	29.4	03 September–09 September	34.6	24.9	0.0	95.0	66.3	2.4	8.9
37	26.3	30.2	10 September–16 September	33.3	24.4	39.2	95.3	76.9	2.5	5.7
38	27.9	32.4	17 September–23 September	31.9	23.8	87.0	97.1	80.1	2.0	4.0
39	28.8	34.6	24 September–30 September	29.5	22.2	116.9	97.6	78.7	3.1	4.9

SMW: standard meteorological weeks; PDI: percent disease incidence; BSH: bright sunshine hours.

Table 5. Role of weather parameters on development of bakanae percent disease incidence (PDI) in basmati rice varieties CSR 30 and PB 1121 during kharif 2021 and 2022

Week No.	PDI		SMW	Temperature (°C)		Rainfall (mm)	Relative humidity (%)		Wind velocity (km/hr)	BSH (hr)
	CSR 30	PB 1121		Max	Min		Morning	Evening		
28	16.5	19.6	09 July–15 July	33.9	26.2	44.1	90.0	79.3	5.8	5.9
29	16.7	20.2	16 July–22 July	33.2	25.9	140.8	89.0	79.9	4.1	4.4
30	17.9	21.4	23 July–29 July	33.5	25.3	80.1	92.1	81.8	4.4	4.4
31	18.1	22.8	30 July–05 August	33.0	25.1	29.5	94.9	78.5	2.9	3.2
32	18.8	23.5	06 August–12 August	33.5	26.5	0.0	91.3	71.6	2.6	5.7
33	19.2	23.8	13 August–19 August	34.2	26.1	0.0	90.6	70.7	3.5	8.7
34	20.3	25.0	20 August–26 August	33.0	25.7	37.2	93.2	74.1	3.6	5.5
35	21.2	25.8	27 August–2 September	33.4	25.2	4.1	94.6	73.0	3.5	7.6
36	22.5	26.4	03 September–09 September	33.6	24.6	17.3	94.9	71.8	2.4	6.7
37	22.9	27.0	10 September–16 September	34.9	24.1	37.1	94.9	80.0	2.7	4.8
38	24.0	28.3	17 September–23 September	34.4	24.3	57.8	95.8	79.1	2.2	5.0
39	25.5	30.5	24 September–30 September	33.6	22.7	77.2	96.2	73.2	2.5	4.3

SMW: standard meteorological week; PDI: percent disease incidence; BSH: bright sunshine hours.



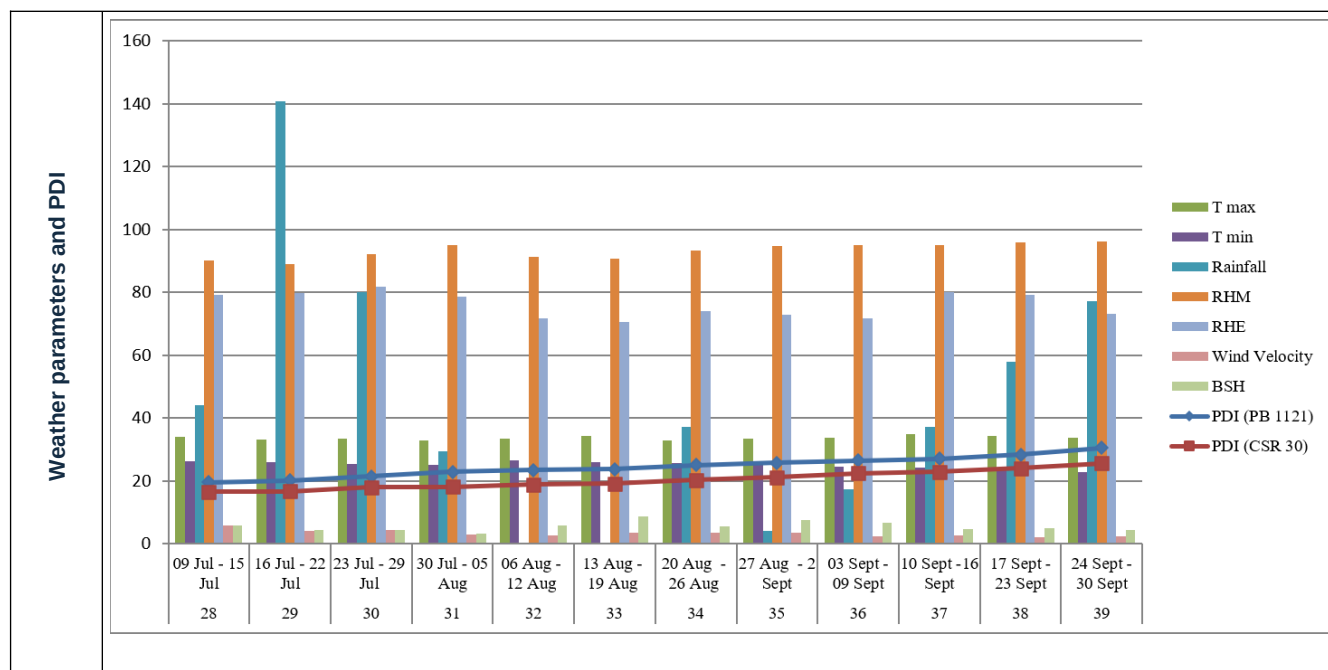
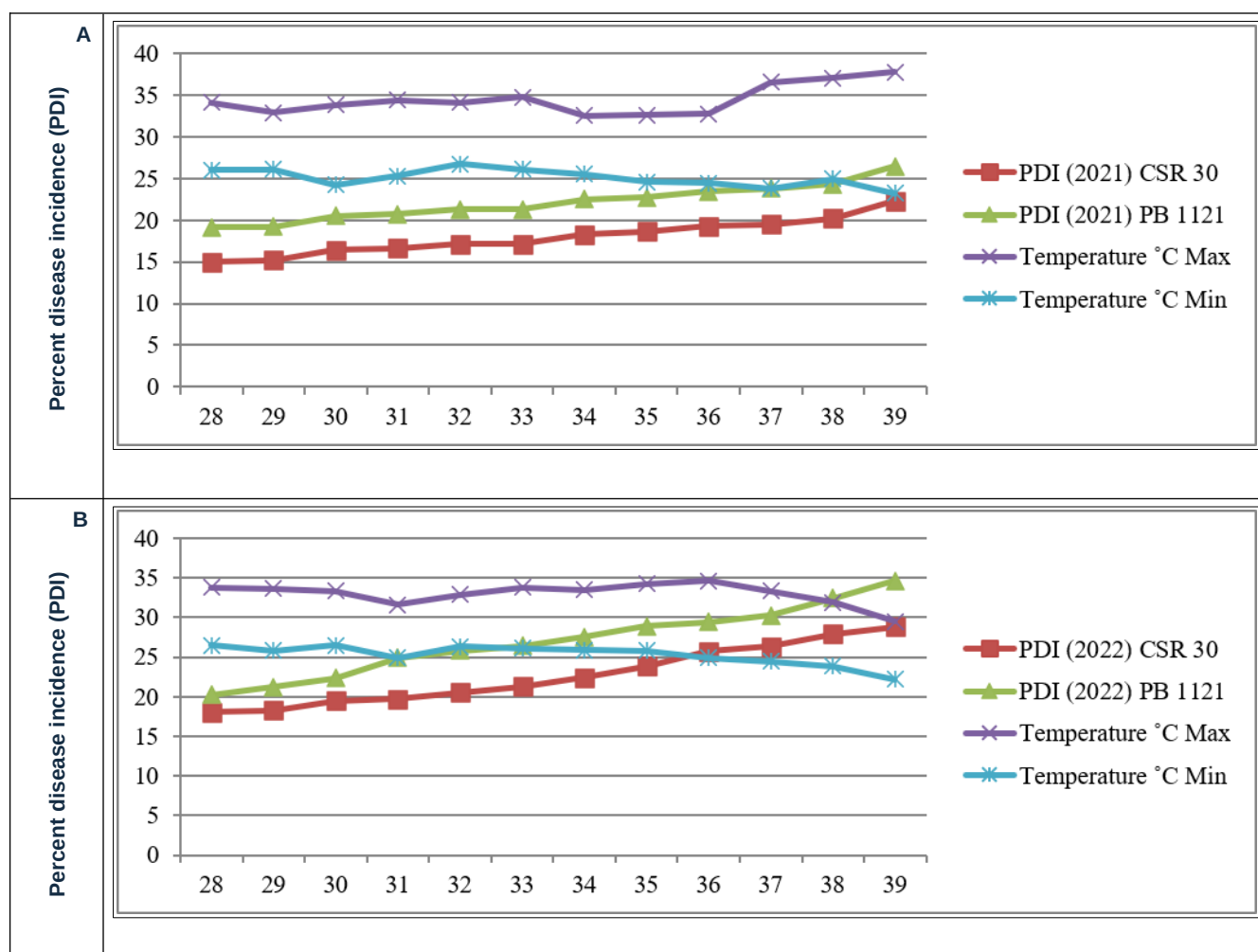


Fig. 2. Relationship between weather parameters and bakanae percent disease incidence (PDI) in basmati rice varieties CSR 30 and PB 1121 during kharif 2021 and 2022 (pooled).



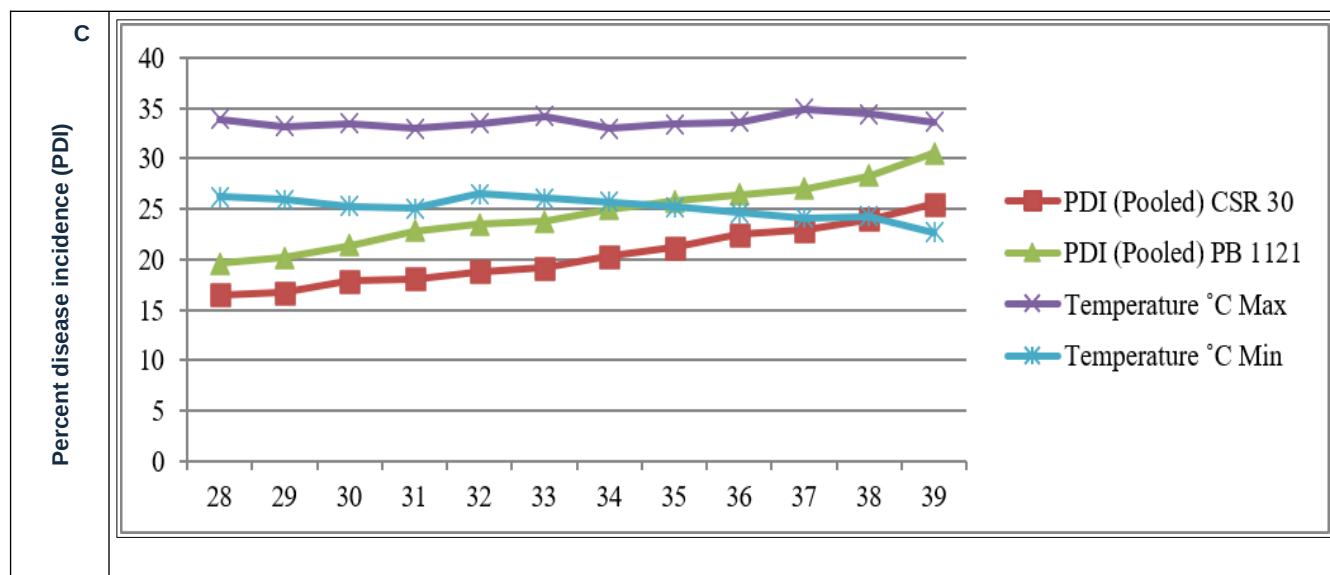
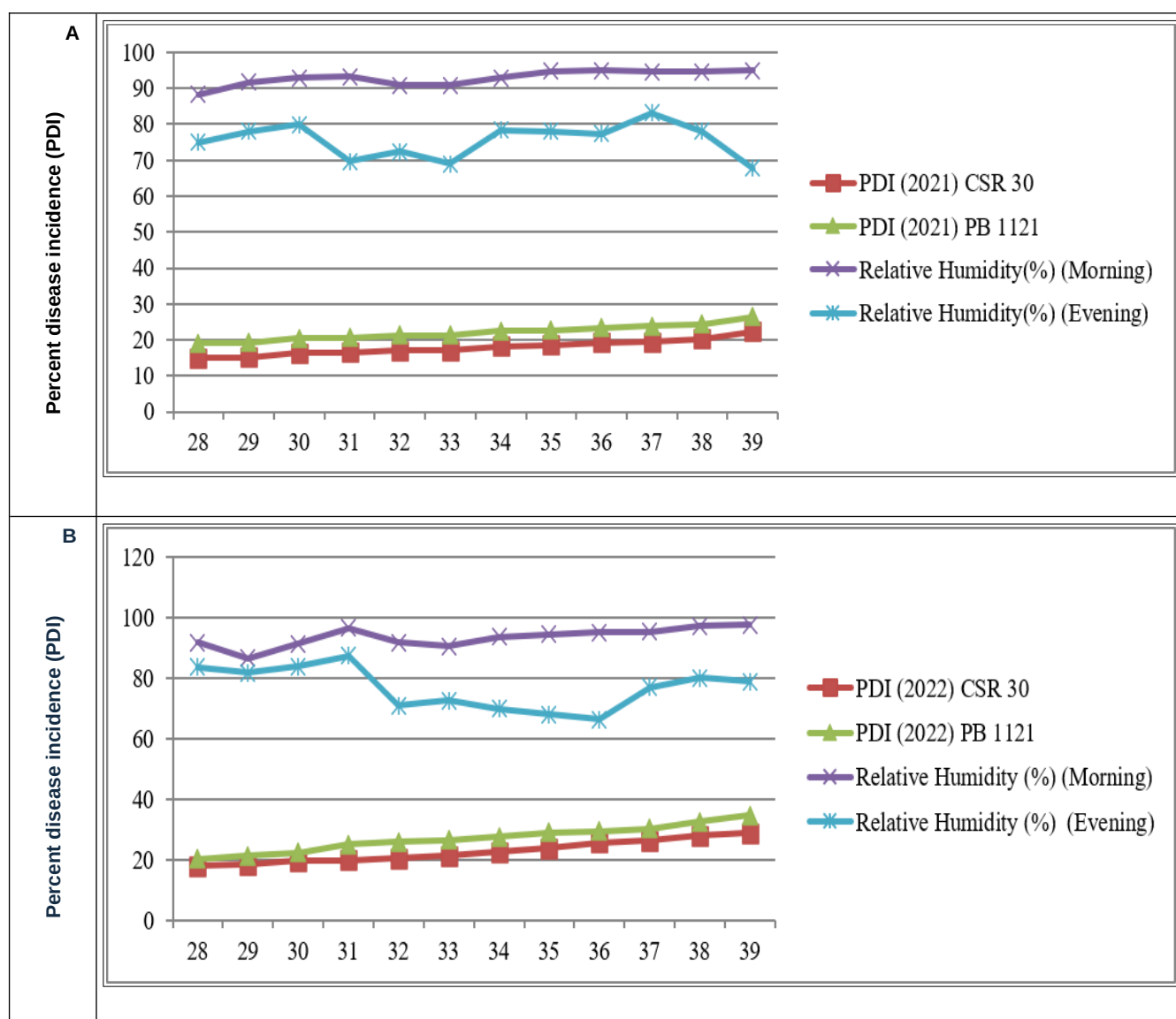


Fig. 3. Impact of maximum (T_{max}) and minimum (T_{min}) temperatures on bakanae disease progression during kharif. A: 2021; B: 2022; C: pooled.



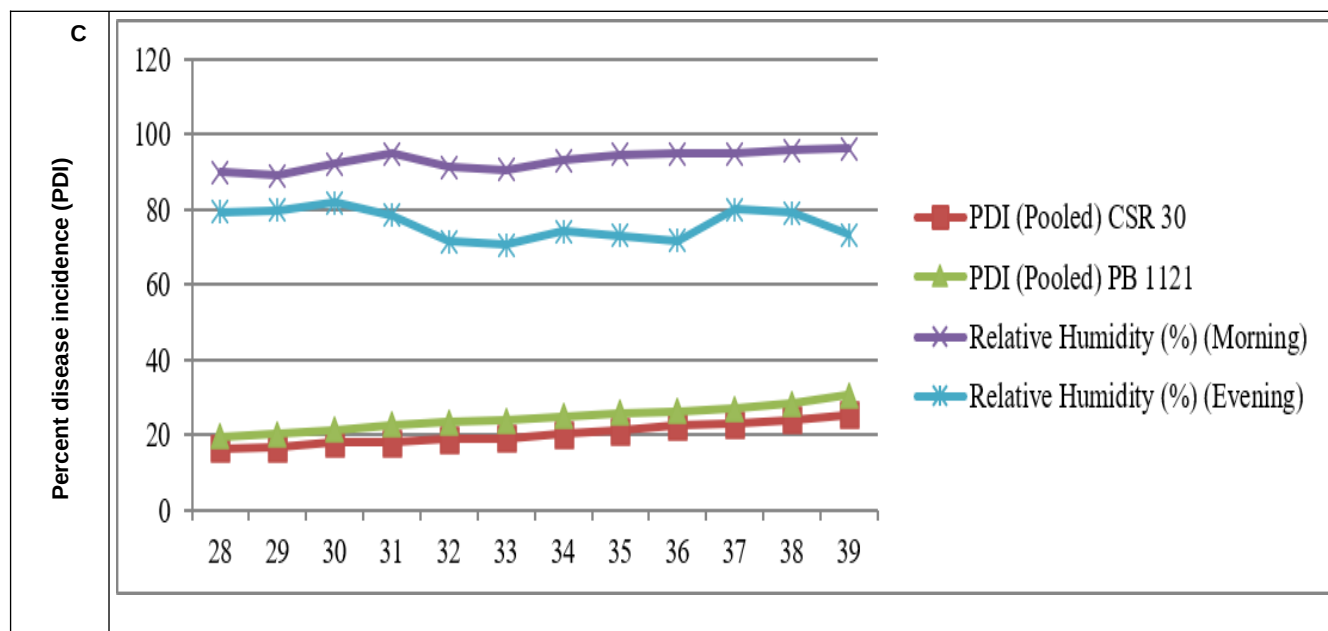


Fig. 4. Impact of relative humidity in the morning (RHM) and evening (RHE) on bakanae disease progression during kharif. A: 2021; B: 2022; C: pooled.

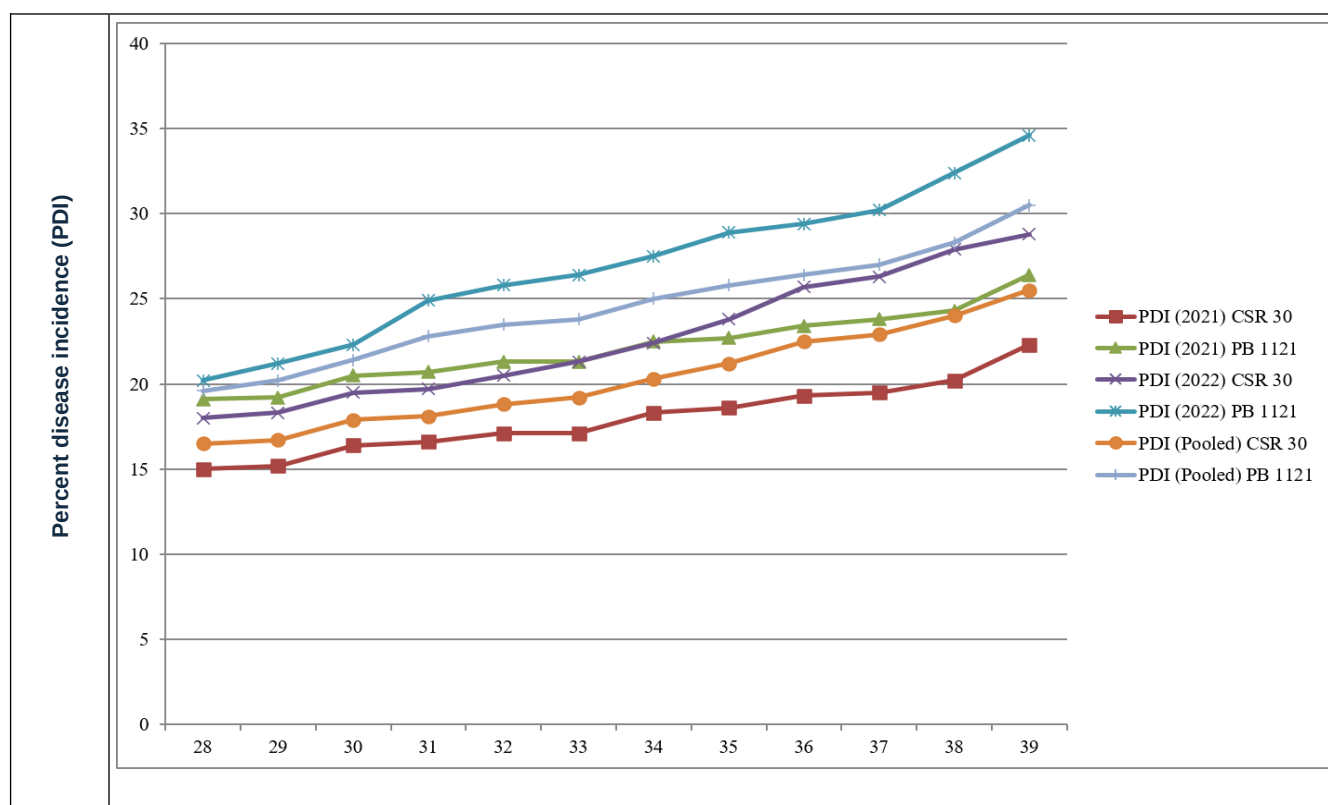


Fig. 5. Comparison of percent disease incidence (PDI) of bakanae in varieties CSR 30 and PB 1121 during kharif 2021, 2022 and pooled.

Influence of weather parameters on disease progression (CSR 30)

During the kharif 2021 season, the maximum temperature fluctuated between 32.5 and 37.7 °C, with the highest disease incidence was occurring at 37.7 °C and the lowest at 34.1 °C. Minimum

temperatures ranged 23.2–26.7 °C. The RHM ranged 88.3–94.9 %, where the peak disease levels aligned with the maximum humidity of 94.9 %. Wind velocity varied from 2.0–6.9 km/hr and notably, the highest PDI (22.3 %) was recorded at the minimum wind speed of 2.0 km/hr. Rainfall was highly variable,

reaching up to 204.2 mm, while the lowest disease incidence was observed when BSH reached 6.9 hr.

In kharif 2022, the maximum temperature ranged 29.5–34.6 °C, with the highest incidence recorded at the lower end of the range (29.5 °C) and the lowest at 33.8 °C. Minimum temperatures ranged 22.2–26.5 °C. The RHM ranged 86.4–97.6 %, with the highest incidence occurring at 97.6 %. Wind velocity remained between 2.0 and 4.9 km/hr, with peak incidence noted at 3.1 km/hr. Rainfall fluctuated between 0.0 and 116.9 mm, while the highest PDI was recorded at 4.3 hr of sunshine.

The pooled data across both seasons indicated that the maximum temperature varied from 33.0–34.9 °C, with peak PDI observed at 33.6 °C. Minimum temperatures ranged from 22.7–26.5 °C, while RHM ranged from 89.0–96.2 %, with peak disease incidence observed at the upper limit. Wind velocity ranged from 2.2–5.8 km/hr, with the highest disease pressure occurring at 2.5 km/hr. Rainfall ranged from 0.0–140.8 mm and BSH ranged from 3.2–8.7 hr, with peak disease incidence observed at 4.3 hr (Table 1–5; Fig. 2–5).

Disease progression in PB 1121

The variety PB 1121 proved to be more susceptible, consistently recording the highest levels of disease incidence and progression across all trials. During kharif 2021, PDI began at 19.1 % and peaked at 26.4 %, while in kharif 2022, the variety experienced severe infection, starting at 20.2 % and increasing to a study-high of 34.6 % PDI. The pooled data reflected this trend, with a range of 19.6–30.5 % (Tables 1–5, Fig. 2–5).

Influence of weather parameters on disease progression (PB 1121)

During the kharif 2021 and 2022 seasons, the PDI for rice variety PB 1121 demonstrated significant fluctuations influenced by prevailing weather parameters. In 2021, PDI ranged 19.1–26.4 %, with the peak incidence coinciding with a maximum temperature of 37.7 °C, RHM of 94.9 % and low wind velocity of 2.0 km/hr. Conversely, the lowest incidence (19.1 %) was observed at a lower humidity of 88.3 % and a higher wind speed of 6.9 km/hr. Rainfall during this period reached a weekly maximum of 204.2 mm, while BSH peaked at 9.0 hr, although the highest disease pressure was observed at 3.8 hr.

The kharif 2022 season recorded a higher PDI range of 20.2–34.6 %. Interestingly, the maximum incidence (34.6 %) occurred at a lower maximum temperature of 29.5 °C and a higher RHM of 97.6 %. Wind velocity remained low, ranging from 2.0–4.9 km/hr, with PDI recorded at 3.1 km/hr. Rainfall was notably lower than in the previous year, reaching a maximum of 116.9 mm, while BSH fluctuated between 3.9 and 9.5 hr.

Analysis of the pooled data provides a consolidated PDI range of 19.6–30.5 %. The findings

suggest that peak disease pressure (30.5 %) is most likely to occur when maximum temperatures are around 33.6 °C and RHM reaches 96.2 %. Furthermore, lower wind velocities (approximately 2.5 km/hr) appear to favour disease progression, whereas higher wind velocities (approximately 5.8 km/hr) correspond to lower disease incidence (Table 1–5, Fig. 2–5).

Correlation and multiple regression between bakanae percent disease incidence in variety CSR 30 and weather parameters during kharif 2021, 2022 and pooled

During kharif 2021, maximum temperature ($T_{\max}$) showed a positive correlation with bakanae disease incidence in CSR 30 ($r = 0.603$), whereas during kharif 2022 and in the pooled data, $T_{\max}$ showed a non-significant relationship with disease incidence. During 2021, 2022 and the pooled period, minimum temperature ($T_{\min}$) showed a highly significant negative correlation with disease incidence, with r values of -0.730 in 2021 and -0.836 in 2022 for CSR 30. Rainfall showed a non-significant relationship with disease incidence. During 2021, 2022 and the pooled period, RHM showed a highly significant positive correlation with disease incidence, with r values of 0.788 in 2021 and 0.754 in 2022 for CSR 30. The RHE showed a non-significant relationship with disease incidence during 2021, 2022 and the pooled period. Wind velocity showed a negative correlation with bakanae disease incidence, with r values of -0.734 in 2021 and -0.659 in 2022 for CSR 30. The BSH had no significant impact on disease incidence (Table 6).

Correlation and multiple regression between bakanae percent disease incidence in variety PB 1121 and weather parameters during kharif 2021, 2022 and pooled

During kharif 2021, maximum temperature showed a positive correlation with bakanae disease incidence in PB 1121 ($r = 0.609$), whereas during kharif 2022 and in the pooled data, it showed a non-significant relationship with disease incidence. During 2021, 2022 and the pooled period, minimum temperature showed a highly negative correlation with disease incidence, with r values of -0.722 in 2021 and -0.825 in 2022 for PB 1121. Rainfall showed a non-significant relationship with disease incidence. During 2021, 2022 and pooled period, RHM showed a highly positive correlation with disease incidence with r values of 0.778 in 2021 and 0.775 in 2022 for PB 1121. During 2021, 2022 and pooled periods, RHE exhibited a non-significant relationship with disease incidence. Wind velocity showed a negative correlation with bakanae disease incidence, with r values of -0.734 in 2021 and -0.680 in 2022 for PB 1121. The BSH had no significant impact on disease incidence (Table 6).

Coefficients of determination (R^2 values)

The coefficient of determination (R^2) values ranged from 0.85–0.99 during kharif 2021, 2022 and the



pooled period for both varieties, indicating that 85–99 % of the variation in disease incidence was explained by the weather parameters. The R^2 values for PB 1121 were 0.85, 0.94 and 0.98 during kharif 2021, 2022 and

the pooled period respectively, while those for CSR 30 were 0.85, 0.93 and 0.99 respectively (Table 6).

Table 6. Simple correlation and multiple regression analysis between bakanae percent disease incidence and weather parameters in varieties CSR 30 and PB 1121 during kharif 2021 and 2022

Year	Varieties	T _{Max}	T _{Min}	Rainfall	RHM	RHE	Wind velocity	BSH
2021	CSR 30	0.603*	-0.730**	-0.338 ^{NS}	0.788**	-0.063 ^{NS}	-0.734**	-0.125 ^{NS}
2021	PB 1121	0.609*	-0.722**	-0.353 ^{NS}	0.778**	-0.059 ^{NS}	-0.734**	-0.116 ^{NS}
2022	CSR 30	-0.417 ^{NS}	-0.836**	0.271 ^{NS}	0.754**	-0.344 ^{NS}	-0.659*	0.091 ^{NS}
2022	PB 1121	-0.485 ^{NS}	-0.825**	0.190 ^{NS}	0.775**	-0.393 ^{NS}	-0.680*	0.141 ^{NS}
2021 and 2022	CSR 30	0.401 ^{NS}	-0.857**	-0.129 ^{NS}	0.845**	-0.291 ^{NS}	-0.742**	0.013 ^{NS}
2021 and 2022	PB 1121	0.335 ^{NS}	-0.820**	-0.203 ^{NS}	0.851**	-0.379 ^{NS}	-0.789**	0.032 ^{NS}

Multiple regression									
Year	Varieties	Equations					R ²	Adj. R ²	p-value
2021	CSR 30	Y = -6.992 + 0.275X ₁ - 0.603X ₂ - 0.006 X ₃ + 0.346 X ₄ - 0.004X ₅ - 0.415X ₆ + 0.1 X ₇					0.85	0.60	0.127
2021	PB 1121	Y = 4.909 + 0.2853X ₁ - 0.655X ₂ - 0.007X ₃ + 0.265 X ₄ + 0.012X ₅ - 0.508X ₆ + 0.91 X ₇					0.85	0.60	0.128
2022	CSR 30	Y = 81.804 + 1.158 X ₁ - 3.379X ₂ - 0.02 X ₃ + 0.301X ₄ - 0.457X ₅ + 1.294X ₆ - 1.397 X ₇					0.93	0.82	0.029
2022	PB 1121	Y = 99.682 - 0.137X ₁ - 2.623X ₂ - 0.016 X ₃ + 0.298 X ₄ - 0.362 X ₅ - 0.326 X ₆ - 0.413 X ₇					0.94	0.84	0.022
2021 and 2022	CSR 30	Y = -257.496 + 3.699 X ₁ + 1.641 X ₂ + 0.065 X ₃ + 1.774 X ₄ - 0.745 X ₅ + 0.797 X ₆ - 0.369 X ₇					0.99	0.97	0.001
2021 and 2022	PB 1121	Y = -262.01 + 3.814 X ₁ + 1.824 X ₂ + 0.065 X ₃ + 1.897 X ₄ - 0.876 X ₅ + 0.729 X ₆ - 0.555 X ₇					0.98	0.99	0.001

**Correlation is significant at the 0.01 level; *Correlation is significant at the 0.05 level.

X₁: maximum temperature; X₂: minimum temperature; X₃: total rainfall; X₄: relative humidity morning; X₅: relative humidity evening; X₆: wind velocity; X₇: bright sunshine hours.

Area under disease progress curve

The disease progression during various standard meteorological weeks (SMW) was computed by AUDPC starting from disease appearance till crop maturity during kharif 2021 and 2022 (Table 7, Fig. 6 and 7). The AUDPC was higher in PB 1121 than in CSR 30 during kharif 2021, 2022 and the pooled period, with disease progression increasing from the 28th to the 39th SMW. The AUDPC for CSR 30 was 1431.14 during kharif 2021 and 1804.60 during kharif 2022. For PB 1121, the AUDPC was 1766.90 during kharif 2021 and increased to 2145.50 during kharif 2022. The pooled AUDPC was 1617.87 for CSR 30 and 1953.35 for PB 1121.

4. Discussion

The quantitative analysis of bakanae disease progression in the north-western region of Haryana reveals that environmental variables are the primary determinants of disease incidence. The findings of the present study indicate that PB 1121 is significantly more susceptible to *F. moniliforme* than CSR 30, with disease incidence showing a consistent temporal increase from week 28 through week 39. During kharif 2021, maximum temperature showed positive correlation with bakanae disease incidence. Minimum temperature exhibited a strong negative correlation with the PDI. Rainfall had a non-significant relationship with disease incidence. The RHM had a highly positive correlation with PDI, whereas the RHE



had a non-significant relationship with disease incidence. Wind velocity showed a negative correlation with bakanae PDI. The BSH had no impact on disease incidence. The high coefficient of

determination (0.85–0.99) underscores the reliability of meteorological parameters as predictors of disease outbreaks in this high-quality aromatic rice zone.

Table 7. Area under disease progress curve (AUDPC) of bakanae in varieties CSR 30 and PB 1121 during kharif 2021 and 2022

Week No.	SMW	AUDPC (2021)		AUDPC (2022)		AUDPC (2021 and 2022) pooled	
		Varieties		Varieties		Varieties	
		CSR 30	PB 1121	CSR 30	PB 1121	CSR 30	PB 1121
28	09 July–15 July	52.5	67.0	63.0	70.7	57.7	68.6
29	16 July–22 July	105.7	134.4	127.0	144.9	116.3	139.3
30	23 July–29 July	110.6	139.1	132.3	152.2	121.4	145.6
31	30 July–05 August	115.5	144.2	137.2	165.2	126.3	154.7
32	06 August–12 August	117.9	147.2	140.7	177.4	129.3	162.0
33	13 August–19 August	119.7	149.4	146.3	182.7	133.0	165.5
34	20 August–26 August	123.9	153.5	152.9	188.6	138.4	170.8
35	27 August–2 September	129.1	158.3	161.7	197.4	145.4	177.8
36	03 September–09 September	132.6	161.5	173.2	204.0	152.9	182.7
37	10 September–16 September	135.8	165.5	182.0	208.6	158.9	186.9
38	17 September–23 September	138.9	168.7	189.7	219.1	164.3	193.5
39	24 September–30 September	148.7	177.8	198.4	234.5	173.6	205.8
Total	AUDPC	1431.1	1766.9	1804.6	2145.5	1617.8	1953.3

SMW: standard meteorological week; PDI: percent disease incidence; BSH: bright sunshine hours.

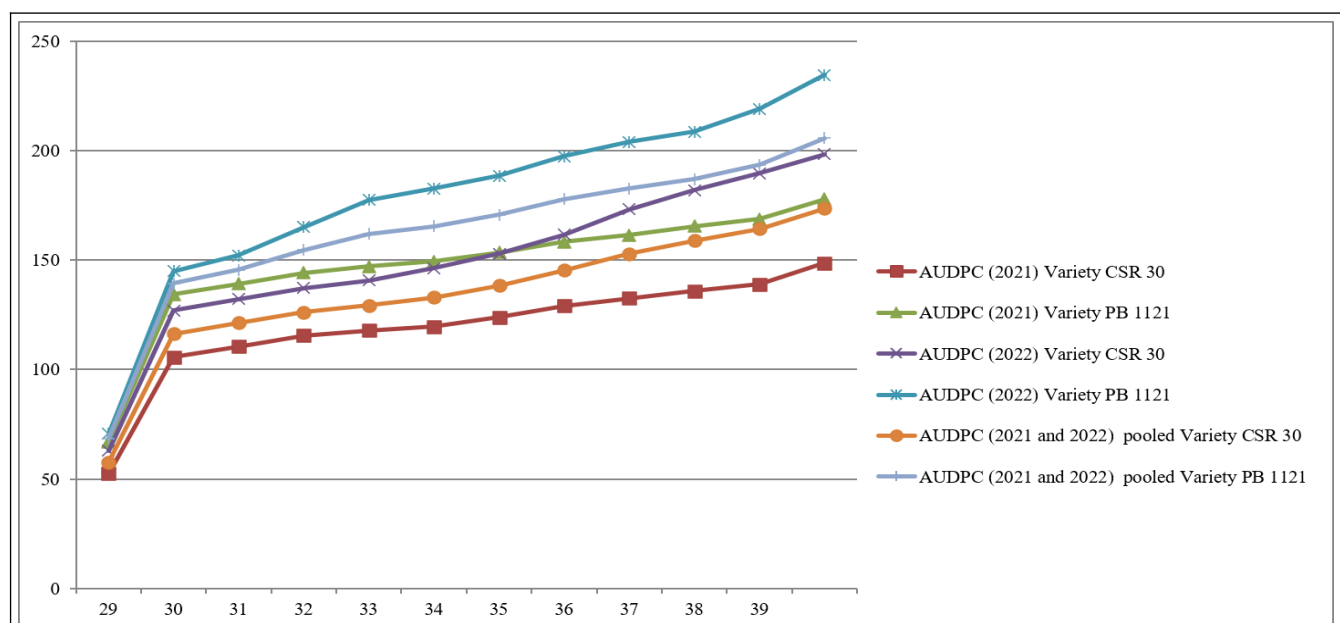


Fig. 6. Area under disease progress curve (AUDPC) of bakanae in varieties CSR 30 and PB 1121 during kharif 2021, 2022 and pooled.

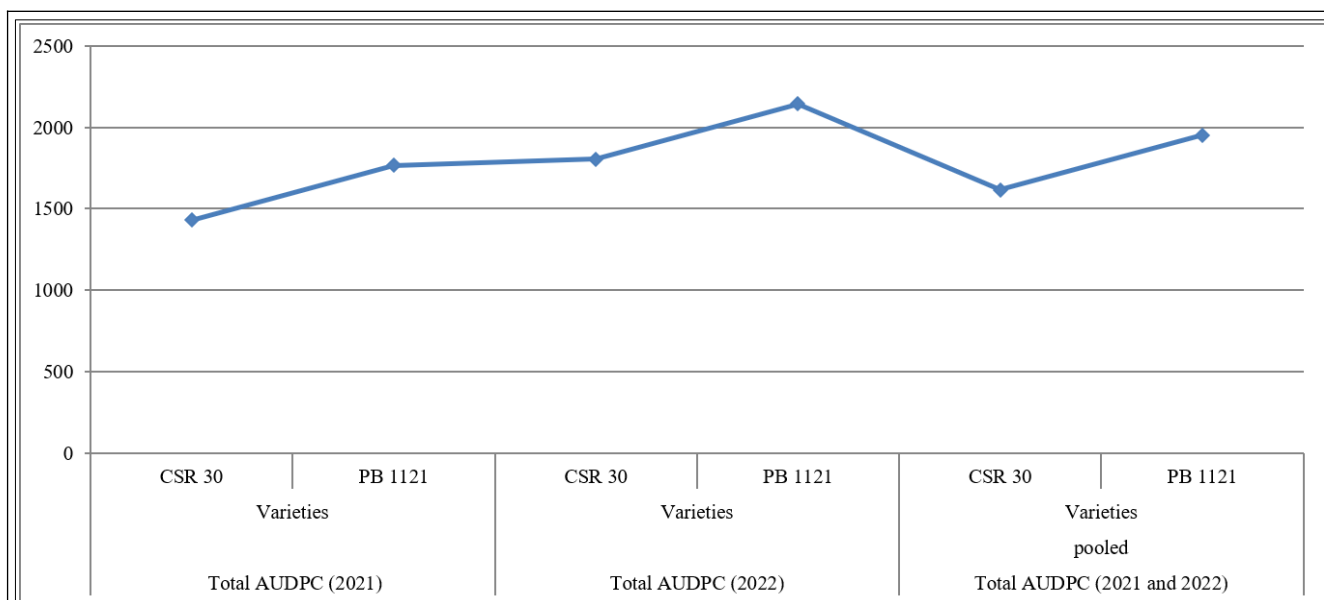


Fig. 7. Total area under disease progress curve (AUDPC) of bakanae in varieties CSR 30 and PB 1121 during kharif 2021, 2022 and pooled.

The epidemiological aspects of rice bakanae disease in relation to environmental conditions have received very little research attention. It is necessary to understand the relationship between the host, pathogen and environmental conditions in bakanae disease in order to manage the disease effectively. Weather influences all stages of the host and pathogen life cycles, as well as disease development. Relationships between weather and disease are routinely used for forecasting and managing epidemic diseases. The present investigation aligns closely with earlier epidemiological and forecasting studies on bakanae disease under diverse rice-growing environments. Temperature and RHM were the most influential abiotic factors governing PDI and showed a significant positive correlation with disease progression. The positive correlation between maximum temperature and PDI observed in 2021 suggests that warmer daytime temperatures accelerate symptom expression, which aligns with the findings of previous studies (30). Conversely, the strong negative correlation with minimum temperature indicates that cooler nights may inhibit pathogen colonisation. This supports the reported thermal optimum of 27–35 °C for disease advancement and the intensified grain infection during the flowering phase reported in previous studies (27, 31). Foot rot disease was also reported to be favoured by high air temperature during the initial growth stage (32). However, the minimum air temperature remained similar across all growing environments and showed no significant effect on foot rot incidence under different planting dates.

The present study revealed a significant positive correlation between maximum temperature and bakanae disease incidence during kharif 2021,

this relationship became non-significant during kharif 2022. This discrepancy was primarily driven by an overall downward shift in the daytime temperature profile during the second trial year. Warmer conditions in 2021 favoured rapid symptom expression, whereas the cooler 2022 season was characterised by near-saturation atmospheric conditions, with RHM reaching up to 97.6 %. Consequently, this extremely high humidity emerged as the dominant environmental driver, effectively masking the linear influence of daily maximum temperature. This shift in microclimatic dominance explains the altered correlation dynamics observed between the two trial years.

In this study, RHM acted as a critical facilitator of sporulation and subsequent infection. Although rainfall showed a non-significant relationship with disease incidence, heavy precipitation may occasionally wash conidia from the phyllosphere; however, high humidity generally remains the dominant driver of the “bakanae effect” (elongation), which is supported by the findings of a previous study (33). High temperature and high relative humidity greatly favour bakanae disease in transplanted rice plants compared with direct-seeded rice plants. In support of the present study, a previous study reported that maximum temperature and RHM are the primary drivers of rice sheath blight, showing a strong positive correlation with disease incidence (34). Similarly, previous workers found that maximum air temperature and RHM were the key factors governing disease development in the field (35). The maximum temperature of around 34 °C and high relative humidity (more than 90 %) facilitate the spread of this disease.

Dispersal and survival mechanisms are vital for understanding the polycyclic potential of bakanae disease. Although wind velocity showed a negative correlation with PDI in the present field trials, wind and water remain the primary vehicles for conidial dispersal. Airborne ascospores produced during the blossoming stage are particularly critical for infecting the next generation of seeds (36, 37). In the present study, the negative correlation between wind velocity and bakanae disease incidence is primarily attributed to the mechanical disruption of the canopy boundary layer, which accelerates moisture evaporation from plant surfaces. This wind-induced drying lowers local canopy relative humidity below the critical threshold required for conidial germination and host colonisation. Furthermore, higher wind velocities dilute airborne spore clouds rather than promoting targeted floral deposition, thereby effectively suppressing disease progression.

The results of this study reinforce the finding that infected seeds are the principal source of primary inoculum (38, 39). Although the pathogen can persist as macroconidia or thick-walled hyphae in soil debris for up to 120 days, it is categorised as a weak soil dweller (40). The rapid decline of soil inoculum following host tissue breakdown highlights the effectiveness of using clean, certified seed lots to minimise field prevalence (41).

Similarly, a previous study also supports that effective management of this emerging threat requires a holistic understanding of the host–pathogen–environment interaction (42).

The calculated AUDPC values based on pooled data for CSR 30 (1617.8) and PB 1121 (1953.3) demonstrate an exceptionally high level of disease progression during the trial seasons. These indices are substantially higher than the baseline AUDPC range of 401–700 established by a previous study (43) for benchmarking susceptible short-grained aromatic rice genotypes. This pronounced elevation highlights that traditional field transplanting practices in North-West India create a highly conducive environment for severe bakanae epidemics compared with standard glasshouse screening baselines.

Research on the role of weather parameters in disease incidence is essential before formulating management measures. The data from this study suggest that forecasting models based on maximum temperature and RHM could provide an early warning system for farmers in Haryana. By integrating weather-based disease forecasting with the cultivation of less susceptible varieties such as CSR 30 and the use of pathogen-free seeds, economic losses, which can reach up to 95 % in this region, can be significantly mitigated. This study also provides valuable information for formulating breeding programs to develop resistant varieties and management strategies for preventing bakanae

disease. Although this study evaluated bakanae disease progression only in two basmati cultivars (PB 1121 and CSR 30), these varieties represent the majority of the commercial basmati acreage in the region. CSR 30 and PB 1121 serve as ideal contrasting baseline models because of their distinct growth habits and regional economic importance. Consequently, although the exact regression models may show minor variations across a broader range of rice germplasm, the epidemiological trends and weather correlations established in this study provide a strong foundation for regional basmati disease forecasting and management.

5. Conclusion

Bakanae disease incidence was higher in PB 1121 than in CSR 30, and it increased progressively on a week-to-week basis in both varieties, as concluded in the present study. Relative humidity in the morning (RHM) showed a highly positive correlation with percent disease incidence (PDI) and played an important role in disease progression. During kharif 2021, maximum temperature (T_{max}) showed a positive correlation with bakanae disease incidence, whereas rainfall had a non-significant relationship with disease incidence. Wind velocity showed a negative correlation with bakanae PDI, while bright sunshine hours (BSH) had no significant impact on disease incidence. The progression of bakanae disease in rice is greatly influenced by environmental factors. Understanding meteorological patterns can assist in predicting bakanae disease in rice, thereby facilitating the development of effective disease management strategies.

This study demonstrates that environmental parameters, particularly RHM and maximum temperature, are the primary drivers of bakanae disease progression in aromatic rice, future research should be built upon these findings to develop more resilient agricultural systems. Future investigations should focus on developing regional computational forecasting models that provide early warnings to farmers based on real-time microclimatic thresholds. Additionally, comprehensive breeding programs should be developed using molecular markers to introduce broad-spectrum resistance into highly susceptible basmati cultivars such as Pusa Basmati 1121.

Acknowledgements

The authors are grateful to the Regional Director, Rice Research Station, Kaul, Kaithal, and the Professor and Head, Department of Plant Pathology, Chaudhary Charan Singh Haryana Agricultural University, Hisar, for providing the resources required to carry out these experiments.



Authors' contributions

VS and AK conceptualised the study, performed the formal analysis and wrote the original draft. VS curated the data. VS, AK, PK, MSB and NR developed the methodology and reviewed and edited the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

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