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Wheat maturity in interaction with leaf rust, cultivar resistance, sowing date and climate

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ABSTRACT

This investigation explored cultivar resistance, sowing date, leaf rust progress, climate, and yield in interaction with wheat maturity. Early maturing wheat cultivars corresponded with a lower area under the leaf rust progress curve (AULRPC), Gaussian parameters, and maximum disease severity compared to late maturity. An earlier disease occurrence was associated with late maturation. A higher yield was associated with early maturation compared to late maturation. A late occurrence of leaf rust corresponded with early maturation. Early sowing was associated with a 182% shorter maturity period than the optimal date. Maturity ranking for the optimal sowing date was 117% lower than very late sowing. There were significant linkages between wheat maturation and leaf rust progress indicators. The number of days with minimum temperature within 5-25˚C and maximum relative humidity ≥ 60% during autumn-winter-spring months was associated with maturity. The mean six-monthly minimum temperature and resistance index were often linked to disease progress indicators. Yield was linked to disease onset, climate, and maturation. Based on principal component analysis, leaf rust progress indicators contributed to the first principal component (PC). The second PC included contributions from wheat yield, sowing date, maturity, and nine months of climatic indicators. Findings provide information necessary to optimize future breeding and epidemiological studies for sustainable wheat production.

Contribution/Originality: This research is original and contributes to advancing our understanding of specific descriptors of leaf rust progress in wheat cultivars with different levels of disease resistance, sowing dates, and maturity during four growing seasons, which has not been previously examined and published worldwide.

1. INTRODUCTION

The fungal pathogen, *Puccinia recondita* f. sp. *Tritici*, causes leaf (brown) rust and yield losses under conducive conditions in the main wheat-growing regions worldwide. In Iran, recent field findings indicated notable associations of the area under the leaf rust progress curve (AULRPC) with disease onset, the maturity period of the cultivar, mean monthly minimum temperature from October 23 to April 20, the number of days with minimum temperature 5-25˚C, and maximum relative humidity (RH) greater than 60% during the first and second months of spring. These factors are also associated with cultivar resistance and sowing date (Naseri & Sasani, 2020). This demonstrated a faster progression of leaf rust in susceptible wheat genotypes, corresponding with early disease occurrence, late sowing and maturation, mild winters, and rainy springs (Naseri & Sasani, 2020). The subsequent investigation aimed to evaluate the interactions of the seasonal progression of wheat leaf rust with specific disease predictors: AULRPC, disease onset, Gaussian parameters, and maximum disease severity, which explained 75% of the total variability in disease progression across commercial cultivars sown at different dates (Naseri & Jalilian, 2021). However, it is still necessary to examine the strength of the linkages between wheat maturity and such influential agro-ecological and specific leaf rust descriptors at the field scale.

Early occurrences of leaf rust epidemics caused yield reductions of up to 40%, based on a significant linkage of tiller grain weight to the AULRPC (El Messoadi et al., 2022). Herrera-Foessel et al. (2006) reported simple correlations of AULRPC and final leaf rust severity with yield descriptors in wheat cultivars having various disease resistance levels sown at optimum and late dates. The remainder of the reports on adult plant resistance to leaf rust have been made according to commonly used disease progress descriptors (Hasanzadeh, Safaie, Eslahi, Dadrezaei, & Tabatabaei, 2020). Khan, Yaqub, and Nasir (1998) examined climatic factors promoting slow rusting at three diverse sowing dates in 15 promising wheat genotypes. They studied interactions of mean leaf rust severity and AULRPC with weekly minimum. and max. air temperature, RH, and rainfall. The maximum and minimum temperatures ranged within 22-28°C and 8-16°C, respectively, and 77-89% RH increased leaf rust progress on early December sowings in 1989. However, these climatic factors were ineffective on the disease progress at the other two sowing dates, late November and December (Khan et al., 1998). None of the earlier investigations focused on wheat maturity linked to specific descriptors of leaf rust seasonal patterns.

Iqbal et al. (2024) characterized leaf rust resistance in bread wheat cultivars based on yield-related morphological indices. In Iran, the seasonal patterns of the four main destructive diseases in wheat stripe, leaf, stem rusts, and powdery mildew were used to estimate productivity (Naseri, 2022). Then, we needed to examine associations of those agronomic, climatic, and disease factors associated with wheat maturation, which have been known to be responsible for yield adaptability and stability across diverse geographical areas. Because sowing various crops at appropriate dates can increase the durability of genetic resistance to different diseases involving leaf rust, and thus, improve productivity (Naseri & Fareghi, 2024). Hence, the current study aims to evaluate complex interrelationships between wheat maturity and specific descriptors of leaf rust progress in commercial cultivars, considering interactions with sowing date, disease resistance, climate, and yield from sustainable production perspectives.

2. MATERIALS AND METHODS

2.1. Field Study

During the years 2013-2017, the development of leaf rust in Iranian bread wheat cultivars was studied across 282 field plot experiments (Naseri, 2022). Field plots were arranged according to a split-plot design with three replicates. Treatments involved eight cultivars and four sowing dates, which are commonly used in the study region. This arrangement of treatments improved the diversity in seasonal trends of leaf rust progress across the plots, varying in cultivars and sowing dates (Naseri, 2022). Considering the highest rating of leaf rust severity recorded during the four growing seasons, the cultivars were classified as resistant for cvs. Parsi, Pishtaz, and Sirwan, moderately resistant for cvs. Bahar, Baharan, and Pishgam and susceptible to cvs. Chamran II and Sivand (Naseri & Sasani, 2020). The monthly sowing dates were tested as follows: October, November, December, and January.

2.2. Leaf Rust and Yield Recordings

The severity of leaf rust was assessed weekly as the percentage of leaf area covered with red-brown pustules on the three newest leaves of 3-5 plants per plot (Naseri & Jalilian, 2021). Then, based on these severity ratings, the disease progress patterns during the four seasons were characterized based on the following descriptors: (1) the disease onset, defined as the time (days) from sowing to the appearance of leaf rust pustules; (2) the AULRPC, based on the disease severity values; (3) maximum leaf rust severity during the entire study; (4) the three Gaussian parameters, *b*, *m*, and *s* (Naseri & Jalilian, 2021). The GENSTAT software (VSN International, Oxford, UK) was used for all the statistical tests. The Gaussian equation involves the height of the curve's peak as the parameter *b*, the central point of the curve's peak as the parameter *m*, and the width of the Gaussian bell as the parameter *s* (Naseri & Jalilian, 2021). The entire grains obtained per plot were weighted for the mean values of wheat yield (kg/plot).

2.3. Climatic Data

Those climatic descriptors of the leaf-rust-wheat pathosystem (Naseri & Sasani, 2020) were considered in this four-year research. The two weather datasets, air temperature-RH and mean six-monthly temperatures, were collected from a synoptic site adjacent to the study station (Table 1).

Table 1. Climatic data recorded at the experimental site for four growing seasons, 2013-2017.

Climatic parameter	No. daily min. temperatures within 5-25˚C + max. RH ≥ 60% in the second and third months of spring	Mean monthly min. temperature from October to April
2013-2014	45 days	-1.0ºC
2014-2015	25 days	-0.5ºC
2015-2016	54 days	4.9ºC
2016-2017	56 days	-7.9ºC

2.4. Statistical Methods

A Kruskal-Wallis one-way ANOVA (by *H*-test) was used to rank the AULRPC, disease onset, Gaussian parameters, maximum disease severity, cultivar resistance, and yield according to the maturity factor. The maturity factor describes the number of days from sowing to physiological maturation, grouped into early (≤ 261 days) and late (> 261 days). Additionally, rankings of cultivar maturity based on the cultivar (considered as the resistance index), sowing date, and growing season were determined by the *H*-test (Kakhki, Taghadossi, Moini, & Naseri, 2023). Correlations among the disease, climatic, cultivar resistance, maturity, and yield descriptors were also examined. An advanced statistical analysis, the principal component analysis, was conducted (Kranz, 2003). Detected interrelationships among disease progress, maturity, sowing date, cultivar resistance, climatic factors, and yield descriptors.

3. RESULTS

3.1. Climatic Data

The number of days with minimum temperatures within 5-25˚C and maximum relative humidity greater than 60% in the second and third months of spring ranged from 25 days in 2014-2015 to 56 days in 2016-2017 (Table 1). According to the mean values for monthly minimum temperatures from October to April each season, the warmest and coolest growing seasons were identified as 2015-2016 and 2016-2017, respectively (Table 1).

3.2. H-Tests

The AULRPC, Gaussian parameters, maximum leaf rust severity, and disease onset influenced cultivar maturation (Table 2). For the AULRPC (*Chi P*= 0.005; adjusted *H*= 7.75), early maturing cultivars were ranked with a lower disease level compared to cultivars maturing as late as 261 days from sowing to maturity. For the Gaussian parameter *b* (*Chi P*= 0.006; adjusted *H*= 7.58), late maturation corresponded with a higher leaf rust progress curve's peak in comparison with early maturation. For the Gaussian parameter *m* (*Chi P* < 0.001; adjusted *H* = 11.48), the early maturity was associated with a lower central point of the leaf rust progress curve peak. For the Gaussian parameter *s* (*Chi P* < 0.001; adjusted *H* = 11.00), A wider Gaussian bell corresponded with late maturation. For the onset of leaf rust (*Chi P*= 0.007; adjusted *H*= 7.24), an earlier disease occurrence was associated with late maturation. For the maximum disease severity (*Chi P*= 0.003; adjusted *H*= 8.82), early maturation was associated with less severe leaf rust (Table 2).

Table 2. Rankings of area under leaf rust progress curve (AULRPC), disease onset, Gaussian parameters, max. disease severity according to wheat maturity.

Disease descriptors		Maturity levels	
AULRPC		**Early**	**Late**
$H = 7.75$	*Chi P-value* = 0.005	39.82	54.55
Gaussian parameter *b*		Early	Late
$H = 7.58$	*Chi P-value* = 0.006	40.18	54.22
Gaussian parameter *m*		Early	Late
$H = 11.48$	*Chi P-value* < 0.001	38.33	55.92
Gaussian parameter *s*		Early	Late
$H = 11.00$	*Chi P-value* < 0.001	38.73	55.55
Leaf rust onset		Early	Late
$H = 7.24$	*Chi P-value* = 0.007	54.33	41.22
Max. severity		Early	Late
$H = 8.82$	*Chi P-value* = 0.003	39.31	55.02

The maturation factor was not affected (*Chi P* = 0.726) by the index of resistance to leaf rust (Table 3), demonstrating no significant difference in the resistance index between the two maturity levels. A higher seed production was ranked (*Chi P* < 0.001; adjusted $H = 27.95$) with early maturation compared to late maturation. It is suggested that wheat reaching maturity as early as 261 days produces a higher seed yield than wheat with later maturation (Table 3).

Table 3. Rankings of leaf rust resistance index and wheat yield according to wheat maturity.

Descriptors	Maturity levels	
Leaf rust resistance index	**Early**	**Late**
$H = 0.12$	48.50	46.58
Chi P-value = 0.726		
Wheat yield (kg/ha)	Early	Late
Adjusted $H = 27.95$	63.02	33.24
Chi P-value < 0.001		

There was a non-significant effect of the maturation factor (*Chi P*= 0.803) on the resistance index to leaf rust in wheat cultivars, which ranged from 0 for cv. Sivand to 70 for cv. Sirwan (Table 4). The disease onset affected (*Chi P* < 0.001; adjusted $H = 11.31$) wheat maturity, with a late occurrence of leaf rust corresponding with an early maturation. The sowing date affected (*Chi P* < 0.001; adjusted $H = 70.59$) maturity, associating the early sowing in October with 182% shorter maturity than the optimal date. The ranking of maturity increased by 117% from the optimal sowing to very late sowing. Sowing at the optimal date reduced the maturation period by 60% compared to late sowing. The year factor affected wheat maturation (*Chi P* < 0.001; adjusted $H = 23.33$), indicating the longest and shortest maturations for the 2015-2016 and 2014-2015 seasons, respectively (Table 4).

Table 4. Rankings of wheat maturity periods (number of days from sowing to maturity) according to cultivar, leaf rust onset, sowing date, and season.

Descriptors	Descriptor levels							
Cultivar	**Bahar/50**	**Baharan/50**	**Chamran II/30**	**Parsi/60**	**Pishgam/50**	**Pishtaz/60**	**Sirwan/70**	**Sivand/0**
Adjusted $H = 1.63$	45.62	45.62	51.61	44.61	45.62	44.61	45.82	54.07
Chi P-value = 0.803								

Descriptors	Descriptor levels			
Disease onset	Early		Late	
Adjusted $H = 11.31$	57.31		38.49	
Chi P-value < 0.001				
Sowing date	Early	Optimum	Late	Very late
Adjusted $H = 70.59$	13.12	36.94	59.24	80.28
Chi P-value < 0.001				
Season	2013-2014	2014-2015	2015-2016	2016-2017
Adjusted $H = 23.33$	56.00	23.07	58.81	50.05
Chi P-value < 0.001				

3.3. Correlations

These analyses indicated significant linkages between wheat maturation and the leaf rust progress curve elements, the AULRPC, Gaussian parameters *b*,*m*, and *s*, the maximum disease severity, and disease onset (Table 5). For the climate, the number of days with minimum temperature within 5-25˚C and maximum relative humidity (RH) ≥ 60% during autumn-winter-spring months was associated with wheat maturity. This climatic descriptor was correlated with the AULRPC, maximum disease severity, and leaf rust onset. The mean six-monthly minimum temperature was linked to the AULRPC, Gaussian parameters *m* and *s*, maximum disease severity, and leaf rust onset. Additionally, there was a correlation between these two climatic descriptors. The cultivar resistance corresponded with the AUYRPC, Gaussian parameters *m* and *s*, and maximum leaf rust severity. Wheat yield was linked to disease onset, the two climatic descriptors, and wheat maturation (Table 5).

Table 5. Correlation analysis of maturation date (M.date), disease development (Area under leaf rust progress curve: AULRPC; Gaussian parameters: Gau.b, Gau.m and Gau.s; max. severity: Max.s; disease onset: O.date), disease resistance (R.index), yield (kg/ha) and climate (mean monthly min. temperature from October to April: M6M; no. daily min. temperatures within 5-25˚C & max. relative humidity ≥ 60% over autumn-winter-spring months: NDT) variables.

Indicators	AULRPC	Gau.b	Gau.m	Gau.s	Max.s	O.date	M6M	NDT	M.date	R.index	Yield
AULRPC	1.00										
Gau.b	-0.01	1.00									
Gau.m	0.43	0.21	1.00								
Gau.s	0.48	0.06	0.77	1.00							
Max.s	0.90	0.02	0.55	0.56	1.00						
O.date	-0.55	-0.12	-0.62	-0.42	-0.66	1.00					
M6M	0.44	0.02	0.37	0.23	0.46	-0.69	1.00				
NDT	0.20	-0.01	0.13	0.08	0.21	-0.27	-0.26	1.00			
M.date	0.25	-0.17	0.41	0.33	0.33	-0.38	0.07	0.47	1.00		
R.index	-0.50	0.08	-0.18	-0.29	-0.48	0.01	-0.00	0.00	-0.12	1.00	
yield	0.03	0.00	0.06	-0.00	0.12	-0.32	0.34	-0.41	-0.49	0.05	1.00

3.4. Principal Component Analysis

The first principal component (x-axis) indicated the significant contributions of the AULRPC, Gaussian parameters *m* and *s*, maximum leaf rust severity, and disease onset (Figure 1).

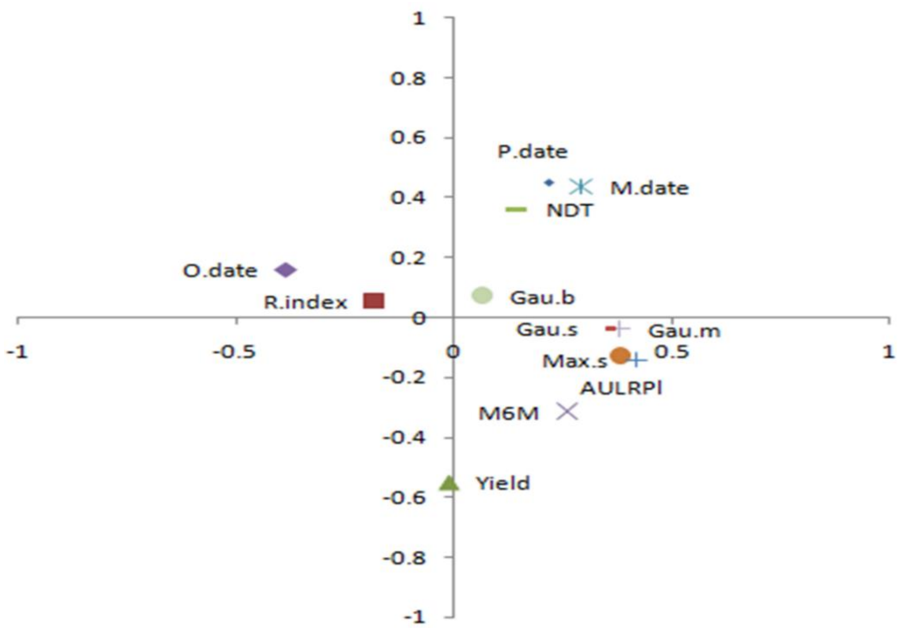

Figure 1. Principal component analysis of maturation date (M.date), leaf rust development (Area under leaf rust progress curve: AULRPC; Gaussian parameters: Gau.b, Gau.m and Gau.s; max. severity: Max.s; disease onset: O.date), disease resistance (R.index), yield (kg/ha) and climate (Mean monthly min. temperature from October to April: M6M; no. daily min. temperatures within 5-25˚C & max. relative humidity ≥ 60% over autumn-winter-spring months: NDT) datasets.

Leaf rust onset had a reverse association with each of the AULRPC, Gaussian parameters, and disease severity. Based on the second principal component (y-axis), wheat yield contributed the most, followed by sowing date, maturity, and the number of daily minimum temperatures within 5-25°C and maximum relative humidity ≥ 60% over autumn-winter-spring months. Therefore, higher yields were associated with earlier sowing, shorter maturity, and lower air wetness during the growing season. Supporting the *H*–test and correlations, this PCA identified a reverse relationship between either maturity or sowing date and wheat yield.

4. DISCUSSION

There are a number of epidemiological studies focusing on 2-3 indicators of climate, genotype resistance, leaf rust, sowing date, cultivar maturity, and wheat yield at the field scale. Early occurrence of leaf rust epidemics caused yield reductions of up to 40%, based on a significant linkage of tiller grain weight to the AULRPC (El Messoadi et al., 2022). Wolfgang (1979) determined a noticeable linkage of *P. recondita* f. sp. *tritici* pustules per leaf to the cultivar resistance. Herrera-Foessel et al. (2006) linked AULRPC and final leaf rust severity indicators with wheat yield in cultivars varying in leaf rust resistance levels and sowing dates. Hasanzadeh, Safaie, Eslahi, Dadrezaei, and Tabatabaei (2019) and Hasanzadeh et al. (2020) measured the adult plant resistance to leaf rust based on general disease progress descriptors. Khan et al. (1998) examined climatic factors promoting slow rusting in 15 wheat genotypes sown at three diverse dates according to mean leaf rust severity, AULRPC, weekly min. and max. air temperature, RH, and rainfall. However, the association of these climatic, plant, and leaf rust indicators with wheat maturity is still little studied. Hence, this investigation aimed to broaden our understanding of the joint analysis of climate, genotype resistance, leaf rust progress, sowing date, wheat maturity, and productivity within a single study framework.

Although leaf rust progress in wheat cultivars, in interaction with the sowing date, maturity, and productivity, has been partially examined previously (Naseri & Jalilian, 2021), we still need information on the complex association of wheat maturity with leaf rust progress in wheat plants treated with not only sowing date but also genotypes and season. Therefore, the current remarkable linkage of earlier wheat maturation to early sowing, late leaf rust onset, slow disease progress, less severe leaf rust, high cultivar resistance, and low air wetness over the growing season appears to be the first report worldwide. This piece of knowledge on these associated agro-ecological indicators adds value to future breeding experiments. To improve the durability and level of resistance to leaf rust, shorten maturity periods, and enhance the stability and level of productivity, wheat breeders are recommended to consider these current observations.

Roelfs (1986) and Sabouri et al. (2022) observed that leaf rust development is linked to air temperature and high relative humidity. The notable association of the growing season with wheat maturity in commercial cultivars showed the latest and earliest maturities in 2015-2016 and 2014-2015, respectively. This observation aligns with the report from Kazakhstan, which indicated that drought and heat stresses occurring at the initial stage of spring wheat growth in early sowings delayed maturity and reduced resistance to pests (Rimma et al., 2022). In addition, the earliest maturity observed in 2014-2015 corresponded not only with the fewest rainy days during the second and third months of spring but also with the fewest favorable days (with minimum temperatures within 5-25°C and maximum relative humidity ≥ 60% over autumn-winter-spring) for leaf rust progress among the seasons examined. The contrasting climatic events occurred in 2015-2016, while the most severe epidemics of leaf rust were recorded in spring (Naseri & Sasani, 2020). This observation may be attributed to the present findings regarding the climate-disease-maturity-sowing date interaction.

It should also be noted that the highest wheat yield was 67.71 kg/ha in 2013-2014, and the lowest was 25.82 kg/ha in 2016-2017 Naseri (2022). A colder winter season in 2016, followed by a flood-prone spring in 2017, may have stressed wheat genotypes, leading to pre-maturity and yield reductions. Moreover, the current findings clarified that early sowing of wheat in October, at the beginning of the autumn season, appeared to shorten the period of maturity and thus slowed down the progression of leaf rust and improved yield. Such a promising dependence of early sowing on early maturing in wheat genotypes at the field plot scale may encourage breeders to improve not only the durability and level of genetic resistance to leaf rust but also the stability and adaptability of wheat yield with the help of early sowing of early-maturing genotypes. There are numerous previous findings on the significant associations of early-maturing wheat with the levels of genetic resistance to wheat diseases such as leaf rust (Mapuranga et al., 2022, Prasad et al., 2021).

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