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Rust Outbreak vs. Heat Stress: Resolving the Weather-Disease Nexus in Wheat

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***Abstract*:** The present study was planned to evaluate the association between meteorological parameters and yellow rust severity in wheat during three contrasting seasons: 2012-13 (rust epidemic year), 2021-22 (heat stress year), and 2022-23 (recent rust year). Rust severity was recorded as 100, 56.75 and 58.42% in 2012-13, 2021-22, and 2022-23, respectively. Correlation analysis revealed that maximum temperature (Tmax) was positively associated with rust severity. Minimum temperature also showed a strong positive correlation Morning relative humidity (RHm) and evening relative humidity (RHe) exhibited negative correlations, with RHm r = -0.65 to -0.72 and RHe r = -0.73 to -0.79, strongest in 2021-22. Rainfall had a weak positive correlation in 2012-13 and 2022-23, but a significant negative one in 2021-22 (r = -0.64). Sunshine hours were positively correlated with rust severity (r = 0.88 in 2021-22). During the disease phases, maximum and minimum temperatures were lowest in 2012–13 and highest in 2021-22. Relative humidity and rainfall were highest in 2012-13, followed by 2022-23, and minimum in 2021-22. Sunshine hours were least in 2012-13 and highest in 2022-23. Thus, 2012-13 was characterized by cooler temperatures, higher humidity, and greater rainfall conditions highly favourable for rust development. In contrast, 2021-22 experienced higher temperatures, lower humidity, and reduced rainfall, contributing to heat stress conditions. The year 2022-23 exhibited intermediate weather conditions, favouring moderate rust development. These findings highlight the importance of integrated weather-based forecasting for effective yellow rust management in wheat.

***Keywords*:** Heat stress, Meteorological parameters, Thumb rules, Weather disease window, Yellow rust

The Earth's average temperature has been steadily rising, stimulating more frequent and intense heat waves worldwide. In India, March and April 2022 were the hottest on record, with extreme temperatures surpassing normal levels by +8 to +10.8°C and rainfall decreasing by 60% to 99% in 10 out of 36 meteorological subdivisions. This period stands as a truthful example of how elevated temperatures and reduced rainfall collectively impacted agricultural production, particularly in northern and central India. The heat wave struck at a critical stage in wheat development i.e. grain filling leading to yellowing of grains, shrivelling and premature maturity, ultimately reducing yields by 15-25% (Bal et al., 2022). In addition to weather aberrations, wheat is attacked by different pathogens in northern India and stripe rust is a devastating fungal disease occurring as major wheat disease in north India. Stripe rust/yellow rust thrives well under cool and humid conditions. It is a major threat to wheat productivity globally, largely due to favourable weather conditions and the evolution of new virulent pathotypes (Hovmoller et al., 2008, Ali et al., 2017). The coexistence of these two contrasting climatic stressors—one triggered by elevated temperatures and the other thriving in cool-humid environments poses a challenge in predicting and managing wheat diseases under changing climatic conditions.

The correlation between weather parameters and the development of stripe rust has been well documented. Temperature, humidity, leaf wetness, sunshine hours and rainfall are critical in modulating the onset and progression of the disease (Brown et al., 2001, Chen 2005). Infection is favoured by daytime temperatures between 10-15°C, relative humidity above 85% and wet leaf surfaces for at least three hours (Line, 2002). In India yellow rust does not survive the summer temperatures of the plains but survives in cooler hill areas and returns with wind-dispersed uredospores during winter (Wang et al., 2010). In contrast, rising temperatures above 25°C which are common under climate change scenarios tend to suppress the disease, though newer stripe rust strains show adaptation to warmer climates (Wellings, 2007, Hubbard et al., 2015). The timing of weather anomalies, such as an unusually warm January or wet February, can trigger or suppress rust outbreaks. Studies have shown that February, with optimum conditions for stripe rust viz., maximum temperatures in range of 15–25°C and relative humidity around 86–98% frequently corresponds with high disease severity years (Sandhu et al., 2018, Kashyap et al., 2018). Moreover, rain splashes and wind currents facilitate spore dispersal and inoculum buildup (Geagea et al., 2000, Isard & Russo, 2011). Conversely, sunshine duration, which limits leaf wetness, has a negative correlation with disease development (Gill et al., 2012). Several models have been developed to forecast stripe rust incidence using meteorological data. ARIMA models, regression analyses, and temperature-humidity indices have all shown high predictive power in determining disease outbreaks (Poudyal et al., 2013, Sandhu et al., 2021, Khushboo et al. 2023). Yellow rust has historically caused up to 70% yield losses in epidemic years (Singh et al., 2004), while heat stress particularly during terminal growth stages can cause yield penalties of 20–40%, particularly in heat-sensitive cultivars. Heat stress, precisely during the reproductive and grain-filling stages, compromises yield and quality by accelerating senescence and reducing grain size (Milus et al., 2009). The convergence of these threats, particularly in wheat-growing belts such as the northwestern plains of India, calls for robust, localized and dynamic disease-forecasting systems.

This study investigates the validation of meteorological thumb rules for yellow rust severity using historical rust outbreak years (2012–13) and heat stress years (2021–22) and recent rust year (2022–23). The key weather variables viz., temperature, relative humidity, sunshine hours and rainfall across critical crop growth months were analysed. The main objective behind this analysis was to identify conditions conducive or suppressive for stripe rust development. This will not only enhance our understanding of the environment-pathogen interaction but will also contribute to adaptive disease management strategies under changing climatic conditions.

MATERIAL AND METHODS

Study area: The research experiments were conducted at Punjab Agricultural University, Ludhiana during different years under study viz., 2012-13, 2021-22 and 2022-23. Ludhiana is located in the trans-Gangetic agroclimatic zone of Punjab at 30°54' N latitude and 75°48' E longitude, lies at an altitude of 247 meters above mean sea level. The region has a subtropical, semi-arid climate. December and January are the coldest months, occasionally experiencing frost, while May and June are the hottest, with temperatures sometimes exceeding 45°C. The annual average maximum and minimum temperatures are 29.8°C and 16.7°C, respectively. Rainfall averages 760 mm annually, with 75-80% occurring during the monsoon season from June to September.

Meteorological data: The meteorological data w.r.t maximum and minimum temperature, morning and evening relative humidity, rainfall and sunshine hours for the study years was collected from the Department of Climate Change and Agricultural Meteorology at PAU, Ludhiana.

Disease incidence: The disease severity involves determination of the plant tissue proportion that was infected by disease. Different scales, such as the modified Mannar's (1960) scale for yellow rust of wheat was employed to estimate the severity in per cent on the leaves (Table 1). Disease severity was calculated from collected data by using following formula:

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

Correlation coefficient analysis: Correlation coefficient analysis was carried out between different meteorological parameters and yellow rust severity using R software. This analysis was carried out to study the strength and direction of linear relationship between two variables.

Validation of thumb rules: To anticipate disease outbreaks, "thumb rule" a simplified empirical guideline (Sandhu et al., 2021) based on key weather variables was validated. This section evaluates the validity of these rules across three contrasting years: a high rust severity year (2012-13), a heat stress year with low rust occurrence (2021-22), and a recent rust year (2022-23).

RESULTS AND DISCUSSION

Meteorological parameters during different years: Rust severity was 100, 56.75, and 58.42% in in 2012-13, 2021-22, and 2022-23 (Fig. 1). During disease initiation, the maximum temperature averaged 16.6°C, 15.3°C 2021-22, and 16.4°C in 2012-13, 2021-22, and 2022-23 (Fig. 2a). Minimum temperatures remained relatively cool, with means of 6.4°C,

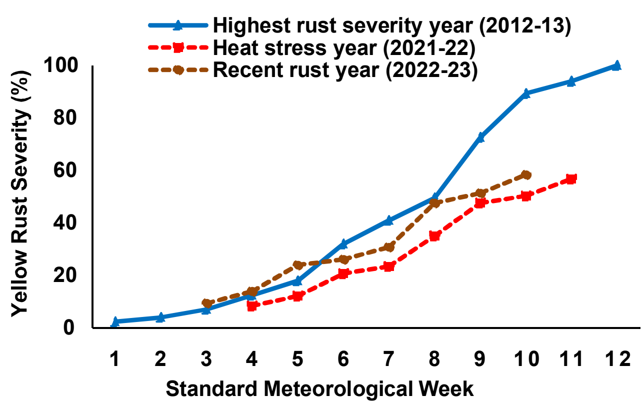

Fig. 1. Yellow rust severity during different years under study

Table 1. Rating scale for yellow rust of wheat

Code	Scale for severity of infection
5	Up to 5 per cent leaf area infected
10	Up to 10 per cent leaf area infected
20	Up to 20 per cent leaf area infected
50	Up to 50 per cent leaf area infected
75	Up to 75 per cent leaf area infected
100	Up to 100 per cent leaf area infected

8.5°C, and 5.8°C, respectively, and ranged between 4.3°C and 8.1°C (Fig. 2b). Morning relative humidity was consistently high across years, averaging 94.0, 93.8 and 91.8% in 2012-13, 21-22, and 22-23 (Fig. 3a). Evening humidity ranged from 49% to 75% in 2012-13 , higher in 2021–22 (74.4%, 68-83%) but relatively lower in 2022-23 (57.5%, 37-77%) (Fig. 3b). Total rainfall during the initiation phase was 8.2 mm in 2012-13, while it was negligible in 2021-22 and 2022-23 (Fig. 4a). Sunshine hours averaged 5.9 hours/day (0.2-8.4 h) in 2012-13, 4.9 hours/day (0.1-9 h) in 2021-22, and 5.2 hours/day (1.4-6.9 h) in 2022-23 (Fig. 4b). The combination of cooler temperatures, high humidity, low sunshine, and occasional rainfall during 2012–13 provided highly favourable conditions for early rust initiation and infection establishment. During disease progression, maximum temperatures increased to averages of 20.3°C (19.8-23.9°C) in 2012-13, 21.1°C (17.5-23.4°C) in 2021-22, and 23.9°C (20.3-27.5°C) in 2022-23. Minimum temperatures averaged 8.7°C, 8.2°C, and 10.7°C, respectively. Morning relative humidity was highest in 2012–13 (97.0%, 97-99%), compared to 91.0% in 2021–22 and 89.5% in 2022–23. Evening humidity averaged 63.0 % in 2012–13 declining to 50.5% in 2021–22 and 47.75% in 2022–23 . Total rainfall during the progression phase was 22.6 mm in 2012–13, whereas it was much lower (3-4 mm) in 2021-22 and 2022-23. Sunshine hours during this phase were lower in 2012-13 (5.8 hours/dayh) compared to 7.3 hours/day and 7.7 hours/day in 2021-22 and 2022-23, respectively. The cool, humid, and moderately rainy conditions in 2012-13 favoured rapid disease multiplication and widespread epidemic spread during this critical phase. In the end phase, maximum temperatures increased to 27.7°C in 2012-13, 29.6° in 2021-22, and 27.1°C in 2022-23. Minimum temperatures followed a similar rising trend, averaging 12.6°C, 15.3°C, and 14.7°C, respectively. Morning relative humidity declined slightly, averaging 95.0% in 2012-

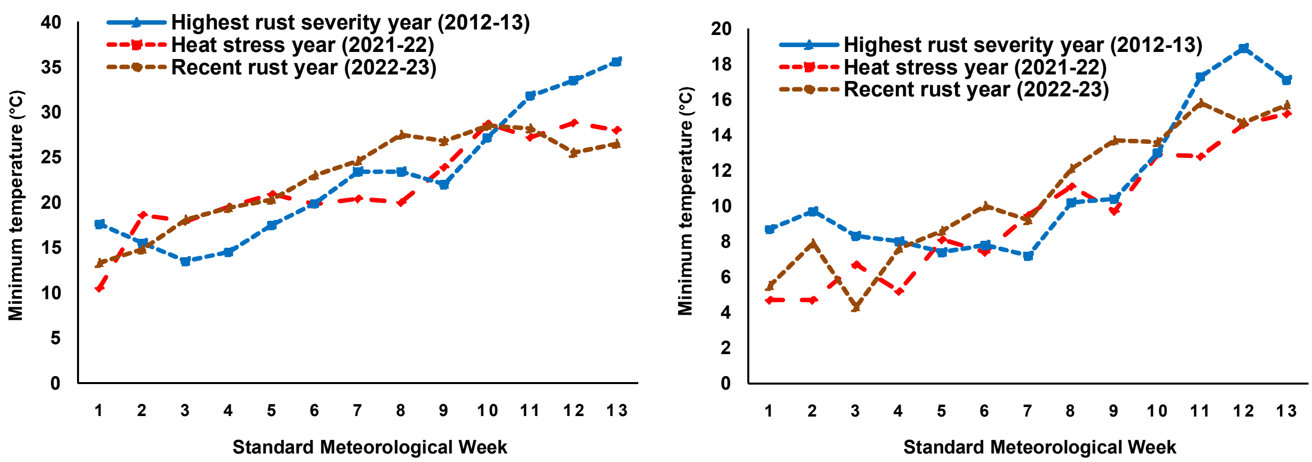

Fig. 2. Comparison of weekly maximum and minimum temperatures during yellow rust occurrence during different years under study

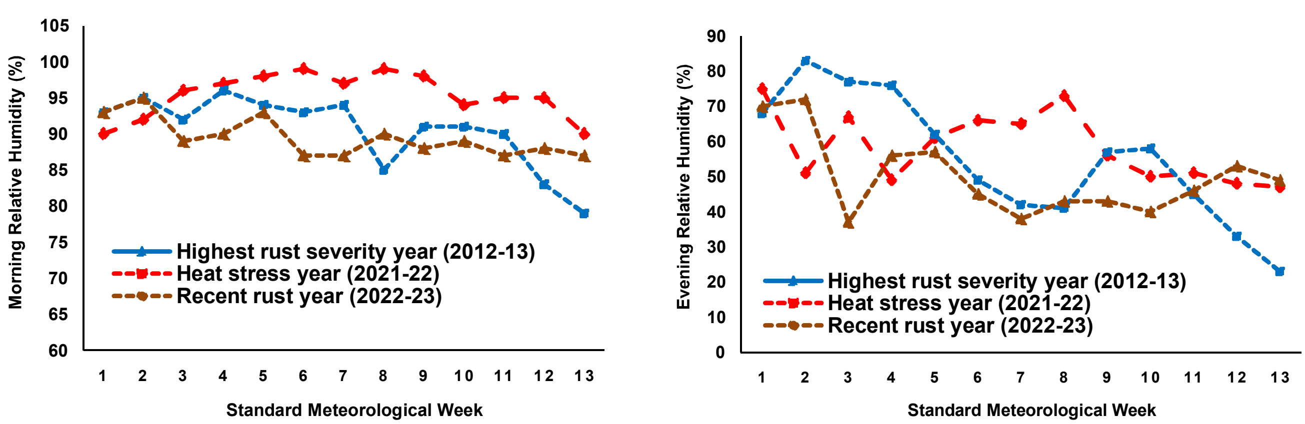

Fig. 3. Comparison of morning and evening relative humidities during yellow rust occurrence during different years under study

13, 87.0% in 2021-22, and 88.2% in 2022-23. Evening humidity was 55.0% in 2012–13, compared to 43.0% in 2021–22 and 46.0% in 2022–23. Total rainfall during the end phase was about 35 mm in 2012–13, almost negligible in 2021-22, and limited (~10 mm) during week 13 in 2022-23. Sunshine hours peaked during 2021-22 (9.4 hours/day) and remained relatively high in 2022-23 (8.2 hours/day) compared to 2012-13 (8.7 hours/. The higher temperatures, reduced humidity, and greater sunshine during the later stages of 2021-22 and 2022-23 led to early crop maturity, limiting late-stage disease development.

Weather-disease window: During the disease initial phase, maximum and minimum temperatures were lowest in 2012–13, intermediate in 2022-23, and highest in 2021-22 (Fig. 5). Morning and evening relative humidity were maximum in 2012-13, followed by 2022-23, and minimum in 2021-22. Rainfall was highest in 2021-22, intermediate in 2022–23, and lowest in 2012-13. Sunshine hours were least in 2012-13 and highest in 2021-22. In the disease progression phase, maximum and minimum temperatures were highest in 2022-23 and lowest in 2012–13. Relative humidity (both morning and evening) and rainfall were maximum in 2012–13, intermediate in 2021–22, and minimum in 2022–23. Sunshine hours were highest in 2022-23 and lowest in 2012-13. During the disease end phase, maximum and minimum temperatures were highest in 2022-23 and lowest in 2012-13. Morning and evening relative humidity were highest in 2012-13, intermediate in 2022-23,

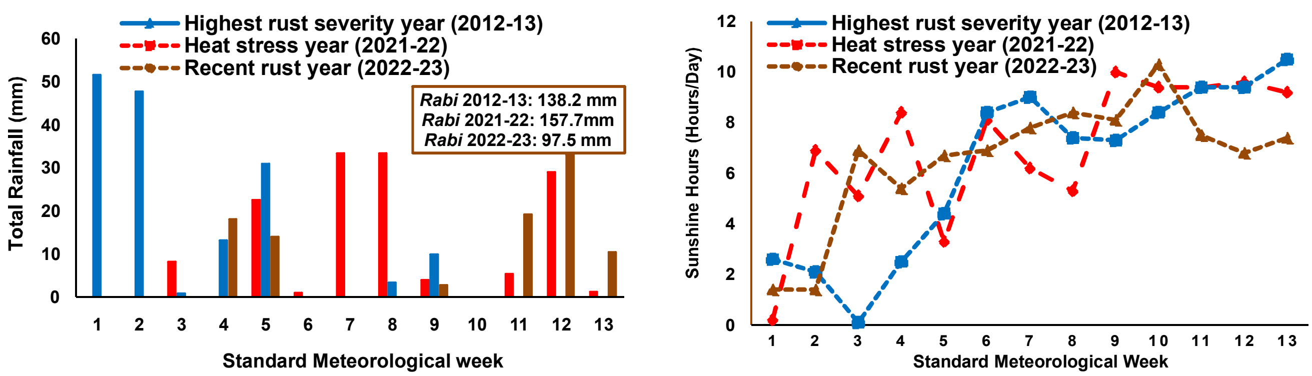

Fig. 4. Comparison of total rainfall and sunshine hours/day during yellow rust occurrence during different years under study

Year	Parameter	Disease initial phase (SMW 1st – 4th)	Disease progression phase (SMW 5th – 8th)	Disease end phase SMW (9th – 13th)
Highest rust severity year (2012-13)	Tmax (°C)	10.5–19.5 (16.6)	20.9–20.4 (20.7)	20–28 (25.6)
	Tmin (°C)	4.7–6.7 (5.3)	8.1–11.1 (9.3)	9.7–15.2 (12.04)
	RHm (%)	90–97 (93.8)	98–99 (98.8)	98–90 (94.2)
	RHe (%)	49–75 (60.3)	61–73 (65.3)	56–47 (51.4)
	Total Rainfall (mm)	8.2	33.4	29
	Ssh (hours)	0.2–8.4 (5.1)	3.3–10 (5.7)	5.3–9.6 (8.7)
Heat-stress year (2021-22)	Tmax (°C)	13.5–17.6 (15.3)	17.5–23.4 (20.9)	22–35.6 (29.9)
	Tmin (°C)	7.4–8.7 (8.1)	7.2–10.2 (8.2)	10.4–17.1 (14.5)
	RHm (%)	92–96 (94)	94–85 (91.5)	91–79 (87)
	RHe (%)	68–83 (76)	62–41 (53)	57–23 (44.2)
	Total Rainfall (mm)	51.6	3.4	9.9
	Ssh (hours)	0.1–9 (3.5)	4.4–9 (7.1)	7.3–10.5 (8.7)
Recent rust year (2022-23)	Tmax (°C)	13.3–19.4 (16.4)	20.3–24.6 (22.9)	25.5–28.5 (27.1)
	Tmin (°C)	4.3–7.9 (6.1)	8.6–12.1 (10.5)	13.7–15.7 (14.7)
	RHm (%)	89–93 (91.5)	93–87 (89.3)	88–87 (88.2)
	RHe (%)	56–70 (62.3)	57–43 (47.8)	43–49 (46.2)
	Total Rainfall (mm)	18.1	0	33
	Ssh (hours)	1.4–6.9 (4.8)	6.7–8.4 (7.8)	6.8–8.4 (7.6)

Maximum among study years

Intermediate

Minimum among study years

Fig. 5. Weather disease window for yellow rust during different phases of disease occurrence

and lowest in 2021-22. Rainfall was maximum in 2022-23, followed by 2012-13, and least in 2021-22. Sunshine hours remained highest in 2022-23 and intermediate in 2021-22. Thus, it is evident that 2012-13 was characterized by cooler temperatures, higher humidity, and higher rainfall conditions highly favourable for rust development. In contrast, 2021-22 experienced higher temperatures, lower humidity, and reduced rainfall, contributing to heat stress conditions. The year 2022-23 exhibited intermediate weather conditions, favouring moderate rust development.

Correlation coefficients: The correlation analysis between yellow rust severity and meteorological parameters during study revealed that both consistent and year-specific trends. Across all three years, maximum temperature and minimum temperature showed a consistently strong positive correlation with yellow rust severity. The maximum and minimum temperatures were significantly correlated with rust severity during three years and maintained significant positive relationships, confirming the critical role of temperatures in promoting yellow rust infection across years. Sunshine hours also showed a positive and significant correlation with rust severity throughout all years, being highest in 2022-23 followed by 2012-13 and 2021-22. This indicates that more sunshine days favoured rust development consistently, with slightly stronger effects observed in 2022-23. In contrast, relative humidity parameters showed negative correlations with rust severity, although their interpretation requires careful understanding of disease progression dynamics. Morning relative humidity (RHm) was significantly negatively correlated with yellow rust severity in 2012-13 and 2022-23 but was non-significant in 2021-22 .). Similarly, evening relative humidity (RHe) exhibited negative correlations across all three years,. Although higher humidity is essential for the initial establishment of yellow rust, as the season progressed, relative humidity declined, yet the disease continued to proliferate under conducive temperatures and sunshine conditions. Consequently, the overall season-long correlation between relative humidity and rust severity appeared negative, reflecting the later-season weather-disease dynamics rather than initial infection conditions. Rainfall exhibited a weak and inconsistent relationship with rust severity across years. In 2012-13 and 2021-22, rainfall was weakly and positively correlated with rust severity, though not significant. However, in 2022-23, rainfall showed a significant negative correlation.

The regression plots further reinforced these relationships by visually depicting the trends between meteorological variables and yellow rust severity. In the scatter plots for maximum and minimum temperatures across all three years, a strong positive slope was observed, indicating that as temperatures increased, yellow rust severity also increased. This positive trendline was steeper during 2012–13 and 2022–23, corresponding to the higher correlation coefficients during these years. In contrast, the regression lines for morning and evening relative humidity showed a negative slope, particularly sharp in 2022–23, further supporting the negative correlation pattern. However, this negative trend represents the later-season decline in humidity rather than the initial favourable conditions for rust initiation. Notably, the sunshine hours regression lines consistently showed a steep positive slope, with tighter clustering of data points around the trendline in 2022–23, highlighting the stronger dependence of yellow rust on sunshine during this year. Rainfall plots showed no consistent trend in 2012–13 and 2021–22, while a mild negative slope was visible in 2022–23, aligning with the observed negative correlation. The spread of data points (as reflected in the scatter) and the fitted regression lines, along with shaded confidence intervals, confirmed that temperature and sunshine were the most consistent and significant predictors of yellow rust severity, while humidity and rainfall played more variable roles depending on the year.

Validation of thumb rules: To anticipate disease outbreaks, several "thumb rules" i.e. simplified empirical guidelines based on key weather variables have been developed by different researchers. In this study the thumb rule developed for yellow rust forecasting by Sandhu et al. (2021) was validated (Table 2). This section evaluated the validity of these rules across three contrasting years: a high rust

Table 2. Validation of thumb rules for forewarning of yellow rust in Punjab

Month	Thumb rule*	Highest rust severity year (2012-13)	Heat stress year (2021-22)	Rust year (2022-23)
January	Tmax : 20-24°C	No	No	No
	Tmin : 7-13°C	No	Yes	No
	RHm : 86-98%	Yes	Yes	Yes
	Ssh : >8 hrs	No	No	No
	Rainfall : > 20 mm	No	Yes	No
February	Tmax : 15-25°C	Yes	Yes	Yes
	Tmin : 7-13°C	Yes	Yes	Yes
	RHm : 86-98%	Yes	No	Yes
	Ssh : 5-10 hrs	Yes	No	Yes
	Rainfall : > 20 mm	Yes	Yes	No
March	RHm : > 80%	Yes	Yes	Yes
	Frequent rainfall	Yes	No	Yes

severity year (2012-13), a heat stress year with low rust occurrence (2021-22), and a recent rust year (2022-23). The thumb rules for January suggests that yellow rust risk increases when maximum temperatures range between 20-24°C, minimum temperatures between 7-13°C, relative humidity (RH) is high (86-98%), sunshine hours exceeds 8 h, and rainfall is above 20 mm. Upon comparison with historical data, only relative humidity consistently matched across all three years, including both rust-prone and rust-free seasons. Notably, in 2012-13 and 2022-23 both rust years most of the other parameters were not aligned with the thumb rules. Conversely, in 2021-22, despite the occurrence of some conducive factors (e.g., high humidity and rainfall), no

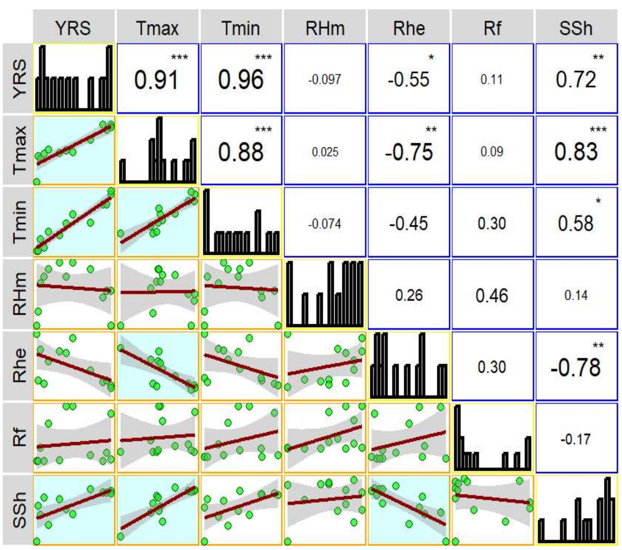

Fig. 6. Correlation coefficients between meteorological parameters and yellow rust severity during 2012-13 year

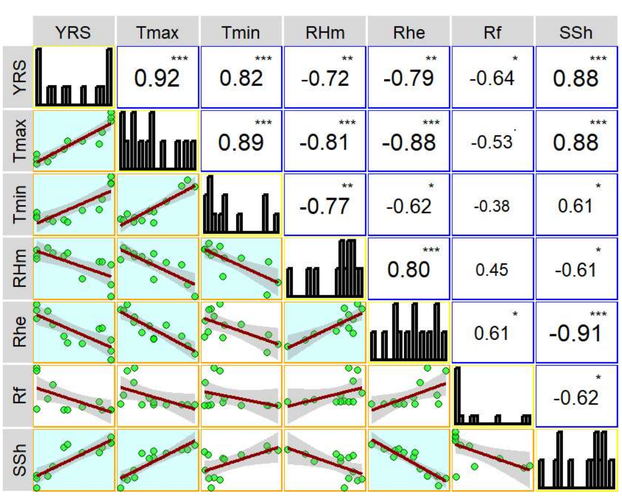

Fig. 7. Correlation coefficients between meteorological parameters and yellow rust severity during 2021-22 year

significant yellow rust outbreak was reported. Thumb rules for January exhibited limited predictive value when considered in isolation. Relative humidity appears to be the most consistently associated factor, but other parameters, such as temperature and rainfall, are not individually sufficient for early rust prediction. In February, the thumb rules hypothesize more rust risk when maximum temperatures fall between 15-25°C, minimum temperatures between 7-13°C, RH remains within 86-98%, sunshine ranges from 5-10 hours, and rainfall exceeds 20 mm. These criteria were fully met in 2012-13, which recorded the highest yellow rust severity, and largely satisfied in 2022-23, a more recent rust year. In contrast, 2021-22 met several thermal and rainfall criteria but did not experience a significant outbreak, potentially due to lower relative humidity and sunshine hour discrepancies. February exhibits the strongest validation of thumb rules. When multiple environmental factors (particularly temperature, RH, and rainfall) converge, the risk of yellow rust escalates considerably. This month serves as a critical window for disease surveillance and management interventions. For March, the thumb rules emphasize RH levels above 80% and the presence of frequent rainfall. All three years fulfilled these criteria. However, yellow rust was maximum during 2012-13. While March conditions can support disease progression, they are not independently predictive of outbreak initiation. Rather, they may contribute to sustained or secondary infection phases if early-season conditions were conducive. The comparative analysis confirms that the thumb rules are most predictive when evaluated cumulatively, particularly in February. Relative humidity is a consistently relevant factor across all months. However, relying on any single parameter may lead to false positives or negatives. Therefore, an integrated approach that considers multiple concurrent weather conditions - especially during February - is essential for accurate forecasting and timely management of yellow rust in wheat.

The comparative analysis of three contrasting wheat seasons: 2012–13 (epidemic year), 2021-22 (heat-stress year), and 2022-23 (recent rust year) provides valuable insights into the complex relationship between meteorological variables and the development of yellow rust. The results underscore that temperature, humidity, sunshine duration and rainfall interact in nuanced ways to influence the onset, progression, and suppression of the disease. Temperature emerged as a key driver of disease onset and severity. During both the 2012-13 and 2022-23 seasons, yellow rust outbreaks coincided with moderately low maximum temperatures (15-17°C) and cool minimum temperatures (5.8-6.4°C) during the initiation phase. These thermal conditions fall within the optimal range for *Puccinia striiformis* development, consistent with findings by Chen (2005) and Line (2002) where favourable growth and infection at day temperatures between 10-15°C and night temperatures between 4-8°C. Minimum temperature showed the strongest positive correlation with rust severity in 2012-13 and 2022-23), highlighting the role of night temperatures in prolonging leaf wetness duration and enhancing nocturnal fungal activity (Sandhu et al., 2021). Conversely, the 2021-22 season, marked by daytime and nighttime temperatures up to 35.6°C and 15.3°C, respectively, recorded minimal disease severity Wellings (2007) and Milus et al. (2009) also observed that higher temperatures negatively affect urediniospore viability, germination, and infection efficiency. Although newer pathotypes of *Pst* have shown some thermotolerance (Ali et al., 2017), the 2021-22 thermal profile likely exceeded even these adapted thresholds, supporting reduced epidemic potential under heat-stress scenarios. Relative humidity also played a pivotal role in disease modulation. Across all three years, morning RH levels were consistently high (91-94%) during the initiation phase, with maximum levels (97%) observed in 2012-13. However, evening humidity levels, which were substantially lower in 2021-22 (43%) and 2022-23 (46%), correlated negatively with rust severity, especially in the former year. The incomplete overlap of high relative humidity across morning and evening in 2021–22 could explain the limited disease spread despite the presence of other partially favourable conditions. Rainfall contributed to disease spread but was not a primary driver. Moderate rainfall during the progression phase in 2012-13 (22.6 mm) likely facilitated spore dispersal and canopy wetness, which is consistent with the disease-promoting role of rain splashes and wind-assisted dissemination described by Isard and Russo (2011) and Geagea et al., (2000). However, the overall weak correlation between rainfall and disease (r = 0.11 to 0.38) suggests that rainfall acts as a secondary or complementary factor, enhancing the conducive environment established by temperature and humidity. Sunshine duration displayed a somewhat paradoxical pattern. While longer sunshine hours are generally thought to reduce leaf wetness and inhibit disease, a positive correlation was observed in all years, particularly in 2021-22 (r = 0.88). Anand et al. (2023) demonstrated that optimal urediniospore germination of *Puccinia striiformis* occurred at 15°C, whereas *Puccinia triticina* peaked at 20°C, with a neutral pH (7) and intense light (1250 lux) further promoting germination. This anomaly may stem from the role of sunlight in regulating host physiology, such as photosynthesis and stomatal conductance, which can indirectly affect disease susceptibility (Brown et al., 2001). In 2021-22, the intense solar radiation and elevated temperatures may have offset any potential disease benefits of increased sunlight by hastening crop maturity and thereby shortening the rust's infection window. The research of relationship of illumination and temperature was instructive, since under natural conditions illumination would always be changing and may affect spore germination. Since, the initial studies by Dillon Weston (1931) and Stock (1931), light has been recognised to alter urediniospore germination of numerous species of rust fungi differently. The type of affect and the degree to which light affects germination, however, differ depending on the light source and the species of rust. There hasn't been a direct comparison of how light affects the urediniospores of different species of rust fungi. At specific temperatures, *P. striiformis* germination was accelerated by fluorescent light (Tollenaar and Houston 1966).

The validation of thumb rules proposed by Sandhu et al. (2021) highlighted February as the most critical month for reliable disease forecasting. In both 2012-13 and 2022-23, all major indicators like favourable temperature ranges (15-25°C max, 7-13°C min), high RH (86-98%), rainfall above 20 mm, and moderate sunshine were met, and yellow rust incidence was prominent. In contrast, the 2021-22 season, though satisfying some thermal and rainfall conditions, failed to meet crucial humidity and canopy wetness thresholds, explaining the absence of a significant outbreak. Poudyal et al. (2013) also emphasized the cumulative effect of multiple parameters rather than single-variable thresholds in predicting disease emergence. The January thumb rules showed limited alignment with actual disease patterns, especially in 2021–22, and March parameters were too general to independently predict disease initiation, the

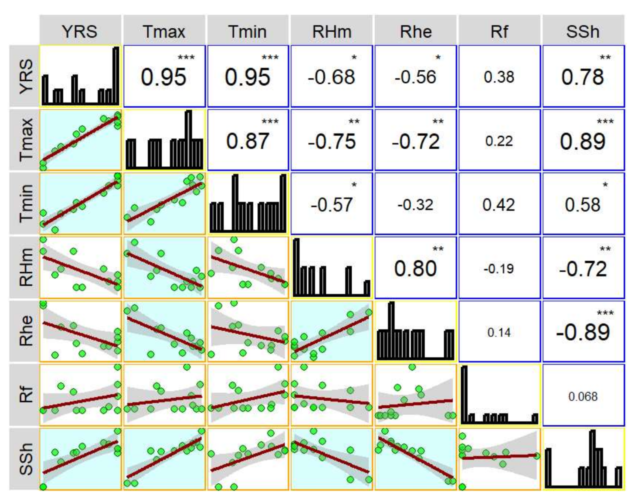

Fig. 8. Correlation coefficients between meteorological parameters and yellow rust severity during 2022-23 year

results strongly advocate for an integrated approach that considers concurrent interactions of temperature, humidity, and rainfall during February. This approach supports the development of robust, dynamic early warning systems that can optimize fungicide application timing and reduce unnecessary chemical use (Kashyap et al., 2018). Anand and Sandhu (2024) highlighted that the early sowing window, marked by ideal weather for rust proliferation, recorded the highest yellow rust severity compared to later sowing periods. Together, these insights underscore the intricate interplay of abiotic factors driving stripe rust epidemics and highlight the potential of predictive modelling in disease management. Overall, the study confirms that yellow rust outbreaks are not driven by single weather variables but by the synergistic effect of multiple favourable conditions, particularly during the disease initiation and progression windows. The reduced rust pressure under high-temperature regimes, as observed in 2021–22, also emphasizes the emerging trade-off between heat stress and rust outbreaks under climate change scenarios. As newer *Pst* pathotypes continue to evolve, continuous surveillance and adaptive forecast models integrating real-time weather data will be indispensable.

CONCLUSIONS

The findings of this study underline that yellow rust development is strongly driven by a combination of cooler temperatures, high humidity and adequate moisture availability. Years marked by such conditions lead to severe disease outbreaks. In contrast, elevated temperatures, lower humidity, and longer sunshine hours restricted disease progression, suggesting that rising temperatures due to climate change could potentially shift disease dynamics in future wheat-growing seasons. These insights point to the need for region-specific disease forecasting systems that integrate real-time weather data. Proactive surveillance and adaptive management strategies will be crucial to safeguarding wheat production under increasingly unpredictable weather patterns.

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