

Wheat Rust Epidemiology Across Various Sowing Windows at Two Agroclimatic Locations of Punjab

Shubham Anand¹, Sarabjot Kaur Sandhu¹, Barun Biswas¹ and Parminder Singh Tak²

¹ Department of Climate Change and Agricultural Meteorology, Punjab Agricultural University, Ludhiana

² Department of Plant Pathology, Punjab Agricultural University, Ludhiana

Article history:

Received: 25 Nov., 2025

Revised: 31 Dec., 2025

Accepted: 16 Jan., 2026

Citation:

Anand S, SK Sandhu, B Biswas and PS Tak. 2026. Wheat Rust Epidemiology Across Various Sowing Windows at Two Agroclimatic Locations of Punjab. *Journal of Cereal Research* **18 (1)**: 69-80. <http://doi.org/10.25174/2582-2675/2026/173258>

*Corresponding author:

E-mail: sanand@pau.edu

© Society for Advancement of Wheat and Barley Research

Abstract

Yellow and brown rust severities were studied in three wheat varieties viz., PB 725, HD 2967 and HD 3086 sown on different dates (14th-15th October, 8th-9th November and 3rd-4th December) with two microclimate modification levels M₁ (recommended irrigation) and M₂ (additional water sprays). Yellow rust severity was reported to be highest in variety HD 2967 while brown rust severity was highest in variety HD 3086 in early date of sowing and M₂ microclimate modification level. The yellow rust disease progression was slow at Ludhiana than Gurdaspur while brown rust disease progression was slow at Gurdaspur than Ludhiana. A significant positive correlation was found between maximum temperature, minimum temperature, sunshine hours with yellow and brown rust disease severities. Morning relative humidity and evening relative humidity had negative correlation with disease severities. Rainfall was negatively correlated with yellow rust severity. From regression analysis, it was concluded that minimum temperature, morning relative humidity, sunshine hours and rainfall were found to be important in rust spread in wheat.

Keywords: Yellow rust, Brown rust, Date of sowing, Correlation coefficient, Regression analysis

1. Introduction

Climate change is now an undeniable reality, with its growing influence on wheat-producing regions (Portner, 2022). Extensive research consistently points to significant reductions in wheat yields due to global warming (Wang *et al.*, 2020; Zhao *et al.*, 2016). The Earth's average temperature has been steadily rising, resulting in more frequent and intense heat waves worldwide. In India, March and April 2022 were the hottest on record with heat wave struck at a grain filling stage leading to grain yellowing, shrivelling and early maturity, ultimately reducing yields by 15-25% (Bal *et al.*, 2022).

Such changes bear critical implications for wheat cultivation, given the principal role of temperature in crop-pathogen interactions. Elevated temperatures and increased humidity could enhance the susceptibility of

crops to severe infections. Diseases such as yellow rust and Karnal bunt may experience reduced susceptibility windows due to changing temperature and humidity fluctuations whereas brown rust, foliar blights and head scab might witness expanded windows. Concerningly, stem rust vulnerability could increase in future varieties adapted to temperate climates (Kaur *et al.*, 2008). Yellow rust (*Puccinia striiformis* f.sp. *tritici*) has been presented in mild to severe forms since 2008 (Pannu *et al.*, 2010). It has resulted in yield losses up to 68.8 per cent (monetary loss of Rs. 236 crore) in Punjab during the epidemic year of 2009-10 (Jindal *et al.*, 2012). In contrast, leaf rust (*Puccinia triticina*) is prevalent wherever wheat is grown (Gangwar *et al.*, 2019).



A disease occurs when a pathogen meets the right host organism under favourable environmental conditions. The concept of disease triangle is by no means new to addition of one or more parameters like humans, vectors, and time by Francl (2001). Stripe rust occurrence is favored by moderately low temperatures and high humidity, with specific temperature conditions during the early growth stage of wheat (Dutta *et al.*, 2014). Suitable planting date is important, so that wheat can flower when there are fewer biotic and abiotic stresses (Zheng *et al.*, 2012). The suggested sowing window for long-lasting wheat varieties in Punjab state (which farmers primarily prefer) spans from the last week of October to the last week of November (Bhatti 2018). Significant meteorological parameter variations have been seen in Punjab (Kaur *et al.*, 2016), which could have an impact on the best time to sow crops. So, present investigation was planned to find intricate relationship among weather variability, dates of sowing and yellow rust severity in wheat.

2. Material and Methods

The research experiments were conducted with three wheat varieties *viz.*, PB 725, HD 2967 and HD 3086 sown on different dates (14th-15th October, 8th-9th November and 3rd-4th December) with two microclimate modification levels with four replications during *rabi* season of 2021-22 and 2022-23 at the Research Experiment Farm, Department of Climate Change and Agricultural Meteorology, Punjab Agricultural University, Ludhiana and Regional Research Station, Gurdaspur. To prepare the field, plank levelling was done and then the field was ploughed thrice using a tractor-drawn disc harrow. In both experiments, wheat was sown by using seed @40 kg/acre at a depth of 4 to 6 cm and with a row spacing of 22.5 cm. The fertilizers were applied in accordance with the recommendations suggested in PAU's Package of Practices for *rabi* crops in Punjab. Nitrogen, Phosphorus and Potassium were applied at rate of 110 kg N/acre, 55 kg P₂O₅/acre and 20 kg K₂O/acre, respectively. At the time of sowing, the full doses of P and K as well as half of the nitrogen dose were applied. After first irrigation, the remaining half nitrogen dose was applied. To promote good seed germination, the crop was provided irrigation prior to sowing. Four irrigations were then given to the crop over the growing season, depending on the crop's needs and the weather. During 2021-22, a special irrigation was provided during March month to

save crop from heat stress at both locations after following the agro advisory issued for both locations. To control the weeds, one litre of pendimethalin (Stomp 30 EC) was used per acre as a pre-emergence herbicide. After the first irrigation, two manual hoeings were also done to control weeds in addition to herbicide spray.

The experiments were laid out in Split Plot Design with dates of sowing as main plots and varieties x microclimate modification levels as sub plots. The plot size was 3 m x 3.5 m. The two microclimate modifications were M₁ (Recommended irrigations) and M₂ (Recommended irrigations + 2 additional water sprays). Power knapsack sprayer was used 10 days and 25 days after disease initiation to give water sprays in M₂. Water sprays were given using cut nozzle to imitate rainfall effect. M₂ treatment plots were sprayed nine times at one hour interval spanning one full day. Daily data of different meteorological parameters was collected from the Agrometeorological Observatory. For yellow and brown rusts, crop was inoculated artificially by spraying with a sporidial suspension of *Puccinia striiformis* f.sp. *tritici* and *Puccinia triticina* obtained from Department of Plant Pathology, PAU, Ludhiana during first week of January. Fresh urediniospores were collected, in a clean dry boiling tube, from a stock pathogen culture. These urediniospores were transferred to the surface of the leaves by means of a paint brush, previously sterilised with ethanol. Disease data on severity of yellow and brown rusts were recorded at weekly interval. The disease severity involves determination of the plant tissue proportion that was infected by disease. The modified Mannar's scale for yellow rust and Modified Cobb scale for brown rust of wheat (Peterson *et al.*, 1948) were employed to estimate the severity in per cent on the leaves. Disease severity was calculated from collected data by using following formula:

$$\text{Disease severity (\%)} = \frac{\sum \text{Number of infected leaves} \times \text{Scale}}{\text{Total number of leaves} \times \text{Maximum grade}} \times 100$$

The severity of yellow and brown rust were determined under different sowing dates, varieties and microclimate modification levels. Area under disease progress curve (AUDPC), relative AUDPC and mean AUDPC were calculated for rusts under different treatments. Using the method provided by Wilcoxson *et al.* (1975), the area under the disease progress curve (AUDPC) was calculated with



the total observations recorded on disease severity. The AUDPC was quantified as follows:

$$AUDPC = \sum_{i=1}^{n-1} \left(\frac{X_i + X_{i+1}}{2} \right) \times (t_{i+1} - t_i)$$

Where,

X_i = Disease severity on date i

t_i = Time in days between i and date $i+1$

n = Number of observations

$$rAUDPC = \frac{\text{Total AUDPC}}{\text{Total time (days)}} \times 100$$

Where, rAUDPC (%) = Relative AUDPC,

Total AUDPC = Sum of weekly AUDPC values

Total time = Total days after disease appearance

Correlation and regression analysis were carried out using R software.

3. Results

3.1. Response of variety PBW 725 to different treatments with respect to rust severity

The variety PBW 725 being resistant did not show much yellow and brown rust diseases despite artificial inoculations at both the locations and years under study (Fig. 1a). Yellow rust was observed in traces on variety PBW 725 which varied from 1.2 to 2.3 per cent during *rabi* 2021-22 and 0 to 2.33 per cent during *rabi* 2022-23 under different treatments at Ludhiana while 0 to 2.61 per cent during *rabi* 2021-22 and 0 to 2.88 per cent during *rabi* 2022-23 at Gurdaspur. Brown rust in PBW 725 it was observed that during *rabi* 2021-22 and 2022-23, brown rust severity was recorded in trace amounts as 0-6.9 per cent and 2.5 - 4.96 per cent, respectively under different treatments at Ludhiana (Fig. 1b).

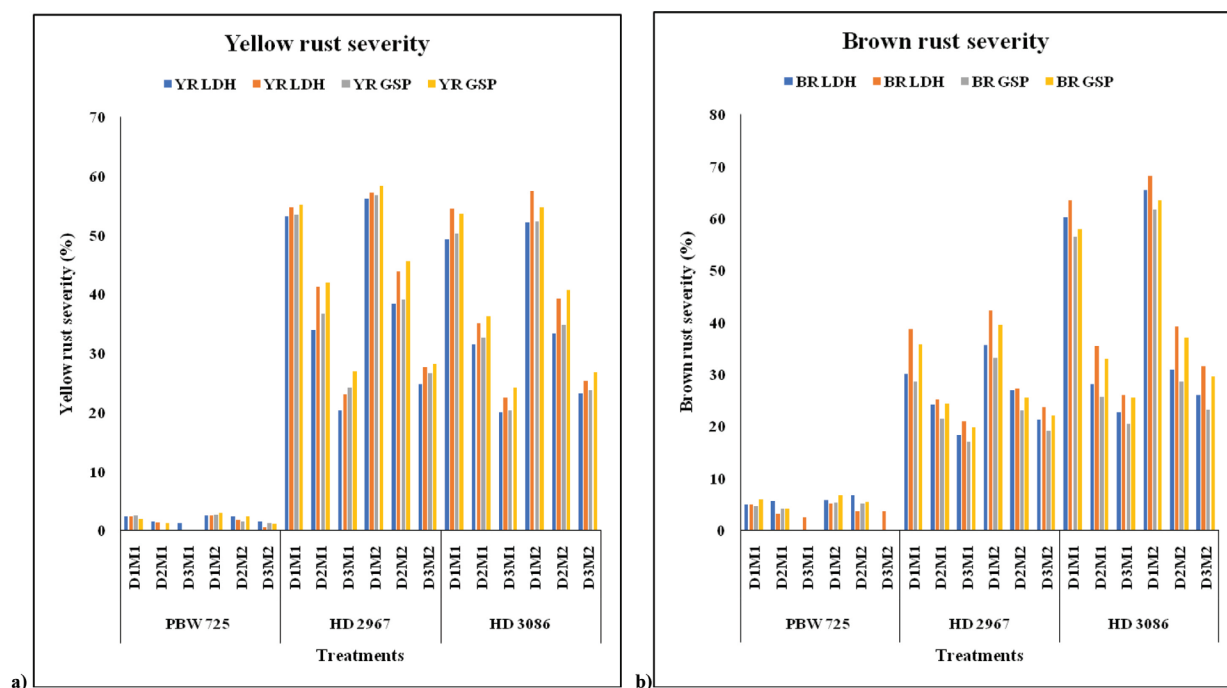


Fig.1 Yellow (a) and brown (b) rust severity under different treatments in Ludhiana and Gurdaspur

3.2. Response of variety HD 2967 to different treatments with respect to rust severity

Among the three different sowing dates, the disease severity was reported to be highest in case of early sowing (15th October) which was 56.14 per cent as compared to normal (38.33%) and late (24.68%) dates of sowing during *rabi* 2021-22 under M_2 microclimate

modification level at Ludhiana. During *rabi* 2022-23, the early sown crop recorded highest rust severity (57.17%) as compared to normal (43.81%) and late (27.65%) dates of sowing under M_2 microclimate modification level. The area under disease progress curve (AUDPC) was more (1580.0,1622.6) in case of early sowing followed by normal (978.4, 1375.3) and it was least recorded in late



sowing (546.0, 720.5) (Table 1). The rust severity in M_2 microclimate modification level was higher than M_1 during both the seasons. Similarly, at Gurdaspur, maximum rust severity (56.75%, 58.42%) was observed in varieties sown on October 14th, higher than November 8th (39.09%, 45.56%) and 3rd December (26.57%, 28.13%) during *rabi* 2021-22 and 2022-23 respectively under M_2 microclimate modification level. The AUDPC value of rust severity in crop sown on December 3rd was less (635.4,790.8) as compared to crop sown on November 8th (1100.1,1459.1) and October 14th (1736.9, 2062.7) under M_2 microclimate modification level during both years under study. Mean AUDPC (193.0, 229.2), rAUDPC (31.0, 36.8) and total AUDPC (1736.9, 2062.7) were also highest in early sowing and M_2 treatment during both the years under study, respectively.

Early sowing (15th October) recorded higher (35.64%, 42.33%) brown rust severity when compared to normal (26.98%, 27.22%) and late (21.17%, 23.6%) dates of sowing during *rabi* 2021-22 and 2022-23, respectively under M_2 microclimate modification level at Ludhiana. The disease progress curve also depicted the similar trend of higher area of rust severity in crop sown on 15th October (783.3,976.2) as compared to 9th November (669.8,765.0) and 4th December (529.8, 558.2) during both years under study (Table 2). Mean AUDPC (87.0,108.5), rAUDPC (14.0,17.4) and total AUDPC (783.3,976.2) were also highest in early sowing and M_2 treatment during both the years under study, respectively. During *rabi* 2021-22, it was determined that the early date of sowing (October 14th), resulted in a higher brown rust severity of 33.15 per cent and 39.43 per cent when compared to both normal sowing date (23%, 25.42%) and late sowing date (19.17%, 22.1%) during *rabi* 2021-22 and 2022-23, respectively in M_2 microclimate modification level at Gurdaspur. The area under disease progress curve (AUDPC) was observed to be more in early sowing (674.2, 869.0) followed by normal (618.5, 669.4), while the least amount was recorded in late sowing (441.5, 490.0). Mean AUDPC (74.9, 96.6), rAUDPC (12.0, 15.5) and total AUDPC (674.2, 869.0) were also highest in early sowing and M_2 treatment during both the years under study, respectively.

3.3. Response of variety HD 3086 to different treatments with respect to rust severity

Yellow rust severity was reported to be highest in case of early sowing (15th October) which was 52.19 and 57.5 per cent as compared to normal (33.33%, 39.21%) and late (23.15%, 25.26%) sowing during *rabi* 2021-22 and 2022-23 under M_2 microclimate modification level at Ludhiana. The area under the disease progress curve was found to be higher in the early sowing (1617.0, 1739.3) followed by 9th November (839.9, 1060.1) and least was found in case of late sowing that is 4th December (559.1, 694.7). The rust severity in M_2 microclimate modification level was higher than M_1 during both the seasons. Mean AUDPC (179.7,193.3), rAUDPC (28.9,31.1) and total AUDPC (1617.0, 1739.3) were also highest in early sowing and M_2 treatment during both the years under study, respectively. At Gurdaspur, the maximum rust severity (52.38%, 54.77%) was observed in varieties sown on October 14th, higher than that on November 8th (34.76%, 40.71%) and December 3rd (23.67 and 26.67%) under M_2 treatment during both the years under study, respectively. The AUDPC of rust severity in crop sown on 4th December was comparatively lower (578.7,726.0) when compared with crop sown on 9th November (920.9, 1192.4) and 14th October (1715.9, 1913.5). Mean AUDPC (190.7, 212.6), rAUDPC (30.6, 34.2) and total AUDPC (1715.9, 1913.5) were also highest in early sowing and M_2 treatment during both the years under study, respectively.

Brown rust severity under two different microclimate conditions revealed that rust severity was higher (65.44%, 68.21%) on 15th October sowing in the microclimate with two extra sprays of water (M_2) than normal (30.78%, 39.17%) and late (25.89%, 31.47%) dates of sowing. The AUDPC of brown rust severity depicted that disease progress in crop sown on 4th December was less (644.9, 767.0) as compared to 9th November (859.2, 1180.9) and 15th October (1864.2, 2215.0) under M_2 treatment during *rabi* 2021-22 and 2022-23, respectively. Mean AUDPC (207.1,246.1), rAUDPC (33.3,39.6) and total AUDPC (1864.2,2215.0) were also highest in early sowing and M_2 treatment during both the years under study, respectively. During the *rabi* 2021-22 and 2022-23, it was observed that higher severity of brown rust was observed in M_2 as compared to M_1 . Specifically, the severity was higher on 14th October sowing i.e. 61.76 and 63.5 per cent in M_2



Table 1: Relative, total and mean AUDPC of yellow rust severity in different treatments at Ludhiana and Gurdaspur

Treatments	D ₁ M ₁		D ₂ M ₁		D ₃ M ₁		D ₁ M ₂		D ₂ M ₂		D ₃ M ₂	
	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23
Ludhiana												
PBW 725												
r- AUDPC	0.3	0.3	0.1	0.2	0.1	0.0	0.5	0.3	0.1	0.3	0.2	0.0
Total AUDPC	18.6	16.6	5.3	11.3	4.2	0.0	28.4	19.3	8.2	16.6	10.5	1.8
Mean AUDPC	2.1	1.8	0.6	1.3	0.5	0.0	3.2	2.1	0.9	1.8	1.2	0.2
HD 2967												
r- AUDPC	25.75	26.78	15.24	22.01	8.37	10.81	28.21	28.98	17.47	24.56	9.75	12.87
Total AUDPC	1442.24	1499.72	853.20	1232.81	468.83	605.36	1579.97	1622.60	978.41	1375.27	545.98	720.48
Mean AUDPC	160.25	166.64	94.80	136.98	52.09	67.26	175.55	180.29	108.71	152.81	60.66	80.05
HD 3086												
r- AUDPC	2708	28.17	13.31	17.08	7.15	10.34	28.87	31.06	15.00	18.93	9.98	12.40
Total AUDPC	1516.50	1577.65	745.45	956.44	400.33	579.22	1616.97	1739.26	839.93	1060.11	559.10	694.65
Mean AUDPC	168.50	175.29	82.83	106.27	44.48	64.36	179.66	193.25	93.33	117.79	62.12	77.18
Gurdaspur												
PBW 725												
r- AUDPC	0.2	0.1	0.0	0.1	0.0	0.0	0.3	0.4	0.1	0.3	0.1	0.1
Total AUDPC	8.8	6.7	0.0	4.2	0.0	0.0	16.1	19.9	5.3	17.9	4.2	3.5
Mean AUDPC	1.0	0.7	0.0	0.5	0.0	0.0	1.8	2.2	0.6	2.0	0.5	0.4
HD 2967												
r- AUDPC	28.5	33.9	17.0	24.0	9.3	12.4	31.0	36.8	19.6	26.1	11.3	14.1
Total AUDPC	1596.4	1897.3	952.4	1343.0	521.0	692.1	1736.9	2062.7	1100.1	1459.1	635.4	790.8
Mean AUDPC	177.4	210.8	105.8	149.2	57.9	76.9	193.0	229.2	122.2	162.1	70.6	87.9
HD 3086												
r- AUDPC	28.8	32.6	15.3	19.4	8.4	11.7	30.6	34.2	16.4	21.3	10.3	13.0
Total AUDPC	1611.3	1827.9	854.5	1088.9	468.8	656.0	1715.9	1913.5	920.9	1192.4	578.7	726.0
Mean AUDPC	179.0	203.1	94.9	121.0	52.1	72.9	190.7	212.6	102.3	132.5	64.3	80.7



Table 2: Relative, total and mean AUDPC of brown rust severity in different treatments at Ludhiana and Gurdaspur

Treatments	D ₁ M ₁		D ₂ M ₁		D ₃ M ₁		D ₁ M ₂		D ₂ M ₂		D ₃ M ₂	
	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23
Ludhiana												
PBW 725												
r- AUDPC	0.9	0.7	1.3	1.0	0.0	0.3	1.4	1.4	1.7	1.2	0.0	0.4
Total AUDPC	49.8	41.8	74.0	58.6	0.0	17.2	79.5	78.2	95.2	65.9	0.0	23.2
Mean AUDPC	5.5	4.6	8.2	6.5	0.0	1.9	8.8	8.7	10.6	7.3	0.0	2.6
HD 2967												
r- AUDPC	11.6	15.5	10.8	11.8	8.3	7.9	14.0	17.4	12.0	13.7	9.5	10.0
Total AUDPC	651.9	865.6	602.9	661.5	465.2	442.5	783.3	976.2	669.8	765.0	529.8	558.2
Mean AUDPC	72.4	96.2	67.0	73.5	51.7	49.2	87.0	108.5	74.4	85.0	58.9	62.0
HD 3086												
r- AUDPC	29.9	36.4	13.4	18.6	9.7	11.9	33.3	39.6	15.3	21.1	11.5	13.7
Total AUDPC	1674.1	2037.5	750.3	1042.8	542.3	665.0	1864.2	2215.0	859.2	1180.9	644.9	767.0
Mean AUDPC	186.0	226.4	83.4	115.9	60.3	73.9	207.1	246.1	95.5	131.2	71.7	85.2
Gurdaspur												
PBW 725												
r- AUDPC	1.2	1.1	1.0	0.9	0.0	0.0	1.5	1.5	1.3	1.1	0.0	0.0
Total AUDPC	64.9	60.7	53.3	50.6	0.0	0.0	81.5	85.2	70.6	63.1	0.0	0.0
Mean AUDPC	7.2	6.7	5.9	5.6	0.0	0.0	9.1	9.5	7.8	7.0	0.0	0.0
HD 2967												
r- AUDPC	9.8	12.8	9.7	10.6	6.1	7.3	12.0	15.5	11.0	12.0	7.9	8.8
Total AUDPC	546.2	719.3	542.5	592.9	344.3	408.1	674.2	869.0	618.5	669.4	441.5	490.0
Mean AUDPC	60.7	79.9	60.3	65.9	38.3	45.3	74.9	96.6	68.7	74.4	49.1	54.4
HD 3086												
r- AUDPC	26.8	31.8	11.8	16.7	8.5	10.0	29.8	34.5	13.0	19.3	10.2	11.9
Total AUDPC	1503.1	1780.1	661.2	937.1	475.4	557.8	1667.1	1930.3	730.3	1080.2	569.5	667.1
Mean AUDPC	167.0	197.8	73.5	104.1	52.8	62.0	185.2	214.5	81.1	120.0	63.3	74.1



under early date of sowing followed by 28.55 per cent and 37.1 per cent (normal) and 23.18 per cent and 29.53 per cent (late) during *rabi* 2021-22 and 2022-23 seasons at Gurdaspur. The AUDPC of rust severity in crop sown on December 3rd was less (569.5, 667.1) than those sown on November 8th (730.3, 1080.2) and October 14th (1667.1, 1930.3). Mean AUDPC (185.2, 214.5), rAUDPC (29.8, 34.5) and total AUDPC (1667.1, 1930.3) were also highest in early sowing and M₂ treatment during both the years under study, respectively.

3.4. Correlation and regression analysis

It was found that maximum temperature (0.93, 0.98) and minimum temperature (0.89, 0.96) had highly significant positive correlation with yellow rust disease severity during *rabi* 2021-22 and *rabi* 2022-23 respectively, at Ludhiana (Fig. 2a,b). A negative correlation between morning relative humidity (-0.59 and -0.25) and evening relative humidity (-0.45 and -0.35) with disease severity was observed. A significant positive correlation (0.72,

0.88) between sunshine hours and disease severity was found during both the years under study. Rainfall was negatively correlated (-0.57, -0.46) with rainfall during *rabi* 2021-22 and *rabi* 2022-23, respectively. Wind speed was found to be positively correlated (0.028) with yellow rust disease severity during *rabi* (2021-22) and negatively correlated (-0.28) during *rabi* 2022-23. A significant positive correlation (0.96, 0.71) and minimum

A significant positive correlation was found between maximum temperature (0.96, 0.71) and minimum

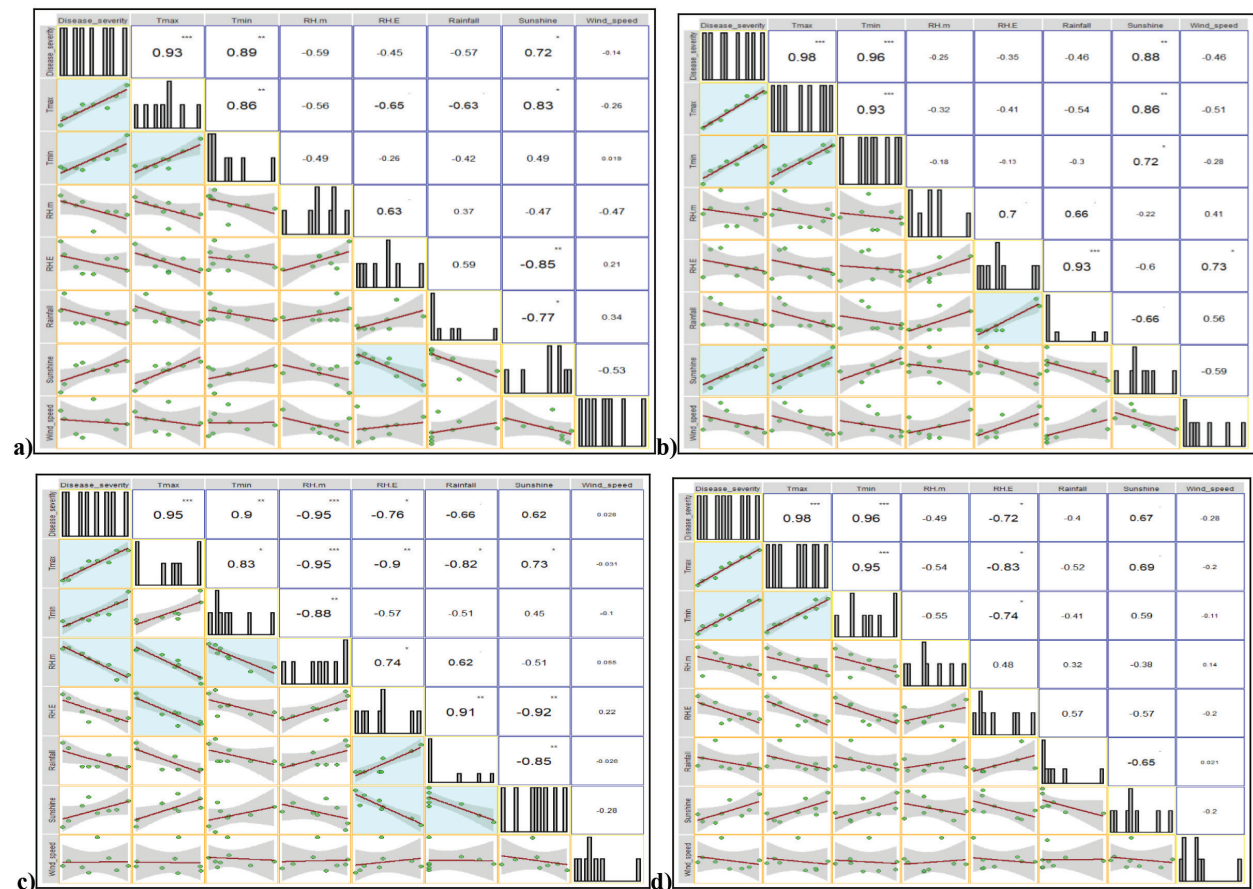


Fig.2 Correlation coefficients between different meteorological parameters and yellow rust severity at Ludhiana (a-2021-22, b-2022-23) and Gurdaspur (c-2021-22, d- 2022-23)



temperature (0.96, 0.92) and brown rust disease severity during *rabi* 2021-22 and *rabi* 2022-23 at Ludhiana (Fig. 3 a,b). Morning relative humidity (-0.67 and -0.4) and evening relative humidity (-0.47, -0.019) had negative correlation with disease severity. A significant positive correlation (0.66, 0.24) between sunshine hours and disease severity was found during both the years under study. Rainfall was negatively correlated (-0.52) with rainfall during *rabi* 2021-22 while it was positively correlated 0.60 during *rabi*2022-23. Wind speed was found to be negatively correlated (-0.11 and -0.31) with brown rust disease severity during *rabi* 2021-22 and *rabi* 2022-23. Similarly, at Gurdaspur, it was found that maximum temperature (0.94, 0.69) and minimum temperature (0.97, 0.91) had highly significant positive correlation with brown rust disease severity during *rabi* 2021-22and *rabi* 2022-23 (Fig. 3 c,d). A negative correlation between morning relative humidity (-0.77 and -0.56) and evening relative humidity (-0.68, -0.01) with disease severity was observed. A positive correlation (0.39) between sunshine hours

and disease severity was found during *rabi* 2021-22 while it was negative (-0.26) during *rabi* 2022-23. A negative correlation (-0.42) between rainfall and disease severity was found during *rabi* 2021-22 while it was positive (0.55) during *rabi* 2022-23. A negative correlation (-0.14) between rainfall and disease severity was found during *rabi*2021-22 while it was positive (0.36) during *rabi*2022-23. Rise in temperature, along with increased humidity, can make the crop more susceptible to severe brown rust infection and other facultative pathogens. Regression models were employed to explore the association between different meteorological parameters and wheat diseases, as presented in the provided Table 3. From regression analysis, it was concluded that minimum temperature, morning relative humidity, sunshine hours and rainfall were found to be important in spread of rusts in wheat crop. Higher (>0.95) values of coefficient of determination (R^2) implies that regression models gave excellent fit. Such models can be used for developing early warning system of rust forewarning in Punjab.

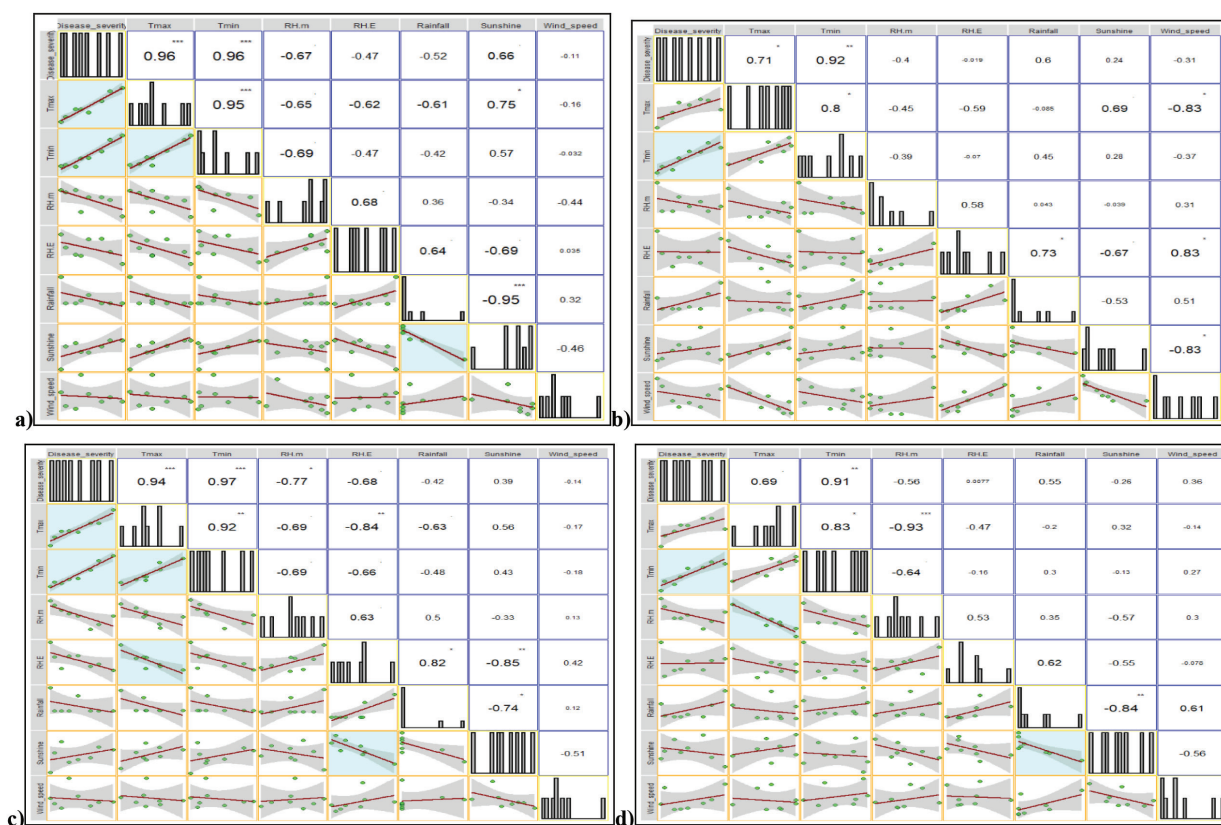


Fig. 3 Correlation coefficients between different meteorological parameters and brown rust at Ludhiana (a-2021-22, b-2022-23) and Gurdaspur (c-2021-22, d- 2022-23)



Table 3: Regression analysis between wheat diseases and different meteorological parameters at Ludhiana and Gurdaspur

Disease	Location	Regression equation	R ²	Adjusted R ²
Yellow rust	Ludhiana	$Y = 0.53 \text{ Tmax} + 2.83 \text{ Tmin} - 0.72 \text{ RHm} + 0.44 \text{ RHe} + 0.08 \text{ RF} + 4.73 \text{ SSh}$	0.98	0.87
		$Y = 4.54 \text{ Tmin} - 0.12 \text{ RHm} - 0.35 \text{ RF}$	0.97	0.89
		$Y = 3.84 \text{ Tmin} - 0.31 \text{ RHm} + 2.96 \text{ Ssh}$	0.98	0.90
	Gurdaspur	$Y = 2.79 \text{ Tmax} + 0.60 \text{ Tmin} - 0.15 \text{ RHm} - 0.23 \text{ RHe} + 0.15 \text{ RF} - 0.60 \text{ SSh}$	0.99	0.88
		$Y = 3.76 \text{ Tmin} + 0.06 \text{ RHm} - 0.32 \text{ RF}$	0.97	0.89
		$Y = 3.58 \text{ Tmin} - 0.06 \text{ RHm} + 1.93 \text{ SSh}$	0.97	0.89
Brown rust	Ludhiana	$Y = 5.14 \text{ Tmax} - 2.59 \text{ Tmin} - 1.96 \text{ RHm} + 0.94 \text{ RHe} + 1.15 \text{ RF} + 8.23 \text{ SSh}$	0.99	0.89
		$Y = 4.15 \text{ Tmin} - 0.15 \text{ RHm} + 0.11 \text{ RF}$	0.97	0.89
		$Y = 4.18 \text{ Tmin} - 0.23 \text{ RHm} + 1.47 \text{ SSh}$	0.97	0.89
	Gurdaspur	$Y = 2.80 \text{ Tmax} + 1.33 \text{ Tmin} - 0.73 \text{ RHm} + 0.06 \text{ RHe} + 0.78 \text{ RF} + 1.34 \text{ Ssh}$	0.99	0.89
		$Y = 4.77 \text{ Tmin} - 0.21 \text{ RHm} + 0.25 \text{ RF}$	0.98	0.90
		$Y = 4.77 \text{ Tmin} - 0.15 \text{ RHm} - 0.74 \text{ SSh}$	0.98	0.90

Where, Y= Rust severity(%); Tmax - Maximum Temperature (°C); Tmin - Minimum Temperature (°C); RHm - Morning Relative Humidity (%); RHe - Evening Relative Humidity (%); SSh - Sunshine Hours (hours/day)
RF - Total Rainfall (mm)

4. Discussion

The present study clearly demonstrated that rust development in wheat is strongly governed by varietal susceptibility, sowing time, and microclimatic conditions across both years and locations. The resistant variety PBW 725 consistently showed negligible yellow and brown rust severity despite artificial inoculation, confirming the durability of its resistance under diverse environments. In contrast, the susceptible varieties HD 2967 and HD 3086 exhibited pronounced rust severity, particularly under early sowing and enhanced microclimate conditions, highlighting their vulnerability when exposed to favourable disease environments. Leaf rust or brown rust was not observed in the state from many years. However, during the cropping seasons 2014-15 and 2015-16, it was recorded on certain cultivars at Gurdaspur and Abohar as revealed by Kaur *et al.* (2018). Across both years and locations, early sowing consistently resulted in the highest rust severity and AUDPC values, followed by normal and late sowing. Early sowing may expose emerging seedlings to conducive conditions for yellow rust establishment as reported by Singh (2019). Disease progression was generally slower in December and January however it got accelerated in February under field conditions. Hence, date of sowing of crop can significantly influence disease development (Sandhu *et al.*, 2017). Rise in temperature, along with increased humidity, can make the crop more susceptible to severe brown rust infection and other facultative pathogens. As temperatures and humidity fluctuate, the susceptibility window for brown rust may expand (Kaur *et al.*, 2008). Microclimate modification through additional water sprays (M₂) further intensified rust severity and disease progress, indicating that post-infection increases in leaf wetness and canopy humidity can substantially enhance secondary infection and disease spread. Weather-disease relationship analysis supported these findings, with maximum and minimum temperatures showing strong positive correlations with both yellow and brown rust severity, while relative humidity generally exhibited negative associations. Our results are in line with Khushboo *et al.* (2023), who found that stripe rust severity had a highly significant positive correlation with maximum and minimum temperatures, while morning relative humidity had a significantly negative correlation in different time periods. Rainfall had a non-significant



correlation with the disease. Similar results were reported by Gupta *et al.* (2017). There is a strong relationship between rainfall and the severity of yellow rust (Sunil 2013). But due to reduced uredospore germination and germination variability, high wetness over an extended length of time can impede the development of disease (Chen 2005). Wind component is a key dispersal vector, which they refer to as wind highways. Depending on the wetness, winds can apply varying forces. Winds can desiccate the free moisture (dew) that is present in the leaf canopy, hence reducing new infections (Golan and Pringle 2017). Regression analysis confirmed the dominant role of temperature, sunshine hours, and rainfall in explaining disease variability, with high R^2 values indicating robust model performance. Sandhu *et al.* (2021) formulated a prediction model for stripe rust and Ali *et al.* (2022) developed disease forecasting models for leaf rust using weather data. Similar regression models were developed by Kumar (2014) and Jamshed (2008). These results emphasize that rust epidemiology in Punjab is increasingly shaped by interactions between sowing time, transient microclimatic events, and prevailing weather conditions, underscoring the need to integrate such factors into rust forecasting and management strategies under a changing climate.

5. Conclusions

Early sowing provides congenial conditions for establishment of yellow and brown rust. Thus, by adjusting sowing date, wheat can be protected from these biotic stresses. The yellow rust disease progression was slow at Ludhiana than Gurdaspur while brown rust disease progression was slow at Gurdaspur as compared to Ludhiana. Yellow rust occurrence is favored by moderately low temperatures and high humidity while rise in temperature and increased humidity can increase brown rust infection.

Funding Acknowledgements

This research was conducted as part of an PhD dissertation. The authors sincerely acknowledge the support, infrastructure and funding provided by the Department of Climate Change and Agricultural Meteorology, as well as the Regional Research Station, Gurdaspur, of Punjab Agricultural University, Ludhiana, India.

Author Contributions

SA and SKS conceptualized the research and designed the experiments. Field experiments along with data collection, were carried out by SA, SKS, PST and BB. Data analysis and interpretation were conducted by SA and SKS. The manuscript was prepared by SA and SKS.

Declarations of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Conflict of Interest

The authors affirm that they have no conflicts of interest, financial or otherwise, that could have influenced the research findings presented in this paper.

Ethical Issues

The authors declare that there are no ethical issues associated with this study.

Use of Generative AI or AI assisted technologies

Authors declare that no Generative AI or AI assisted technologies have been used in preparation of this manuscript.

References

1. Ali Y, A Raza, S Iqbal, A A Khan, H M Aatif, Z Hassan and L Sas-Paszt. 2022. Stepwise regression models-based prediction for leaf rust severity and yield loss in wheat. *Sustainability* 14:13893.
2. Bal S K, J V N S Prasad and V K Singh. 2022. Heat wave 2022 Causes, impacts and way forward for Indian Agriculture. Technical Bulletin No. ICAR/CRIDA/TB/01/2022, ICAR-Central Research Institute for Dryland Agriculture, Hyderabad, Telangana, India, p50.
3. Bhatti D S. 2018. *Package of Practices for Crops of Punjab Rabi 2018-19*. Pp. 1-18
4. Bolton M D, J A Kolmer and D F Garvin. 2008. Wheat leaf rust caused by *Puccinia triticina*. *Molecular Plant Pathology* 9: 563-75.
5. Chaves M S, J A Martinelli, C L Wesp and F A S Graichen. 2008. The cereal rusts: An overview. *Pest Technology* 2: 38-55.



6. Chen. 2005. Epidemiology and control of stripe rust (*Puccinia striiformis* f.sp. *tritici*) on wheat. *Canadian Journal of Plant Pathology* **27**: 314-37.
7. Dutta S, S K Singh and M Khullar. 2014. A case study on forewarning of yellow rust affected areas on wheat crop using satellite data. *Journal of Indian Society of Remote Sensing* **42**: 335-42.
8. Francl L. 2001. The Disease Triangle: A plant pathological paradigm revisited. *Plant Health Instructor* **52**: 13-19.
9. Gangwar O P, S Kumar, S C Bhardwaj, P L Kashyap, P Prasad and H Khan. 2019. Characterization of three new Yr9-virulences and identification of sources of resistance among recently developed Indian bread wheat germplasm. *Journal of Plant Pathology* **101**: 955-63.
10. Golan JJ and A Pringle. 2017. Long distance dispersal of fungi. *Microbiol Spectrum* **5**: 24p.
11. Gupta V, A Khajuria, V K Razdan, D Kher and A Kumar. 2017. Effect of epidemiological factors on the severity of stripe rust of wheat caused by *Puccinia striiformis*. *Journal of Agrometeorology* **19**: 62-66.
12. Jamshed U. 2012. Correlation and regression for prediction of wheat leaf rust severity in Bahawalpur and Multan using relevant meteorological data. *Mycopathologia* **6**:1-2.
13. Jarroudi M, L Kouadio, P Delfosse and B Tychon. 2014. Brown rust disease control in winter wheat: I. Exploring an approach for disease progression based on night weather conditions. *Environmental Science and Pollution Research* **21**:4797-4808.
14. Jindal M M, C Mohan and P P S Pannu. 2012. Status of stripe rust of wheat in Punjab during 2011-12 seasons. *Proceedings of Brain Storming Session*. pp 56 (Abstr.) Department of Plant Pathology, PAU, Ludhiana, India.
15. Junk J, L Kouadio, P Delfosse and M Jarroudi. 2016. Effects of regional climate change on brown rust disease in winter wheat. *Climate Change* **135**: 439-51.
16. Kaur J, R Bala, H Kaur, P P S Pannu, A Kumar and S C Bhardwaj. 2018. Current status of wheat diseases in Punjab. *Agricultural Research Journal* **55**: 113-16.
17. Kaur P, S S Sandhu, H Singh, N Kaur, S Singh and A Singh. 2016. *Climatic Features and Their Variability in Punjab. Bulletin*: AICRPAM, School of Climate Change and Agricultural Meteorology, PAU, Ludhiana. Pp. 88.
18. Kaur S, L Dhaliwal and P Kaur. 2008. Impact of climate change on wheat disease scenario in Punjab. *Journal of Agricultural Research* **45**: 161-170.
19. Khushboo S S, V Gupta and D Pandit. 2023. Forewarning of stripe rust (*Puccinia striiformis*) of wheat in Jammu plains. *Indian Phytopathology* 1-10.
20. Kolmer J A. 2005. Tracking wheat rust on a continental scale. *Current Opinion on Plant Biology* **8**: 441-49.
21. Pannu P P S, C Mohan, G Singh, J Kaur, S K Mann, G K Bala, M Prashar, S C Bhardwaj, M Meeta, I Sharma and H S Rewal. 2010. Occurrence of yellow rust of wheat, its impact on yield viz-a-viz its management. *Plant Disease Research* **25**: 144-50.
22. Peterson, R F, A B Campbell and A E Hannah. 1948. A Diagrammatic Scale for Estimating Rust Intensity of Leaves and Stem of Cereals. *Canadian Journal of Research Section: 26*: 496-500.
23. Portner H O. 2022. *Climate Change 2022: Impacts, Adaptation and Vulnerability*. IPCC.
24. Roelfs A P, R P Singh and E E Saari. 1992. *Rust diseases of wheat: Concepts and methods of disease management*. Pp. 7-14. Mexico, DF (Mexico). CIMMYT.
25. Sandhu S K, P S Tak and P P S Pannu. 2021. Forewarning of stripe rust (*Puccinia striiformis*) of wheat in central zone of Punjab. *Journal of Agrometeorology* **23**: 435-441.
26. Sandhu Sarabjot Kaur and L K Dhaliwal. 2017. Assessment of weather-disease-yield Interactions in wheat under central Punjab. *Journal of Agricultural Physics* **17(2)**:216-23.
27. Singh P. 2019. *Over summering behaviour of Puccinia striiformis f.sp. tritici Erikss., the incitant of yellow rust of wheat and its management*. Ph.D. dissertation, Punjab Agricultural University, Ludhiana.
28. Singh R P, J Huerta-Espino and A P Roelfs. 2002. The wheat rusts. In: Curtis BC, Rajaram S, Gomez



- Macpherson H (eds) *Bread wheat: improvement and production*. Pp. 317-30. Plant Production and Protection Series no. 30. FAO, Rome.
29. Sunil. 2013. *Influence of weather factors on occurrence and development of stripe rust of wheat and its management*. Ph.D. dissertation. Punjab Agricultural University, Ludhiana, India.
30. Vijaya Kumar P. 2014. Development of weather-based prediction models for leaf rust in wheat in the Indo-Gangetic plains of India. *European Journal of Plant Pathology* **140**: 429-440.
31. Wang X H. 2020. Emergent constraint on crop yield response to warmer temperature from field experiments. *Nature Sustainability* **3**: 908-16.
32. Zhao C, S Piao and Y Huang. 2016. Field warming experiments shed light on the wheat yield response to temperature in China. *Nature Communications* **7**, 13530. <https://doi.org/10.1038/ncomms13530>.
33. Zheng B, K Chenu, M F Dreccer and S C Chapman. 2012. Breeding for the future: What are the potential impacts of future frost and heat events on sowing and flowering time requirements for Australian bread wheat (*Triticum aestivium*) varieties. *Global Change Biology* **18**: 2899-2914.

