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Trade-offs between early planting and yellow rust resistance in wheat: Insights from screening experiments in the Indo-Gangetic plain

Md. Farhad[1,2] | Shashi B. Tripathi[1] | Ravi P. Singh[3] | Arun K. Joshi[4] |
Pradeep K. Bhati[4] | Uttam Kumar[5]

[1]Department of Biotechnology, TERI
School of Advanced Studies, Vasant Kunj,
New Delhi, India

[2]Bangladesh Wheat and Maize Research
Institute (BWMRI), Dinajpur, Bangladesh

[3]CIMMYT, Texcoco, Mexico

[4]Borlaug Institute for South Asia (BISA),
New Delhi, India

[5]Astralyn Agro (OPC) Pvt. Ltd., Ludhiana,
Punjab, India

Correspondence
Md. Farhad, Bangladesh Wheat and Maize
Research Institute (BWMRI),
Dinajpur-5200, Bangladesh.
Email: farhadnabin@gmail.com

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Abstract

Wheat crops (*Triticum aestivum*) that are conventionally planted may exhibit susceptibility to yellow rust (YR). However, the disease can be mitigated if the crops are planted earlier than the recommended planting time. A wheat screening experiment was carried out at the Borlaug Institute of South Asia located in Ludhiana, Punjab, India. The purpose of the study was to gain a deeper understanding of the adaptation patterns of early planted wheat. Early planting was found to be more advantageous for production potential, as well as phenology, stature, and physiological traits. In a separate experiment, each year, the same number of genotypes were screened for YR by artificially inoculating them with pathogen spores. The well-adapted genotypes for early establishment tend to possess a greater vulnerability to YR infection. Furthermore, the infection type score for the genotype selected for early planting showed a significantly greater proportion of S (susceptible) type reactions than for the genotypes adapted to early planting. Intriguingly, more R (resistant) and moderately resistant types of reactions were observed in early-adapted genotypes than in timely-adapted ones. Therefore, further concentrated research on YR screening is required to assess the possibility of breeding early sown wheat in the northwest part of the Indo-Gangetic region.

Plain Language Summary

Wheat planted at the usual time is often at risk of yellow rust, a damaging wheat disease. This study explored whether planting wheat earlier than recommended can help reduce yellow rust infections. Conducted at the Borlaug Institute of South Asia

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Abbreviations: BISA, Borlaug Institute for South Asia; CIMMYT, International Maize and Wheat Improvement Centre; CTIR, canopy temperature increasing rate; EP, early planting; GDD, growing degree days; GRYLD, grain yield; HUS, height upto spike; MGIDI, multi-trait genotype-idiotype distance index; MR, moderately resistant; MS, moderately susceptible; NARS, National Agricultural Research System; PG_BTH, photo-growing degree days for height upto spike; PG_DTB, photo-growing degree days for days to booting; PG_GFD, photo-growing degree days for grain filling duration; PH, plant height; SABWGPYT, South Asia Bread Wheat Genomic Prediction Yield Trials; SI, selection intensity; SpkLng, spike length; SR, senescence rate; TGW, 1000-grain weight; TP, timely planting; YR, yellow rust; YRCI, yellow rust coefficient of infection.

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in Ludhiana, India, the research tested different wheat genotypes by exposing them to yellow rust each year to see how they responded. Results showed that early planting improves wheat growth, yield, and development. However, some wheat varieties that adapt well to early planting are more prone to yellow rust. Interestingly, these early-adapted varieties also showed more resistance to yellow rust compared to normally planted ones. This suggests that breeding wheat varieties for early planting may provide a solution to yellow rust challenges in parts of the Indo-Gangetic region.

1 | INTRODUCTION

Approximately 50% of the population residing in the densely populated Indo-Gangetic region rely on wheat as a means of sustenance. Terminal heat stress and diminishing water resources express significant challenges to wheat production (Joshi et al., 2007). The observation of wheat lines in India exhibiting an earlier heading by 4–9 days suggests that extending the crop duration by a specific duration may serve as a compensatory measure to counteract the negative impact of seasonal temperature increases on crop yield (Singh et al., 2007). Extending the temporal boundaries for cultivating spring wheat can be achieved by implementing an advanced planting time. The findings indicate that advancing the planting time by 1–2 weeks is a more favorable approach as it facilitates a substantially extended crop growth period and reduces irrigation requirements due to the availability of moisture after the monsoon season. Due to the high precipitation levels during the monsoon season, farmers in numerous areas of northwest and central India opt to sow wheat at an early stage to capitalize on the residual moisture.

The northwest part of the Indo-Gangetic plain requires breeding for early sown conditions and genotype screening to fulfil the massive demand of farmers (Kumar et al., 2021). Conversely, the impact of three rust diseases on wheat, namely, yellow rust (YR) or stripe rust caused by *Puccinia striiformis f.* sp. *trititici*, leaf rust or brown rust caused by *Puccinia triticina*, and stem rust or black rust caused by *Puccinia graminis f.* sp. *tritici*, is noteworthy in the context of worldwide wheat production. YR is considered as one of the most significant diseases among the primary wheat-producing countries globally due to its swift evolution, distribution, and the emergence of new pathotypes. Under severe epidemic conditions, wheat YR can lead to a reduction in production of up to 70%, thereby affecting both grain fill and quality. The annual cost of YR to the world economy is estimated to be $1 billion (Beddow et al., 2015). YR has traditionally been linked with warm high-altitude areas that have humid summers and cool nights, as well as high-altitude places that are humid during the day and cooler at night (Rapilly, 1979; Stubbs, 1985). In more recent years, however, it has been demonstrated that the disease is capable of

exhibiting a more astonishing adaptation in warmer temperatures, even though in the past it was either less prevalent or completely absent in these areas (Hovmøller et al., 2010). YR outbreaks can be influenced by various factors, such as the developmental stage of the plant and its nutritional status (Neumann et al., 2004), as well as the resistance mechanism of the host to infection (Johnson, 1984, 1992). Additionally, the presence of initial infection during crop growth (Zadoks et al., 1974) and the pathogenicity characteristics of the most common pathogen races (Ali et al., 2017; Bhat et al., 2016; de Vallavieille-Pope et al., 2012; Hovmøller & Henriksen, 2008; Singh et al., 2016) can also play a role in YR outbreaks. According to Chatrath et al. (2007), the northwest regions of India and Pakistan exhibit a higher degree of severity in stripe rust as compared to the other two types of rust. The northern region of India is currently facing a significant threat to its wheat production, as stripe rust is posing a risk to approximately 10 million ha of crops. In contrast to stem rust, the aforementioned pathogen poses a threat to an estimated 7 million ha of land in Central and Peninsular India, as reported by Bhardwaj et al. (2019). This report also established and extended a methodical system of Wheat Disease Trap Plot nurseries to neighboring nations within the South Asian Association for Regional Cooperation platform. This system was implemented to investigate the prevalence of wheat infections and the pathways through which they migrate.

To understand the host plant resistance dynamics under early and normal sown conditions, we carried out a wheat screening trials for three seasons at the Borlaug Institute for South Asia (BISA) research farm located in Ludhiana of Punjab State located in the north-western region of India. Our objective was to assess the resistance patterns of three distinct sets of wheat genotypes that are adapted to early sowing conditions.

2 | MATERIALS AND METHODS

2.1 | Location

An experiment was carried out at BISA located in Ludhiana, Punjab, India, to explore the possibility of extending

the wheat-growing season through early planting (EP). Moreover, a YR screening was carried out at the same location to facilitate additional analysis of YR prevalence in the location.

2.2 | Planting time

An annual EP was conducted at the same location with an identical set of genotypes, approximately 3 weeks prior to the standard planting/timely planting (TP) period. The EP was carried out 17 days earlier during season 1, 24 days earlier during season 2, and 23 days earlier during season 3.

2.3 | Genotypes

The germplasms used in the experiment were developed at the International Maize and Wheat Improvement Canter, commonly known as International Maize and Wheat Improvement Centre (CIMMYT), Mexico, and were identified as the South Asia Bread Wheat Genomic Prediction Yield Trials (SABWGPYT). They were dispatched to India to evaluate the adaptability and performance of these lines in the irrigated ME1 and hotter ME5 environments. Most of these lines exhibited sufficient quality parameters, offering CIMMYT's partners within the National Agricultural Research System (NARS) the opportunity to select well-adapted genotypes suited to their specific breeding and development programs. This adaptability may also allow NARS partners to directly release certain genotypes as varieties tailored to specific environmental conditions, enhancing crop productivity and resilience in targeted regions. Each year, CIMMYT supplies a unique set of genotypes to SABWGPYT. The trials included 540 genotypes in the 2017–2018 (season 1) season and 530 in 2018–2019 (season 2) and 2019–2020 (season 3) seasons.

2.4 | Experimental design and establishment of agronomic trials

The experiment for early and TP had an alpha lattice design where each replicated block was subdivided into six subblocks containing 10 plots. For an easy experiment management, the entries were grouped into six trials with 54 genotypes and six checks. Each plot was characterized by dimensions of 1.32 m by 3.80 m and comprised six rows. The seed rate utilized in both planting methods, namely, EP and TP, was consistent at 50 g/plot.

2.5 | Agronomic management of the trials

The operation of field trials adhered to the conventional agronomic procedures that are advised for the specific geo-

Core Ideas

- Conventionally planted wheat, which often gets exposed to yellow rust, can be planted earlier to reduce vulnerability to this disease.
- Early-planted wheat exhibits benefits in production potential, phenology, stature, and favorable physiological attributes.
- Genotype screening reveals that well-adapted early-planted wheat shows higher yellow rust (YR) presence and susceptibility.
- Early-adapted genotypes demonstrate increased resistance to YR, suggesting potential for breeding in the region.

graphical region. Five irrigations were applied during the starting 21 days after the initial seeding. Other irrigations occurred every three to 4 weeks, depending on weather conditions. The fertilizer application rate was 150N:60P:40K kg/acre.

2.6 | YR screening trials

Every year, each set of entries was screened for YR in a separate nursery. The unique plot size was one meter long, in two rows, and screened over inoculated conditions (Figure 1). YR was recorded in the field by the guideline published by CIMMYT as illustrated in Figure 2 (CIMMYT, 1986). The categorization of host-pathogen reaction and coefficient of infection value was calculated by the survey protocol mentioned by Ali and Hodson (2017). Yellow rust coefficient of infection (YRCI) was calculated by using the following formula from the protocol: YRCI = S × RT, where S is the severity percentage in the plot and RT is the increment of the coefficient values (Table 1).
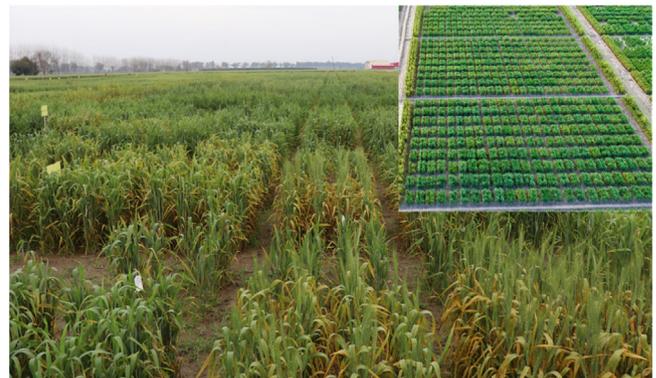

FIGURE 1 Infected plots ready for scoring at highest infection stage (aerial view of the plot in the top right corner).
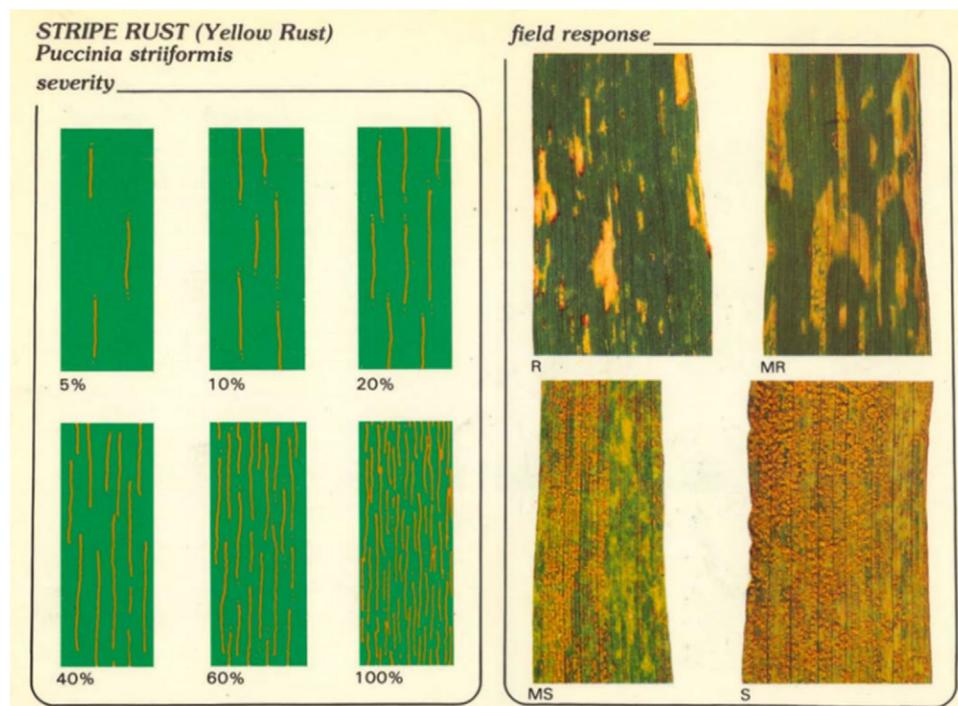
FIGURE 2 Yellow rust recording guideline based on the International Maize and Wheat Improvement Centre (CIMMYT) guideline.

TABLE 1 Recording host reaction categories and symptoms during field rust infection scoring.

Symptom	Host reaction	Host reaction (symbol)	CI[a] values
No visible infection	Immune	I	0.00
Necrotic areas with or without small pustules	Resistant	R	0.10
Small pustules surrounded by necrotic areas	Moderately resistant	MR	0.25
Combination of both MR and MS	Moderately resistant–moderately susceptible	M	0.50
Medium-sized pustules, no necrosis, some chlorosis	Moderately susceptible	MS	0.75
Large pustules, no necrosis or chlorosis	Susceptible	S	1.00

[a]Coefficient of infection = increment × severity (e.g., 20MR = 30 × 0.25 = 7.5).

2.7 | Field phenotyping

For field phenotyping, several morpho-physiological traits were measured in the field (Table 2). Those traits were grouped based on their type. Phenological traits include all the recurrent natural events in the wheat life cycle. Separately and in conjunction with the photoperiod, growing degree days (GDD) were determined using the Wang and Engel (1998) approach.

The effect of photoperiod and GDD on wheat growth between emergence and floral initiation is called photo-growing degree days. Plant stature traits are the measurement of the height of different plant organs. Physiological traits include some of the field-measurable physiological activities in wheat that can be determined by high throughput phenotyping. We also collected the yield and yield contributing characters for this study. For precision phenotyping, Field-Book App developed at Kansas State University (Rife & Poland, 2014) was used to collect the data to save time and effort and minimize errors in data entering to computer.

2.8 | Statistical analysis

The study utilized the mixed effect model using restricted residual maximum likelihood/best linear unbiased prediction analysis (Henderson, 1975; Patterson & Thompson, 1971). The mixed effect model for multiple environments (Basford et al., 2004; Olivoto et al., 2019; Voss, 1999) is expressed as $y = X\mu + Zg + Wb + Ti + Qp + \varepsilon$, which is used to analyze the agronomic and physiological traits in the experiment. In this model, y is the observed response variable, such as

TABLE 2 List of traits observed in field phenotyping.

1	**Phenology**	
a	DTB	Days to booting
b	DTHD	Days to heading
c	DAYSMT	Days to maturity
d	BTH	Booting to heading days
e	GFD	Grain filling period
f	PG_DTB	Photo growing degree days of days to booting
g	PG_DTHD	Photo growing degree days of days to heading
h	PG_DAYSMT	Photo growing degree days of days to maturity
i	PG_BTH	Photo growing degree days of booting to heading days
j	PG_GFD	Photo growing degree days of grain filling period
2	Plant stature	
a	PH	Plant height (cm)
b	SpkLng	Spike length (cm)
c	PDG	Ground to Peduncle note distance (cm)
d	PDL	Peduncle length (cm)
e	HUS	Hight up to spike (cm)
f	FLGLFL	Flag leaf length (cm)
g	FLGLFW	Flag leaf width (cm)
h	FLGLFA	Flag leaf area (cm^2)
3	Physiology	
a	EGC	Early ground cover
b	NDVI_DTB	Normalized vegetation index at booting
c	NDVI_DTHD	Normalized vegetation index at heading
d	NDVI_Max	Maximum value of normalized vegetation index
e	SR	Senescence rate
f	CTIR	Canopy temperature increasing rate
4	Yield and TGW	
a	TGW	1000-Grain weight (g)
b	GRYLD	Grain yield (kg/ha)

yield, measured across different genotypes, environments, and replicates.

The fixed effects are represented by $\mathbf{X}\boldsymbol{\mu}$, where $\mathbf{X}$ is the design matrix that relates the fixed effects (e.g., overall mean or controlled treatments like irrigation, fertilization, or management) to the observed response, and $\boldsymbol{\mu}$ is the vector of these fixed effects. Fixed effects are consistent across the experiment and are used to account for systematic factors that influence the response variable.

The term $\mathbf{Z}\mathbf{g}$ captures the random genotypic effects, where $\mathbf{Z}$ is the design matrix linking genotypes to the observations, and $\mathbf{g}$ is the vector of random genetic effects. These effects are assumed to follow a normal distribution, $\mathbf{g} \sim \text{NID}(0, \sigma_g^2)$, reflecting the inherent variability in performance among genotypes due to genetic differences. Another source of random variation is $\mathbf{W}\mathbf{b}$, which represents block effects or replication effects within environments. Here, $\mathbf{W}$ is the design matrix, and $\mathbf{b}$ is the vector of random block effects, typically modeled as $\mathbf{b} \sim \text{NID}(0, \sigma_b^2)$. This term accounts for spatial variability within experimental blocks, ensuring the trial's design is robust and unbiased.

The $\mathbf{T}\mathbf{i}$ term captures the genotype-by-environment interactions, where $\mathbf{T}$ is the design matrix, and $\mathbf{i}$ represents the vector of interaction effects. This term is essential for understanding how genotypes respond differently to varying environmental or treatment conditions. Additionally, $\mathbf{Q}\mathbf{p}$ represents other random effects, such as plot-level variability or nested effects within the experimental structure, with $\mathbf{Q}$ as the design matrix and $\mathbf{p}$ as the vector of plot-specific random effects. Finally, ε is the residual error, representing the random noise or unexplained variation in the data, assumed to follow $\varepsilon \sim NID(0, \sigma^2)$. In each case, NID means normally, identically, and independently distributed.

This mixed-effects model is a powerful tool for partitioning the observed variability into its components. The statistical package Metan in R (Olivoto & Lúcio, 2020) was used in the analysis, enabling us to estimate the genetic potential of genotypes (via $\mathbf{g}$), assess environmental influences and interactions (via i), and account for design-specific effects like block variability (via $\mathbf{b}$).

On the other hand, the individual environment was analyzed using a single experiment mixed effect model (Möhring et al., 2015) according to the following equation: $y_{ijk} = m + g_i + r_j + b_{jk} + e_{ijk}$, where y_{ijk} is the response variable of the ith genotype in the kth block of jth replicate, m is the intercept, g_i is the effect for jth genotype, r_j is the effect of jth replicate, b_{jk} is the effect of the kth incomplete block of jth replicate, and e_{ijk} is the plot error effect corresponding to y_{ijk}.

The multi-trait genotype-ideotype distance index (MGIDI) was utilized to simultaneously select for mean performance across traits within each environment, following the method of Olivoto and Nardino (2021). The genotype with the lower MGIDI was considered closer to the ideotype and thus presented the desired values for all the analyzed traits. Selection intensity (SI) was expressed as a percentage of the total number of genotypes using the SI argument, ranging from 0 to 100. The ideotype argument was used to indicate the trait's higher or lower value, which was desirable to calculate the final index, as described by Farhad et al.
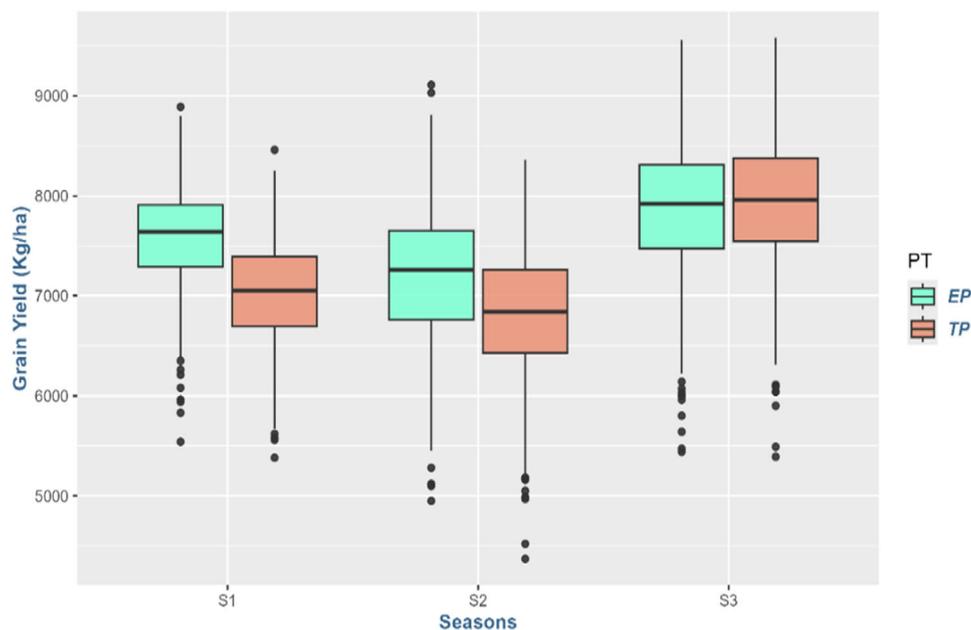
FIGURE 3　Grain yield of wheat across different seasons (S1 = Season 2017–2018; S2 = Season 2018–1019, and S3 = Season 2019–2020) and planting times (early planting [EP] and timely planting [TP]). PT, planting time.

(2021, 2023), Olivoto and Nardino (2021), and Olivoto et al. (2019). The $MGIDI_i$ index was computed by the formula, $MGIDI_i = \sqrt{\sum_{j=1}^{f}(F_{ij} - F_j)^2}$ where, $MGIDI_i$ is the multi-trait genotype-idiotype distance index for ith genotype; F_{ij} is the score for the ith genotype in the jth factor ($i = 1.2 \ldots ., g$; $j = 1, 2, \ldots, f$), g and f being the number of genotypes and factors, respectively; and Fj is the jth score of the idiotype. The fitted model automatically calculated heritability, allowing for an easy estimation of selection gain for each trait or factor.

3 | RESULTS

3.1 | Environmental condition

During the 2017–2018 season, the region experienced optimum temperature and rainfall, which led to ideal growing conditions for the crop. The wheat plants received sufficient moisture and temperature to support healthy growth and development, resulting in a bountiful harvest (Figure 3). However, the following year, 2018–2019, brought high rainfall and hailstorms during the booting stage. These extreme weather conditions resulted in significant damage to the wheat crop, with some plants being damaged by heavy rains and hailstorms. Fortunately, the crop recovered soon after drainage of excess water from the experimental plot. In contrast, the 2019–2020 season was characterized by a prolonged winter, which favored the growth and development of the wheat crop (Figure 4). The prolonged winter led to an extended growing

period, allowing the plants to fully mature and reach optimal yield potential. Additionally, the cooler temperatures during the winter months helped to reduce the risk of disease outbreaks in the crop. The combination of extended growing period and reduced disease pressure led to an increase in wheat yield.

3.2 | Contribution of traits to grain yield and 1000-grain weight, ideotype design, and genotype selection

Early sowing was found to extend the wheat growing season by prolonging vegetative growth. The prolonged duration of the vegetative phase resulting from early sowing significantly increased the yield from multiple genotypes. The significant positive correlation of 1000-grain weight (TGW) with photo-growing degree days for grain filling duration (PG_GFD) but a negative correlation with other phenological traits at both planting dates suggested that the yield increase at EP could be attributed to an increased number of grains due to a more substantial number of fertile spikelets in the spike. Increasing the length of time for vegetative growth and leaf area during EP increases the accumulation of dry matter at the source, which is subsequently transmitted to the sink. This seems to enhance the weight and quantity of grains. The flag leaf traits and spike lengths (SpkLngs) did not exhibit any impact on TGW. Nevertheless, a noteworthy positive correlation was detected between height upto spike (HUS) and TGW in EP during both season 1 and season 2. Greater plant height (PH) during the EP
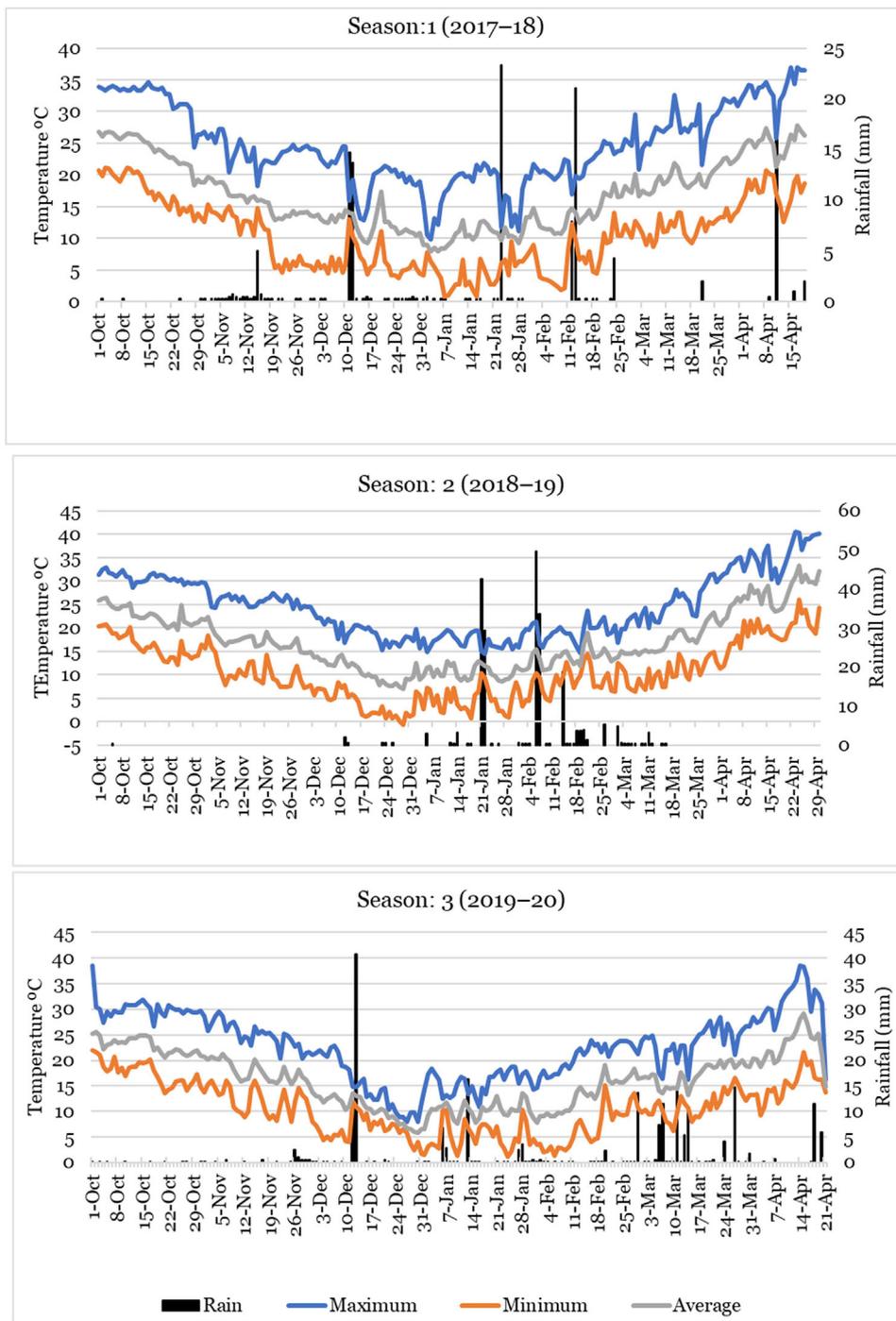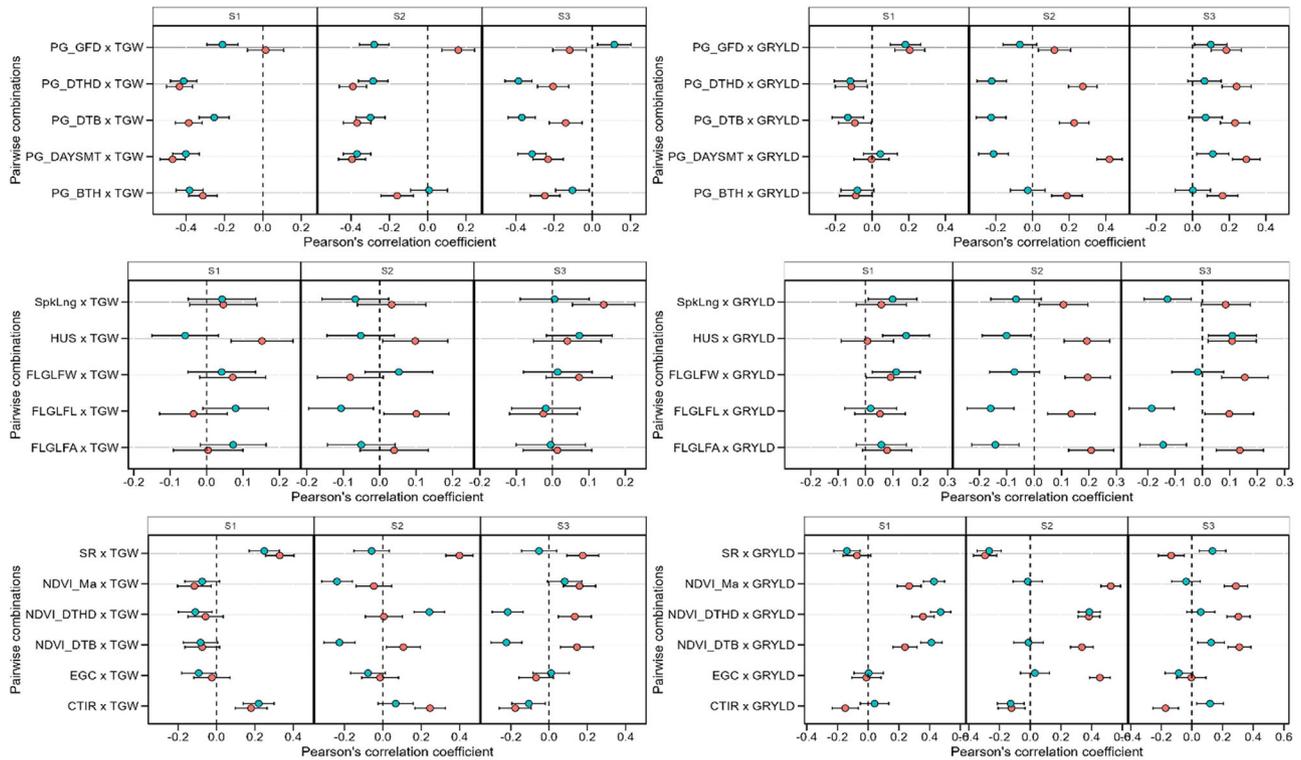
FIGURE 4 Weather pattern in the consecutive three season at Borlaug Institute for South Asia (BISA) farm, Ludhiana.

stages is positively correlated with boldness of grain, resulting in a higher grain weight. Similarly, the HUS exhibited a noteworthy affirmative correlation with the production of grains, with the exception of EP during the first season and TP during the second season. The correlation between SpkLng and TGW was largely insignificant, while its association with grain yield (GRYLD) was found to be inconsistent. The study found that flag leaf traits did not exert any discernible impact on TGW. However, a significant correlation was observed

between these traits and GRYLD. The width of the flag leaf exhibited a noteworthy positive correlation with GRYLD in the EP group, whereas it was insignificant in the TP group, except for season 1. The study found a significant positive correlation between flag leaf length and area and with GRYLD in the EP, while a significant negative correlation was observed in the TP, except for season 1. However, it should be noted that season 1 did not show a significant association between either planting time. The study reveals a positive

S1= Season 1, S2= Season=2, S3= Season 3, EP= Early Planting, TP= Timely Planting, Traits name elaborated in Table 1.

FIGURE 5 Pearson correlation confidence interval of grain yield and 1000-grain weight (TGW) with different trait groups. EP, early planting; S1, season 1; S2, season 2; S3, season 3; TP, timely planting. Traits name is elaborated in Table 1.

correlation between TGW and SR in EP across all three seasons; however, in TP during season 2 and season 3, the association was negative, indicating that genotypes exhibiting rapid senescence tend to exhibit higher TGW in EP. Maintaining a green status during the grain filling stage in TP cultivars may result in a reduction of grain weight in comparison to EP cultivars. The timing of canopy temperature increasing rate for planting exhibits inconsistency across different seasons. The trait is predominantly linked with unfavorable associations with TGW and GRYLD, except for TP in season 3 for GRYLD and both planting times for TGW, as illustrated in Figure 5.

Phenological events have a significant impact on GRYLD and TGW, according to the design of ideotypes. Longer photo-growing degree days for days to booting (PG_DTB) showed a substantial positive connection with both GRYLD and TGW. In our analysis of PG_DTB, photo-growing degree days for height upto spike (PG_BTH), and PG_GFD, demonstrates its potential to improve these qualities. Based on the study's overall performance analysis, EP is likely to cause a protracted vegetative stage.

According to the study's findings, over the course of 3 years, the traits showed distinct patterns of strength and weakness in relation to early TPs. The phenological traits PG_DTB and PG_GFD strongly support selection gain in EP across

all seasons. The traits TGW and GRYLD, however, show somewhat less support for the chosen genotypes in EP over the course of two seasons. An extended grain filling period (PG_GFD) is projected to increase support for GRYLD and grain weight. As a result of the occurrence of terminal heat stress during its grain-filling period, EP, on the other hand, may hasten the maturation process of a plant.

To achieve early establishment within the selected genotypes, breeders must be meticulous in searching for genotypes with specific, trait-based characteristics. We have selected the following traits for further ideotype design and genotype selection based on their contribution to TGW and GRYLD in our phenotyping experiment. Genotypes closest to the designed ideotype, as identified by the MGIDI index, were chosen for further analysis. To ensure adaptation in both early and TP conditions, we selected superior genotypes based on the ideotype designed (Table 3) with a 10% SI.

3.3 | Response of early adapted genotypes to the prevalence of YR disease

It was found that normally planted wheat might be vulnerable to YR. In the genotype evaluation nursery (SABWGPYT 1–10), however, it was able to escape when planted earlier than

TABLE 3 Incorporating increasing/decreasing selection pressure on multi-trait stability with multi-trait genotype-idiotype distance index (MGIDI) index.

Traits	S1 EP	S2 EP	S3 EP	S1 TP	S2 TP	S3 TP
PG_DTB	↑N	↑N	↑	↑	↑	↑
PG_BTH	↑	↑	↑	↓	↓N	↓N
PG_GFD	↑	↑	↑	↓N	↓N	↓N
HUS	↓	↓	↓N	↓	↓N	↓N
FLGLFL	↑	↑	↑	↑	↑	↑
FLGLFW	↑	↑	↑	↑	↑	↑
EGC	↑N	↑N	↑N	↑	↑	↑N
SR	↓	↓	↓	↓	↓	↓
CTIR	↓	↓	↓	↓N	↓	↓
TGW	↑N	↑N	↑N	↑	↑	↑N
GRYLD	↑	↑	↑	↑	↑	↑

Note: N denotes that the selection gain did not match with desired selection pressure.

Abbreviations: CTIR, canopy temperature increasing rate; EP, early planting; EGC, early ground cover; FLGLFL, flag leaf length; FLFLFW, flag leaf width; GRYLD, grain yield; HUS, height upto spike; PG_BTH, photo-growing degree days for height upto spike; PG_DTB, photo-growing degree days for days to booting; PG_GFD, photo-growing degree days for grain filling duration; TGW, 1000-grain weight; TP, timely planting.

the time that was advised. Superior genotypes were selected for better adaptation in early as well as TP conditions based on the designed ideotype with 10% SI. The best genotypes close to the designed ideotype based on the MGIDI index (Figure 6) were selected for further analysis. Detailed MGIDI selection and ideotype design are discussed in our other studies (Farhad et al., 2021, 2023). These selected genotypes were then evaluated against YR infestation data from the YR screening nursery each year. The severity and reaction type were studied from the separate YR screening trials.

The Satterthwaite *t*-test (adjusted for unequal variances) shows a significant difference (*p*-value = 0.0038) between the mean YRCI of EP and TP. Based on the analysis, there's strong evidence to reject the null hypothesis (no difference in mean YRCI). We can conclude that, on average, EP has a significantly higher YRCI compared to TP. Although EP was found more suitable for yield potential along with a better performance in phenology, stature, and physiological traits, unfortunately, the well-adapted genotypes for early establishment tend to have higher percentages of YR spots. In the first season, 40% of the selected genotype exhibited an immune response when planted early, whereas 64% showed an immune response in TP conditions. Similarly, in the second season, 13% of the selected genotypes showed an immune reaction when planted early, while 22% exhibited an immune response in TP conditions. Finally, in the third season, 36% of the selected genotypes displayed an immune reaction when planted early, whereas 42% showed an immune response in TP conditions. These observations suggest that deviating from the recommended planting schedule by planting earlier may lead to the selection of genotypes with increased susceptibil-

ity to YR infection, compared to those planted at the optimal time. The selected genotypes exhibited varying degrees of susceptibility to S reaction across the three seasons. Specifically, 9% of the genotypes displayed susceptibility in season 1, 7% in season 2, and 11% in season 3 for EP. In contrast, 7% of the genotypes were susceptible in season 1, no S reaction was observed in season 2, and 13% were susceptible in season 3 for TP. The results indicate that there was a consistent trend of moderately susceptible (MS) reaction for EP across the three seasons, with 35%, 43%, and 22% of samples exhibiting such a response in season 1, season 2, and season 3, respectively. Conversely, the proportion of samples exhibiting MS reaction for regular planting was found to be 24%, 26%, and 27% in season 1, season 2, and season 3, respectively, as illustrated in Figure 7b.

The findings indicate that the selected genotype exhibits a greater incidence of S and MS types of YR reactions during EP as compared to TP. Conversely, the results indicate that during season 1, a reaction type of 4% R with 13% MR was observed in conjunction with a reaction type of 7% R with 30% MR during season 2, and a reaction type of 9% R with 22% MR was observed during EP. However, no reaction type of R with 5% MR was observed during season 1, while a reaction type of 11% R with 41% MR was observed during season 2, and a reaction type of 5% R with 13% MR was observed during season 3 under TP conditions, as illustrated in Figure 7. The investigation into the severity of the infection revealed that a greater percentage of severity is present in the chosen genotypes during each season for early-adapted genotypes in contrast to TP conditions.
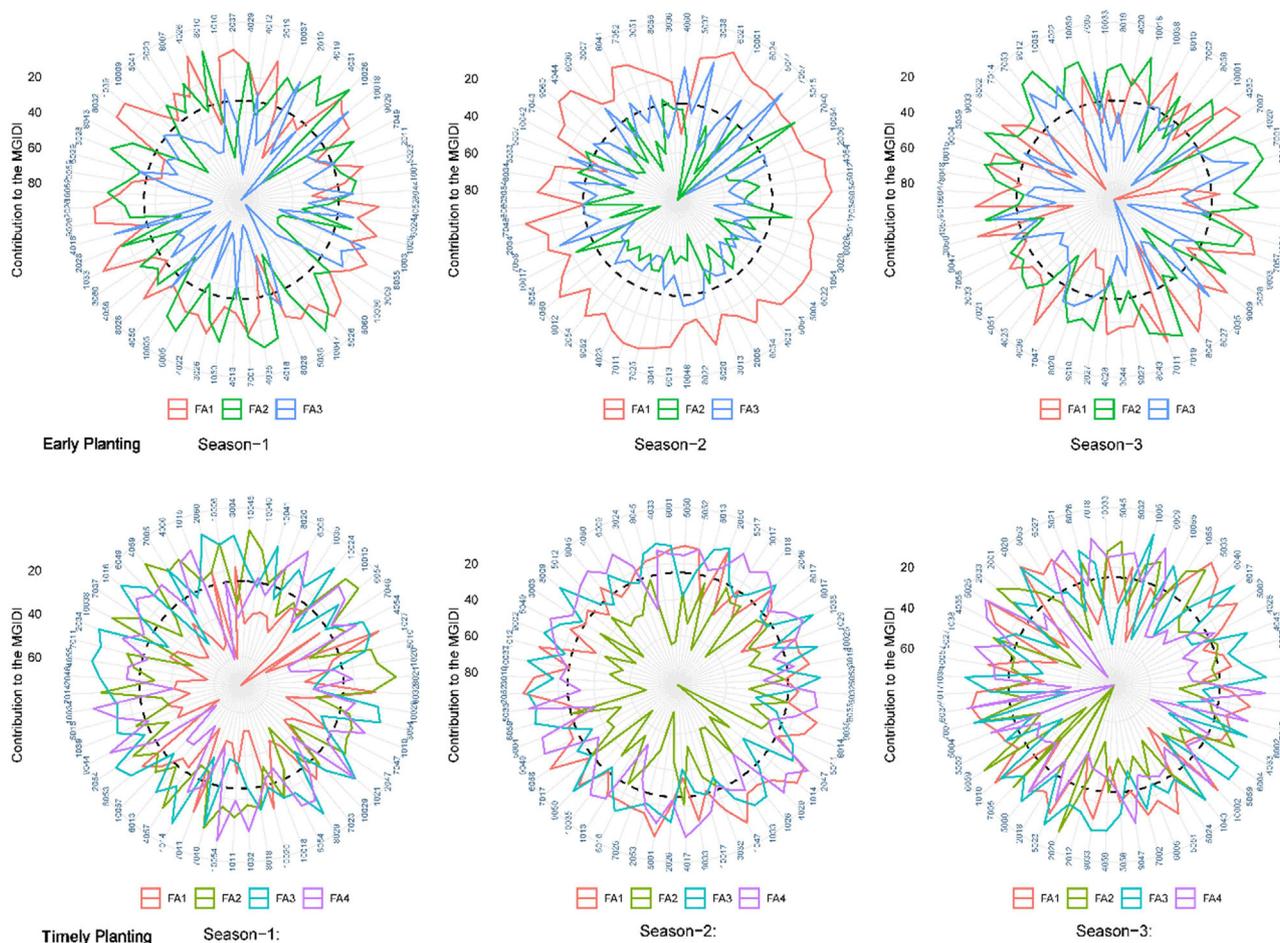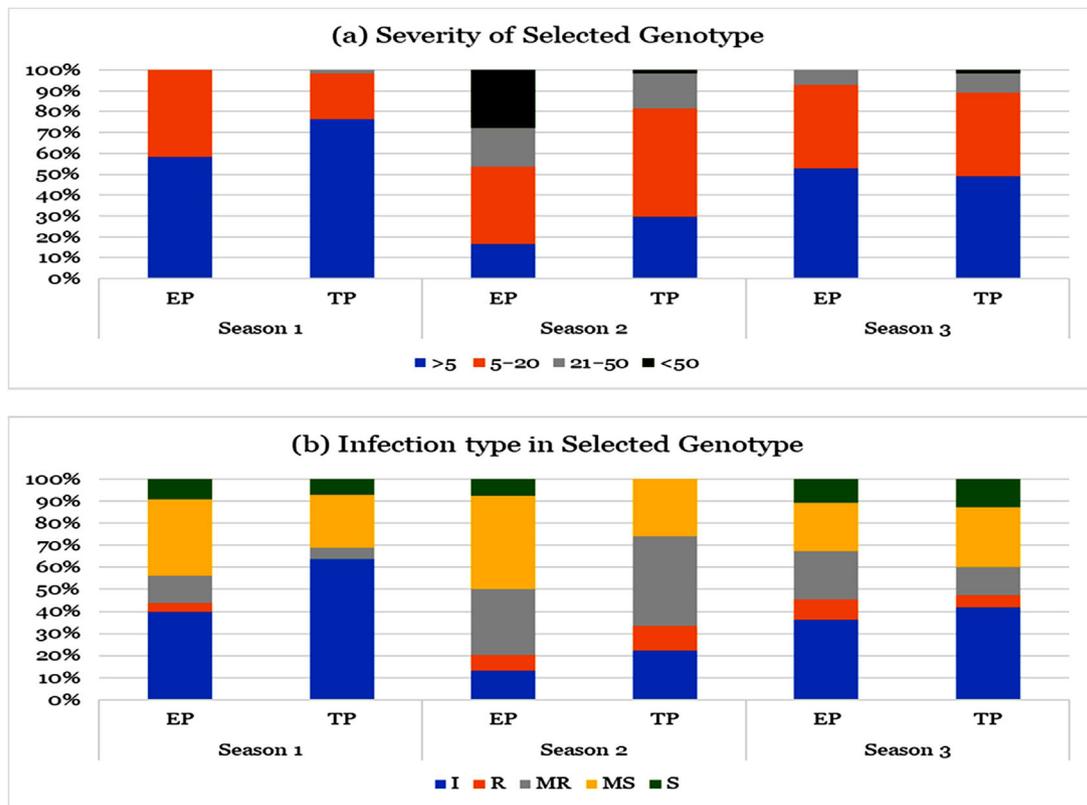
FIGURE 6 The present study aims to investigate the multi-trait genotype-idiotype distance index (MGIDI) index as a means of assessing the strength and weakness of selected genotypes and factors within a season. Traits that were closely related were categorized together within a single factor, while traits that were distantly related were categorized into separate factors. The factors located near the edge exhibit reduced distance from the desired ideotype, thereby facilitating genotype selection.

3.4 | Observations from the YRCI and traits correlation analysis

The observed similarity in the association patterns between seasons 1 and 3 suggests potential for meaningful conclusions. Conversely, season 2 exhibits the same YRCI association for both EP and TP. This inconsistency may limit the interpretability of results from season 2, and they can be excluded from further discussion. The absence of a strong and consistent association pattern between most traits and YRCI across the three seasons suggests a weak overall linkage between these traits and YRCI, with the exception of phenological and stature traits. While this implies that YRCI might be a reliable indicator for phenology and stature, caution is warranted. Since YRCI and other traits were potentially recorded from different experiments, a true biological relationship may not be definitively established based solely on correlation analysis. However, a reliable pattern of association is observed.

The correlation coefficients reveal an interesting pattern for phenological traits like PG_DTB and PG_BTH. These traits show a similar association with YR infection. Specifically, longer durations in EP are linked to higher YRCI values. This suggests a potential link between extended vegetative growth stages and increased susceptibility to rust infection during EP. An interesting finding is the link between longer booting to heading days in EP and higher YRCI in TP (Figure 8). This suggests a potential carry-over effect of EP on rust susceptibility, even in crops planted at the recommended time. However, further investigation is needed to elucidate the underlying mechanisms of this potential effect. A positive correlation is observed between flag leaf length and YRCI in EP. As expected, EP often promotes increased vegetative growth, leading to longer flag leaves. This extended leaf area could potentially provide a larger target for rust infection, contributing to higher YRCI values. Similarly, increased PH observed in EP may also expose the wheat to a greater risk of YR infection.

*EP= Early Planting, TP= Timely Planting and the host reaction abbreviations are defined in Figure 2 and Table

FIGURE 7 Yellow rust severity (a) and infection types (b) of selected wheat genotypes evaluated under early and timely planting across three seasons following the International Maize and Wheat Improvement Centre (CIMMYT) guideline. EP, early planting; TP, timely planting. The host reaction abbreviations are defined in Figure 2 and Table 1.

Based on the observed YR severity patterns across different seasons, nine genotypes were chosen for further investigation due to their apparent resistance (R) to moderately resistant (MR) reactions. These selections included four lines exhibiting resistance in season 1, three lines in season 2, and two lines in season 3. Among these nine genotypes, five displayed immune (I) responses, one showed a resistant (R) reaction, and two demonstrated MR reactions (Table 4).

4 | DISCUSSION

The identified association pattern indicates that the act of planting early exerts selection pressure on the adoption of genotypes that exhibit an extended phenological period. The occurrence of YR epidemics results in detrimental effects on both the vegetative and reproductive components of the affected plants. The primary location of YR infection has been observed to be on wheat leaves. This results in a reduction in light interception and radiation usage efficiency, leading to a decrease in crop yields due to the consequential damage to photosynthetic tissues. YR infection has been observed to transpire on the glumes, lemma, and palea of the wheat ear,

particularly in the presence of moderate to severe epidemics. This occurrence can lead to a reduction in both grain production and quality (Bouvet, Holdgate, et al., 2022; Bouvet, Percival-Alwyn, et al., 2022). According to the findings of this study, the effect of vegetative development on GRYLD is greater than that of TGW when EP is compared to TP. Phenological variations, plant stature, and physiological attributes like SR and CTIR support higher vegetation, resulting in more biomass accumulation supporting more GRYLD than TGW. In research, YR infection did not affect TGW, even though the pathogen negatively impacted the yield (Sharma et al., 2016). There may be a connection between this statement and the YR infestation, which is primarily responsible for affecting the green vegetation. The study found that the fungus was prevalent in most of the wheat-growing states of India and that farmers were relying heavily on fungicides to control the disease. However, it does not specifically mention early-planted wheat. Our observations suggest that YR susceptible genotypes that are adapted to EP conditions may be associated with increased biomass production. This extended vegetative stage in EP could be a mechanism for these genotypes to survive during infection, but further investigation is needed to confirm this hypothesis.
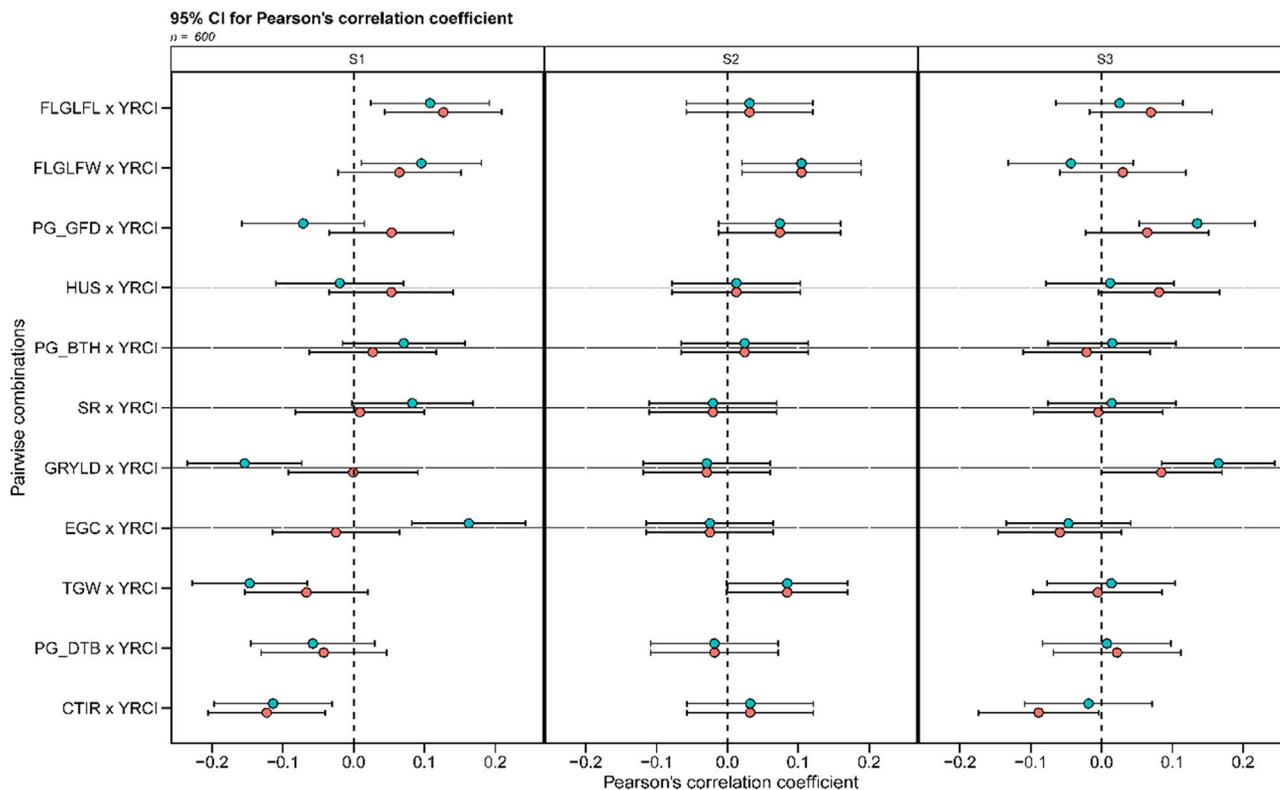
FIGURE 8 Season-specific association patterns between traits and yellow rust infection (YRCI) in wheat.

TABLE 4 List of genotypes having immune to moderate resistance yellow rust (YR) reaction in both the planting times.

Sl	Season	GID	Pedigree/selection history	Severity	Reaction	YRCI
1	S1	GID7625959	KUTZ/BORL14 CMSS12B00382S-099 M-0SY-22 M-0WGY	0	I	0
2	S1	GID7629518	BOKOTA//BECARD/QUAIU #1/3/BOKOTA CMSS12Y00713T-099TOPM-099Y-099 M-0SY-16 M-0WGY	0	I	0
3	S1	GID7631006	SUP152/BAJ #1/3/KACHU//WBLL1*2/BRAMBLING CMSS12B00147S-099 M-0SY-39 M-0WGY	1	MR	0.25
4	S1	GID7631846	KACHU//WBLL1*2/BRAMBLING/3/KACHU/KIRITATI CMSS12Y00241S-099Y-099 M-0SY-9 M-0WGY	0	I	0
5	S2	GID7175970	CROC_1/AE.SQUARROSA (205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/5/CIRO16 CMSS10Y00023S-099Y-099 M-099NJ-099NJ-4WGY-0B	0	I	0
6	S2	GID8047442	NADI*2/3/MUTUS/AKURI #1//MUTUS CMSS12B00767T-099TOPY-099 M-099NJ-099NJ-7Y-0WGY	5	MR	1.25
7	S2	GID8052693	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/WBLL4//OAX93.24.35/ WBLL1/5/BORL14 CMSS13B00614S-099 M-0SY-1 M-0WGY	0	I	0
8	S3	GID8234898	BORL14//KACHU/KIRITATI CMSS13B00053S-099 M-099NJ-099NJ-27Y-0WGY	1	MR	0.25
9	S3	GID8243244	BABAX/LR42//BABAX*2/3/SHAMA/4/TRCH/SRTU//KACHU/5/NGL/ 4/PFAU/MILAN/3/BABAX/LR42//BABAX/6/KACHU/KIRITATI CMSS14B01752T-099TOPY-099 M-0SY-24 M-0WGY	10	R	1

Abbreviations: GID, genotypic ID; MR, moderately resistant; YRCI, yellow rust coefficient of infection.

The optimal temperature range for the germination of *P. striiformis* spores is between 2.8 and 21.7°C, while a temperature of 10–12°C is optimal for their prompt germination (Line, 2002). The lower and upper limits of temperature necessary for the growth and proliferation of pathogens are 3 and 20°C, correspondingly (Line, 2002; Roelfs & Bushnell, 2014; Sharp, 1965; Tollenaar & Houston, 1966). The duration of the latent period in *P. striiformis* exhibits variability across isolates, with a range spanning from 11 to 180 days under optimal conditions (Roelfs & Bushnell, 2014; Sharp, 1965; Wellings, 2011). The growth and survival of the pathogen is impeded by temperatures that exceed 30°C. Infections commonly occur at night, when low temperatures lead to the formation of dew (Khanfri et al., 2018). Wheat that is planted early may escape from favorable conditions for YR during the vegetative growth period, thereby reducing the likelihood of infection by the pathogen.

Genotypes that are well-adapted are expected to exhibit greater stability in terms of performance across different planting dates compared to other genotypes. The Indo-Gangetic wheat-growing region, spanning 20 MHA, exhibits a unique belt that extends from the cooler and drier North-Western Plain Zone to the warmer and more humid North Eastern Plain Zone in India. This region is characterized by small to marginal farmers who seek a wheat variety that can be cultivated across a range of sowing periods and is resistant to various diseases, including YR. Moreover, it is probable that sporadic and comparatively mild YR epidemics will occur in areas where volunteer hosts perish prior to the emergence of fresh crops. The demolition of the green bridge, because of premature wheat farming, presents a significant prospect for mitigating the prevalence of such ailments within the neighboring populace. It is imperative to exercise caution when releasing early-adapted genotypes to support farmers, particularly with regard to susceptibility to YR, as there exists a potential risk of adopting genotypes that are susceptible. It is recommended that no cultivar be made available for initial adoption without undergoing additional YR screening tests conducted independently.

5 | CONCLUSION

The genotypes that were adapted to early sowing displayed relatively elevated levels of susceptibility (S and MS). While EP of wheat typically involves overlooking the response to YR, it is important to prioritize the identification of genotypes that exhibit desirable resistance to YR during the breeding process for EP. Studies conducted on YR in South Asia have primarily concentrated on the cultivation of resistant cultivars, comprehending the epidemiological aspects of the ailment, and devising efficacious measures for its management. The tasks encompass the identification of the pathogen

and comprehension of its genetic variability, the identification of virulence factors and genetic diversity of the pathogen, and the creation of novel and efficacious fungicides. This task focuses on identifying the YR pathogen, understanding its genetic variability and virulence factors, and enhancing host resistance through the development of resilient wheat varieties. Hence, it is imperative to persist with breeding endeavors aimed at advancing EP techniques in the north-western region of the Indo-Gangetic zone, with a specific focus on the screening of YR, which continues to pose a significant obstacle in this locale.

CONFLICT OF INTEREST STATEMENT
The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT
The datasets generated for this study are available on request from the corresponding and first author.

ORCID
Md. Farhad https://orcid.org/0000-0001-9004-8427
Uttam Kumar https://orcid.org/0000-0002-6618-3810

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