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Influence of Cultivar Resistance, Powdery Mildew, Planting Date, and Weather on Wheat Maturity and Yield

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ABSTRACT

Background and Objective: Powdery mildew threatens wheat production worldwide. Cultivar maturity in interaction with climate, planting date, powdery mildew and production is little understood. Association of wheat maturity with powdery mildew, date of planting, wheat resistance and weather were observed in this study during four growing seasons. **Materials and Methods:** The H-test, correlation and Principal Component Analysis (PCA) characterized maturity time of eight commercial wheat cultivars planted at different dates during four growing seasons in Western Iran, Kermanshah. For H-test and correlations, a significance level was considered at 5%. The PCA confirmed H-test and correlation results. **Results:** Early maturing cultivars showed 12% earlier disease onset, 17% lower area under powdery mildew progress curve (AUPMPC), less severe disease, greater yield compared to late maturity. An early disease onset corresponded with a 33% longer maturation period at field scale. Early planting in October was associated with a 182% shorter maturity ranking in comparison with the optimum date in November. Ranking of maturation increased by 117% as planting was delayed from the optimum date to very late plantings in January. Correlations were significant between maturity period and disease onset, AUPMPC, exponential parameter r, maximum disease severity, average minimum temperature, rainy days, and wind speed in spring, and yield. **Conclusion:** This study provided a systematic understanding of the complex interaction of wheat maturity with powdery mildew, planting date, cultivar resistance, weather and yield that is required for a sustainable agriculture.

KEYWORDS

Cereals, fungal pathogens, air-borne, climate, *Blumeria graminis*

INTRODUCTION

Blumeria graminis f. sp. *tritici* causing powdery mildew decreases wheat (*Triticum aestivum*) yield worldwide. Powdery mildew progressed in wheat crops according to the disease occurrence, maturation time, disease resistance, planting date, mean monthly minimum temperature, rainy days, and wind speed in spring[1]. In addition to this epidemiological finding, widely diverse patterns of powdery mildew

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epidemics progressed in commercial wheat cultivars were studied in the forms of concise, specific, and simple wheat powdery mildew progress curves. Later plantings in December and early January corresponded with greater area under powdery mildew progress curve (AUPMPC), maximum disease severity and exponential parameters b and r in wheat[2]. Moreover, the disease onset was advanced in late planted wheat cultivars, irrespective of the cultivar susceptibility to powdery mildew. The maximum disease severity also increased significantly in late planted moderately resistant and susceptible cultivars, respectively. The exponential parameter r, representing the rate of disease progress, was greater by 14-18% in late planted resistant to susceptible cultivars of wheat[2]. Also according to an array of epidemiological studies performed recently in Iran, specific disease progress curve elements described for the complex of yellow, brown and black rusts and powdery mildew were used to model wheat production at field scale[3]. Hence, it is still required to unravel how strongly wheat maturity is affected by a combination of powdery mildew progress, weather, planting date and cultivar.

The three-year field studies reported the significant effect of sowing density for Indian dwarf wheat, *T. sphaerococcum*, and Persian wheat, *T. persicum*, at 400, 500 and 600 seeds/m^2 on yield and occurrence of powdery mildew, depending on seasonal rainfalls[4]. Tahir *et al.*[5] also tested associations of seed rate and sowing dates on wheat productivity in semi-arid environments. Wheat plants exert the highest susceptibility following drought stresses from tillering to maturation stages[6]. In Kazakhstan, early planting of the 'Triso' variety of wheat was influenced by heat and water stresses at the initial stage of plant growth, which delayed its maturity and increased its susceptibility to pest damage[7]. Prasad *et al.*[8] reviewed the present status of climate changes in relation to the changing wheat powdery mildew spectrum and its management strategies. This brief review of the literature reminded us that a systematic understanding of the complex interaction of wheat maturity with powdery mildew, planting date, cultivar resistance, weather and yield is required for a sustainable agriculture. Therefore, associations of wheat maturity with powdery mildew progress, date of planting, resistance levels of cultivars, and weather indicators were studied under different environmental conditions occurred over four growing seasons.

MATERIALS AND METHODS

Field studies: From the autumn in 2013 to the summer in 2017, patterns of powdery mildew spread across Iranian wheat cultivars were characterized across 282 field plots[1,2]. Experiments were conducted according to a split plot design with three replicated plots per treatment (cultivar and planting date). This experimental arrangement provided variations in the patterns of disease developed across the plots with diverse wheat cultivars and planting dates. Based on the maximum powdery mildew severity detected over the four seasons, the genetic resistance to the disease observed in the cultivars were as follows: Resistance for Chamran II; semi-resistance for Baharan, Sirwan and Sivand; susceptibility for Bahar, Parsi, Pishgam and Pishtaz[1]. The following dates of plantings were tested: October, November, December and January.

Disease and yield measurements: The severity of powdery mildew was measured weekly as the percentage grayish hyphae of *B. graminis* f. sp. *tritici* covering aerial part for at least 9 arbitrarily wheat plants per plot[1,2]. The disease severity was measured across 282 plots at 4-6 times every growing season. This methodology provided a big dataset involving 11664, 6804, 8505, and 9072 disease measurements during the four seasons. Such a high variability in the progression of powdery mildew across plots, treatments and years improved the predictability of the disease indicators as advised previously[3]. Wheat yield was determined as the weight of seeds obtained per plot (kg/ha)[3].

Weather data: Weather data reported to be influential on the powdery mildew-wheat pathosystem[1,2], was collected over the four seasons as follows: The average minimum temperatures in Ordibehesht and Khordad, number of rainy days in Ordibehesht and Khordad, autumn-winter monthly average minimum temperature, and wind speed in Khordad. This data was obtained from a synoptic climatic station adjacent to the research site (Table 1). The monthly average minimum temperature over autumn-winter seasons was not included in Table 1 due to the non-significant associations with the other variables studied.

Table 1: Climatic data collected at study site for four spring seasons, 2014-2017

Climatic parameter	Mean minimum temperature (°C)	Rainy days	Wind speed (m/s)
2014			
Ordibehesht	7.8	4	4.5
Khordad	10.8	2	4.3
2015			
Ordibehesht	6.5	2	5.4
Khordad	13.3	0	5.3
2016			
Ordibehesht	8.1	10	12.0
Khordad	9.3	0	13.0
2017			
Ordibehesht	7.3	5	Not recorded
Khordad	9.2	0	Not recorded

Data analysis: To characterize the seasonal patterns of wheat powdery mildew progress across the treatments and plots, the fitness of four-season disease severity datasets to the exponential model was examined earlier by Naseri and Sheikholeslami[2] using the GENSTAT software. According to the exponential model, the parameter b described the factor of disease progress and the parameter r described the rate of disease progress. The following indicators were used to describe seasonal patterns of the disease progress: (1) Number of days from planting to powdery mildew occurrence considered as the disease onset date; (2) AUPMPC of the over-season recording disease severity; (3) Maximum disease severity during the four study years and (4) Parameters b and r of exponential model[2].

Average values for the disease severity and yield for different cultivars, planting dates, over-season measurements, and study years were determined in previous articles[2,3]. A Kruskal-Wallis One-way ANOVA at a significance level of 5% (by H-test) was used to rank the AUPMPC, disease onset, exponential parameters b and r, maximum disease severity, resistance index and yield based on wheat maturity factor. The maturity time was defined as the number of days from planting to physiological maturation that was classified in early ($\leq$261 days) and late (>261 days). Furthermore, rankings of wheat maturity period based on the cultivar (regarded as the resistance index), planting date and study year were examined using the H-test. Correlations among the maturation date, the AUPMPC; exponential parameters b and r, maximum disease severity, disease onset, disease resistance, yield and weather indicators (average minimum temperature in Ordibehesht and Khordad, total number of rainy days in Ordibehesht and Khordad, autumn-winter monthly average minimum temperature, wind speed in Khordad) were analyzed using the GENSTAT. A Principal Component Analysis (PCA) provided an advanced analysis of associations among the disease progress, maturity and planting date, resistance index of cultivars, weather and yield indicators.

RESULTS

H-test: The H-test results determined that exponential parameters b and r describing the seasonal progression of powdery mildew did not affect the maturity time of the eight commercial wheat cultivars studied over the 4 years (Table 2). In contrast, the timing of wheat powdery mildew onset (Chi p = 0.132; Mean H = 2.27), AUPMPC (Chi p = 0.017; Mean H = 5.72) and maximum disease severity (Chi p = 0.048; Mean H = 3.92) affected the maturity time of cultivars studied. Early maturing cultivars showed a lower ranking of the AUPMPC than the late maturing cultivars which matured in more than 261 days from planting. This suggested a lower AUPMPC by 17% in the early maturity of wheat cultivars compared to the late maturity. Early onset of powdery mildew in wheat cultivars differing in planting dates corresponded with a lower ranking of maturity time, suggesting a 12% earlier disease onset in late maturing cultivars. A greater ranking of the maximum disease severity was detected for the late maturing cultivars that demonstrated a less severe powdery mildew in the early maturing cultivars studied (Table 2).

Table 2: Rankings of area under powdery mildew progress curve (AUPMPC), disease onset, exponential parameters b and r, maximum disease severity based on wheat maturity

	Maturity levels	
Disease descriptors	Early	Late
AUPMPC		
Adjusted H = 5.72	43.02	51.61
Chi p = 0.017		
Disease onset		
Adjusted H = 2.27	50.69	44.57
Chi p = 0.132		
Exponential parameter b		
Adjusted H = 0.25	48.41	46.66
Chi p = 0.616		
Exponential parameter r		
Adjusted H = 2.00	44.47	50.29
Chi p = 0.156		
Maximum severity		
Adjusted H = 3.92	43.51	51.16
Chi p = 0.048		

Table 3: Rankings of powdery mildew resistance index and wheat yield based on wheat maturity

	Maturity levels	
Descriptors	Early	Late
Powdery mildew resistance index		
Adjusted H = 0.68	45.11	49.69
Chi p = 0.410		
Wheat yield (kg/ha)		
Adjusted H = 27.95	63.02	33.24
Chi p<0.001		

The H-test determined the non-significant (Chi p = 0.410) and significant (Chi p<0.001; Mean H = 27.95) effects of the maturity time on powdery mildew resistance and wheat yield, respectively (Table 3). There was no significant difference in the resistance level between the early and late maturing cultivars. For the yield of wheat cultivars (kg/ha), those cultivars maturing within fewer than 261 days produced a greater yield compared to the later maturing cultivars (Table 3).

The final H-test showed a non-significant association of maturity factor with the cultivar resistance (Chi p = 0.920; Table 4). The occurrence of powdery mildew affected (Chi p = 0.030; Mean H = 4.71) the maturity time in the eight commercial wheat cultivars planted at diverse dates. This finding ranked an early disease occurrence with a 33% longer maturation. Considering planting date which affected (Chi p<0.001; Mean H = 70.59) maturation, the early planting shortened maturation by 182% in comparison with the optimum date of planting. Then, the maturation became longer as the planting was delayed from the optimum date to very late date. This showed 117% longer maturation for very late plantings in January when compared to optimum plantings in November. Planting at the optimum date in November shortened maturity by 60% in comparison with the late date. The study year also affected the maturation factor (Chi p<0.001; Mean H = 23.33), declaring a longer and shorter maturity observed in 2015-2016 and 2014-2015 seasons, respectively (Table 4).

Correlation analysis: Correlations demonstrated significant linkages between the wheat maturity period and the powdery mildew progress curve elements, the AUPMPC, exponential parameter r, maximum disease severity and disease onset (Table 5). For correlations of the maturity variable with the weather indicators, the variables of average minimum temperature in Ordibehesht and Khordad, total number of rainy days in Ordibehesht and Khordad, and wind speed in Khordad were linked significantly to the maturity period. Wheat yield also was associated significantly with the maturation variable, suggesting a greater wheat yield following an earlier maturity in the cultivars planted at different dates studied (Table 5).

Table 4: Rankings of wheat maturity period (number of days from planting to maturity) based on powdery mildew onset, planting date, study year and cultivar resistance index

Descriptors	Descriptor levels							
Cultivar	Bahar/80	Baharan/50	Chamran II/100	Parsi/20	Pishgam/30	Pishtaz/40	Sirwan/80	Sivand/85
Adjusted H = 2.60 Chi p = 0.920	45.00	53.57	51.61	44.54	40.50	44.68	45.82	54.07
Disease onset		Early				Late		
Adjusted H = 4.71 Chi p = 0.030		58.81				44.25		
Planting date		Early		Optimum		Late		Very late
Adjusted H = 70.59 Chi p<0.001		13.12		36.94		59.24		80.28
Study year		2013-2014		2014-2015		2015-2016		2016-2017
Adjusted H = 23.33 Chi p<0.001		56.00		23.07		58.81		50.05

Table 5: Correlation analysis of maturation date (M.date)

Indicators	AUPMPC	Exp.b	Exp.r	Max.s.	O.date	Mordt	Mkhrt	O-Kr.	6% mt	wkho	M.date	R.index	Yield
AUPMPC	1.00												
Exp.b	-0.16	1.00											
Exp.r	0.61	-0.32	1.00										
Max.s.	0.94	-0.17	0.68	1.00									
O.date	-0.60	0.35	-0.98	-0.67	1.00								
Mordt	0.37	-0.22	0.61	0.42	-0.62	1.00							
Mkhrt	-0.25	0.14	-0.41	-0.28	0.42	-0.73	1.00						
O-Kr.	0.51	-0.29	0.84	0.57	-0.85	0.94	-0.73	1.00					
6% mt	0.43	-0.25	0.71	0.49	-0.72	0.37	0.23	0.50	1.00				
wkho	0.45	-0.26	0.74	0.50	-0.75	0.43	-0.73	0.67	0.10	1.00			
M.date	0.22	-0.11	0.26	0.22	-0.28	0.52	-0.47	0.48	0.07	0.26	1.00		
R.index	-0.26	0.03	-0.10	-0.29	0.06	0.00	0.07	-0.04	0.03	-0.13	0.13	1.00	
Yield	-0.11	0.03	-0.09	-0.07	0.11	-0.01	0.43	-0.11	0.34	-0.50	-0.49	0.07	1.00

Disease development, AUPMPC: Area under powdery mildew progress curve, Exp.b and Exp.r: Exponential parameters, Max.s.: Maximum severity, O.date: Disease onset, R.index: Disease resistance, yield (kg/ha) and seasonal climatic (average minimum temperature in Ordibehesht and Khordad: Mordt and Mkhrt, total number of rainy days in Ordibehesht and Khordad: O-Kr., autumn-winter monthly average minimum temperature: 6% motem and wind speed in Khordad: wkho characteristics

The correlation matrix presents the relationships among various indicators influencing wheat yield. AUPMPC, Max.s., and Exp.r. exhibit strong positive correlations, while O.date shows a strong negative correlation with Exp.r. and O-Kr. Yield correlates positively with Mkhrt and 6% mt but negatively with wkho, M.date, and O-Kr. These relationships highlight the complex interactions among planting date, disease resistance, and environmental factors in determining wheat maturity and productivity.

Principal component analysis: Figure 1 presented the interrelationships among the maturity of wheat cultivars planted at different dates to the indicators of powdery mildew progress, planting date, cultivar resistance index, weather and yield. The date of planting demonstrated the strongest association with the maturity variable, followed by the wind speed in Khordad, the average minimum temperature in Ordibehesht, and the index of cultivar resistance. For the indicators of powdery mildew progress over the four seasons, the exponential parameter b provided the largest linkage with the maturity variable, followed by the disease onset date, AUPMPC, maximum disease severity, and exponential parameter r. The variable describing the yield of wheat provided the indirect linkage with the maturity, the average minimum temperature in Khordad and the autumn-winter monthly average minimum temperature.

This PCA suggested that the maturity of wheat cultivars varied in the greatest correspondence with variations in the planting date, followed by the wind speed in Khordad, the average minimum temperature in Ordibehesht, the index of cultivar resistance and the exponential parameter b. Therefore, a longer

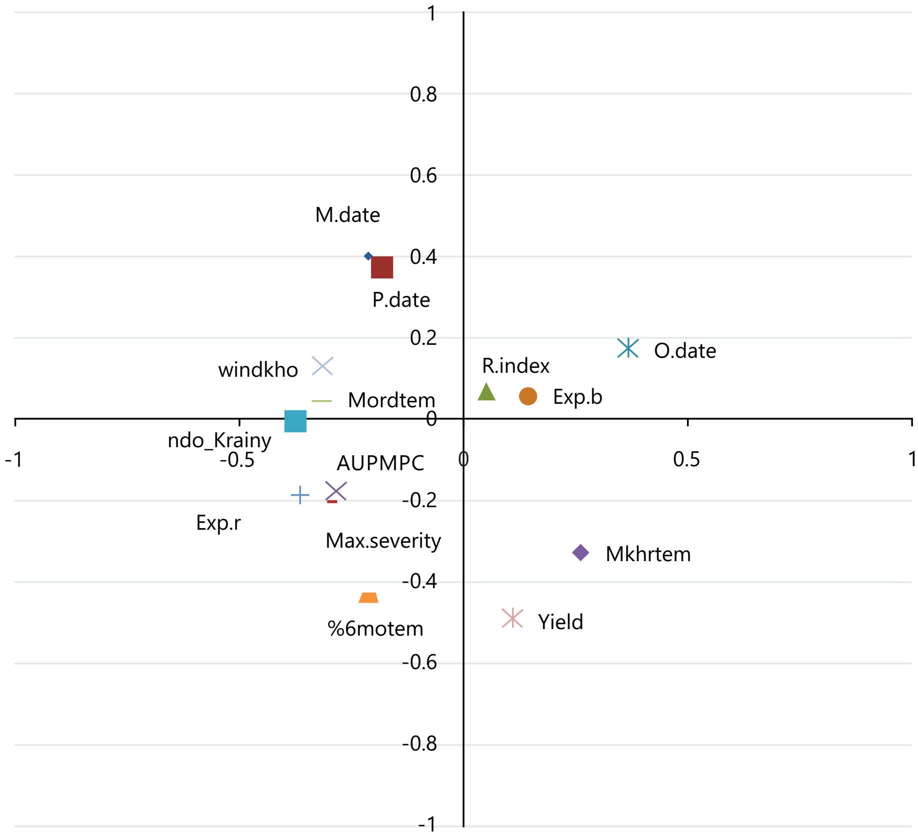

Fig. 1: Principal component analysis of datasets from eight wheat cultivars

Wheat cultivars varying in maturation (M.date) and P.date: Planting date, powdery mildew AUPMPC; exponential parameters: Exp.b and Exp.r; Maximum severity; O.date: Disease onset, R.index: Disease resistance, yield and climatic minimum temperature in spring: Mordtem and Mkhrtem; rainy days in spring: ndO-Krainy; 6 monthly minimum temperature: 6% motem; wind speed: windk4ho characteristics

period of wheat maturity corresponded with a late planting, more speedy winds in Khordad, warmer air in Ordibehesht, higher resistance index, and a lower powdery mildew progress factor. In agreement with the H-test and correlation analysis, the PCA results also indicated a reverse interaction of wheat maturity and yield.

DISCUSSION

There are a large number of previous studies focusing on just 2-3 variables of powdery mildew, planting date, genetic resistance of cultivar, weather and yield in interaction with the growth and maturity of wheat at field scale. For instance, sowing density significantly affected maturation, yield, and occurrence of powdery mildew in Indian dwarf and Persian wheat depending on seasonal air temperature and rainfalls[4]. Elsewhere, Tahir *et al.*[5] reported associations of seed rate and sowing date on wheat growth and yield under semi-arid conditions. In Kazakhstan, early sowing delayed wheat growth and increased plant susceptibility to pest damage due to heat and water stresses in the beginning of season[7]. Climatic changes appear to correspond with variations in wheat powdery mildew progress and disease management tools, in particular, biological or chemical control, agronomic practices such as planting date, and genetic resistance deployment mainly by breeding for early maturity in wheat[8-10]. Therefore, in the current research attempts were made to provide a comprehensive insight to the joint associations of wheat maturity with powdery mildew progress, planting date, cultivar resistance, weather and yield tested within a single research framework.

Although the development of powdery mildew in wheat cultivars in interaction with planting date, wheat maturity and yield has been studied previously[3,4], it was required to unravel the association of maturity time with powdery mildew progress not only at different planting dates, but also with specific disease development indicators. Moreover, such an influential association was examined under different environmental conditions over the four growing seasons. Because earlier findings confirmed remarkable interactions of these crop-disease-weather indicators[2]. Thus, the present correspondence of a longer period of wheat maturity with a later planting, more speedy winds in Khordad, warmer air in Ordibehesht, further rainy days in Ordibehesht and Khordad, a higher resistance index, an earlier powdery mildew onset, a more severe disease development, a faster disease progress, and a lower yield appears to be novel for the literature. Such a systematic understanding of these agro-ecological variables assessed within a singular experimental framework seems valuable for future breeding studies. The current findings encourage breeders to consider major aspects of wheat production according to the above-mentioned influential factors in order to develop more durable resistance to powdery mildew, and higher genetic resistance and productivity in wheat cultivars worldwide. Wheat breeders are recommended to seek early maturing genotypes with a high stability not only in the resistance to powdery mildew but also in high yielding when planted early according to the current epidemiological findings.

The study year also affected the maturation period in wheat, suggesting a longer and shorter maturity periods detected in 2015-2016 and 2014-2015 seasons, respectively. This observation is in agreement with earlier reports on significant linkages of maturity with abiotic and biotic stresses and planting date[11,12]. For instance, over the tillering to maturation of wheat, the susceptibility of wheat plants to the drought stress increased[6]. In Kazakhstan, early sowing of spring wheat provided heat and water stresses at the initial stage of plant growth that delayed its maturity and increased its susceptibility to pests[7]. According to the current findings, the lowest ranking of wheat maturity period was determined in 2014-2015 with a combination of cooler Ordibehesht, warmer Khordad, fewer rainy days over Ordibehesht-Khordad, and slower winds in Khordad compared to the other seasons studied. The contrast trend of this climatic condition occurred in 2015-2016, coinciding with the most severe epidemics of powdery mildew over this field study[1]. It was suggested that such weather conditions may have restricted and intensified powdery mildew spread on wheat cultivars in 2014-2015 and 2015-2016, respectively. Hence, all these differences in maturity period and powdery mildew could be partially explained based on the current significant disease-maturity-weather interaction.

Earlier report ranked the four study years in this research according to the yield levels of wheat cultivars as follows: 67.71 in 2013-2014, 59.74 in 2014-2015, 41.07 in 2015-2016, and 25.82 in 2016-2017[13]. One may conclude that the cold winter and flooding spring conditions recorded in 2016-2017 may have caused abiotic stresses on wheat growth, resulting in pre-maturation and yield reduction. This opinion was supported by the significantly positive correlation of wheat yield with the average minimum monthly temperature over the autumn-winter duration in this study. A lower ranking of wheat yield in 2015-2016 was also attributed to the mild winter and rainy cool spring, which favored the development of powdery mildew epidemics[1,2], corresponding with the longest maturity period in this study. Furthermore, this investigation added to our knowledge that early planting in October, early autumn, shortened the maturity period of commercial wheat cultivars and thus, restricted powdery mildew and improved the cultivars' productivity. This is a valuable observation which indicated the beneficial association of early planting with early maturing in wheat. Early maturing has been reported as a potential tool to manage abiotic and biotic stresses in wheat[6,8]. Further research in the future could study those mechanisms and genetic bases responsible for such field-scale observations.

There are a large number of previous documents reporting the early-maturity in wheat to be responsible for resistance to wheat diseases[8,14,15]. The current findings showed that a shorter maturation period of wheat cultivars corresponded with a less severe powdery mildew in the forms of lower levels of the AUPMPC, exponential parameter r, and maximum disease severity, and a later disease onset. These remarkable linkages of maturity period to the specific indicators of powdery mildew progress in wheat appear to be the first report for this important pathosystem. Such information can improve the accuracy of yield estimations in breeding programs seeking early-maturity resistance to powdery mildew. Moreover, early planting of wheat had corresponded with higher productivity[16]. However, it appears to be the first reports of wheat maturity in significant association with specific powdery mildew progress indicators in conjunction with cultivar resistance, planting date, weather and yield.

CONCLUSION

This study reminded us that a systematic understanding of the complex interaction of wheat maturity with powdery mildew, planting date, cultivar resistance, weather and yield is required for a sustainable agriculture. The present findings also revealed that an earlier maturity of wheat cultivars was associated with a cooler Ordibehesht, warmer Khordad, fewer rainy days in Ordibehesht and Khordad, slower winds in Khordad, later disease onset and less severe powdery mildew, and higher yielding.

SIGNIFICANCE STATEMENT

Cultivar maturity in interaction with climate, planting date, powdery mildew, and production was investigated. Early maturing cultivars showed earlier disease onset, lower AUPMPC, less severe disease, and greater yield compared to late maturity. Early planting in October shortened maturity in comparison with the optimum date in November. This study provided a systematic understanding of the complex interaction of wheat maturity with powdery mildew, planting date, cultivar resistance, weather and yield for sustainable agriculture purposes.

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