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Powdery Mildew Development is Highly Associated with a Combination of Sowing Date, Weather, Wheat Cultivar, and Maturity

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ABSTRACT

Following favourable agro-ecological conditions, powdery mildew becomes a destructive disease in wheat worldwide. Efficiency of the most common control methods (fungicide application and plant resistance) for wheat powdery mildew improves by using a better understanding of the effects of highly influential agronomic practices and weather factors on disease development. Disease severity was rated at plot scale according to a manageable number of agro-ecological variables in Kermanshah province, Iran in 2013 to 2017. Disease severity rating was varied by cultivar, disease-assessment date, and sowing time. Kruskal-Wallis one-way ANOVA determined a high area under disease progress curve (AUDPC) based on disease severity rated in 2016. A greater AUDPC was detected for early disease onset than late onset. Later sowings had greater AUDPC values compared to earlier sowings. From Principal Component Analysis (PCA), four principal components accounted for 88% of data variance. From PCA-based regression analysis, earlier powdery mildew onset corresponded with further rainy days and higher wind speed in spring, later sowing and maturity, lower disease resistance, and warmer growing season of commercial wheat cultivars. The present findings recognized proper sowing time as effective as genotypic resistance for sustainable management of wheat powdery mildew and provided valuable information on cultivar, disease, maturation, sowing date, and weather interactions.

Keywords: *Blumeria graminis* f., Disease control, Disease progress curve, Epidemiology.

INTRODUCTON

Powdery mildew, caused by *Blumeria graminis* f. sp. *tritici* Em. Marchal, has been reported as a potentially damaging disease of wheat worldwide. Wheat is cultivated across 5,864,554 ha of irrigated and rain-fed lands producing 13,715,258 t of grains in Iran (Anonymous, 2019). Under proper environmental conditions, severe epidemics of stripe (Naseri and Marefat, 2019), leaf (Naseri and Sasani, 2020), and stem rusts (Naseri and Sabeti, 2021), and powdery mildew threaten wheat productivity in Kermanshah Province as one of the major wheat producers in Iran. An improved understanding of climatic and non-climatic predictors of temporal dynamics in the progression of plant disease epidemics must provide essential information to develop more economic, effective, and sustainable disease control programs (Naseri and Sharifi, 2019). There are a number of previous reports on associations of cultivar resistance and weather variables on the intensity of powdery mildew epidemics. For instance, a system dynamic model was developed to predict wheat powdery mildew epidemics using stages of the disease cycle, air temperature, relative humidity, rainfall, wind, plant susceptibility, and leaf position studied at several locations in northern Italy

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during 1991–98 (Rossi and Giosuè, 2003). Wind in December to February, and temperature, humidity, and rain in April to June were identified as key climatic indicators of the development of damaging wheat-powdery-mildew epidemics (> 5% severity) for qualitative predictions based on 12 field sites in the UK, studied from 1994 to 2002 (Te Beest *et al.*, 2008). In China, wheat powdery mildew epidemics corresponded with higher temperature, humidity, rainfall and wind assessed from 1981 to 2010 under climate changes (Zhang *et al.*, 2017). Highlighting decreasing predictive value of climatic indicators during the 30-year study of Zhang *et al.* (2017), increasing influence of non-climatic variables was attributed mainly to fungicide applications and resistant genotypes. Elsewhere, Ge *et al.* (1998) reported variability in temperature-sensitivity among *B. graminis* f. sp. *tritici* genes or among associations of wheat genotypes with corresponding pathogen genes. However, the combined interactions among climatic conditions, cultivar resistance, and development of powdery mildew epidemics deserve further consideration.

Furthermore, many remarkable linkages of sowing and maturity dates to crop disease development have been reported as potential tools for disease management purposes (Jones and Hayes, 1971; Naseri and Mousavi, 2013; Naseri, 2013, 2014a, b; Naseri and Marefat, 2019; Younesi *et al.*, 2019). Therefore, the study of interactions among the above-mentioned agronomic and climatic predictors to wheat powdery mildew development deserves much further consideration. Moreover, such information are highly desired for more economic and sustainable wheat production purposes that may lower fungicide applications and improve durability of resistant wheat cultivars. Preliminary field experimentation have determined the joint interaction of cultivar-sowing-date-maturity-temperature-rain-wind with the occurrence of wheat powdery mildew epidemics. Therefore, the current plot-scale research aimed to investigate: (i) Whether variability in wheat powdery mildew intensity corresponds with the timing of sowing and maturity, and genotypic resistance, (ii) How fluctuations in wheat maturity and powdery mildew onset as a consequence of varying sowing dates are associated with disease dynamics, and (iii) How strongly these different crop-disease descriptors are linked to air temperature and rainfall in powdery-mildew-affected wheat plants.

MATERIALS AND METHODS

Experimental Plots Preparation

The progression of powdery mildew disease was characterized based on a four-growing-season (2013-2017) research on a number of commercial bread-wheat cultivars grown at Islam-Abad Research Station (latitude 34˚ 7΄ N, longitude 46˚ 28΄ E) as one of the major Iranian wheat breeding stations, in Kermanshah Province. The average annual precipitation is about 538 mm, with the mean annual temperature of 13˚C. Climatic data recorded by the synoptic weather station located adjacent to the Research Station were obtained via online access to the Kermanshah Met Office. The experiment had a split-plot design with three replicates for each of four sowing times examined as the main experimental treatment. In addition, sowing dates were chosen on the basis of monthly intervals according to commonly practiced cultivation methods in the region. The following sowing times were evaluated: October 10, November 7, December 3 and 31 for the first growing season (2013-2014); October 12, November 14, and December 19 for the second season (2014-2015); October 27, December 13 and 30 for the third season (2015-2016); and October 11, November 15, December 11, and January 5 for the fourth season (2016-2017) of the study. According to the list of Iranian wheat cultivars registered on a yearly basis for temperate zone, either seven or eight cultivars (sub-

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plot treatment) were randomly sown within the main plots. Hence, cv. Bahar was excluded from the study from the second growing season because of broken resistance to wheat rusts. The size of experimental plots differed among the growing seasons as follows: 19.2 m^2 in the first growing season, 24 m^2 in the second season, and 6 m^2 in the third and forth seasons. Seeding rates varied on the basis of the sowing time evaluated: 400 seed/m^2 for the early (the first sowing time, early autumn) and optimal (the second sowing time, mid-autumn) sowing dates, 450 seed m^{-2} for the late and very late (the third and forth sowing times, late autumn and early winter, respectively) dates of planting. The higher seeding rate for late and very late sowing times coincided with cold climatic conditions provided efficiently similar densities of plants over experimental plots. Field trials were managed according to standard strategies advised to local irrigated-wheat producers. The field plots were fertilized with urea 225 kg ha^{-1} and superphosphate 50 kg ha^{-1}, irrigated by sprinkler system at 7-10 days intervals, and hand-weeded.

Powdery Mildew Measurement

The progression of wheat powdery mildew was evaluated on a weekly basis from the flag leaf (early May) to maturation (75% of the spike turning yellow; mid-June) stage (Naseri and Kazemi, 2020). To detect ratings of powdery mildew severity for every plot, plants in three arbitrary spots were assessed for foliar symptoms of powdery mildew (Naseri and Marefat, 2019). Then, the proportion of leaf and stem surfaces covered by whitish talcum-like powdery growth of the pathogen was determined for at least three plants per observed spot. In addition to the disease measurements, powdery mildew severity ratings were used to determine the disease resistance index. This variable was used in this study as an indicator of powdery mildew development according to the genotypic resistance of each wheat cultivar to the disease assessed. The powdery-mildew-resistance index was determined by reduction of the greatest value of severity rating (recorded during the four growing seasons for each test cultivar) from 100 (Naseri and Sasani, 2020). The disease onset was defined as the time of the appearance of the first powdery mildew symptoms covering either leaf or stem tissues.

Statistical Analysis

In this epidemiology-based disease management research, a total of 282 (72 in 2014, 63 in 2015, 63 in 2016, and 84 in 2017) wheat plots were evaluated for powdery mildew intensity. The disease assessments in the trials were undertaken in the year subsequent to the year when planting was carried out. To examine effects of planting date and cultivar, the multiple-point-assessment data on powdery mildew severity was subjected to the Analysis Of Variance (ANOVA). The normality of data distribution was evaluated according to the kurtosis and skewness criteria. The structure of wheat powdery mildew progress across experimental plots over four growing seasons was characterized based on the Area Under the Disease Progress Curve (AUDPC). The AUDPC value was measured by the time midpoint between the two sequential powdery mildew assessments of the mean disease severity ratings as described by Naseri and Marefat (2019). The powdery-mildew-severity AUDPC data was subjected to Kruskal-Wallis one-way ANOVA and *H*-test to compare factor levels for the disease progression over the growing season of wheat.

Considering correlation matrix, powdery-mildew-affected wheat data was subjected to Principal Component Analysis (PCA) to calculate loading values for Principal Components (PCs), which simplified interpreting the cultivar-climate-mildew-sowing-date interaction. A loading greater than or equal to 0.35 was considered

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significant (Kranz, 1974). An eigenvalue was used for further evaluations if it was ≥ 1.0. Because of the wide range of temperature favorable for powdery mildew development (Ge *et al.*, 1998), no temperature-range variable was considered in this study. Preliminary statistical analyses of plot-scale data demonstrated noticeable linkages of powdery mildew progression to the mean monthly minimum temperature for two months of Iranian calendar i.e. Ordibehesht (from April 21 to May 21) and Khordad (from May 22 to June 22), the number of rainy days over Ordibehesht-Khordad, the six-monthly (from October 23 to April 20) mean minimum temperature, and wind speed for Khordad. Under environmental conditions in Islam-Abad district, epidemics of wheat powdery mildew occur commonly in the third month of spring, June.

According to the simplified interactions among agro-ecological and powdery mildew descriptors resulting from the PCA, the considered principal components were entered into the regression equation with the disease severity AUDPC as the dependent variable. Because of the optimized spatial patterns of new variables (PCs) described by the PCA, each PC is independent from the other PCs, and thus, their involvement in the multivariate regression analysis overcomes common complications caused by multicollinearity among ordinary variables (Naseri, 2014b). As each PC represents the linear correlation of those variables involved in, the significant linkage of a PC in regression analysis indicates associations of the dependent variable with independent variables with moderate to high loading values based on the PCA output. Then, the best model fitness was determined based on the *F*-test, R^2, and normality of residuals. To evaluate the regression estimation, fitted data were regressed to the calculated (response) powdery-mildew-severity-AUDPC data. GENSTAT (VSN International, Oxford, UK) was used to perform all the statistical methods.

RESULTS

According to the ANOVA results, the three-way interaction of powdery mildew assessment time, sowing date and wheat cultivar affected the disease severity (Table 1). There was a lack of, or slight, powdery mildew infection in spring seasons of 2014, 2015 and 2017. In late May 2016, first symptoms of powdery mildew were observed on the wheat cultivars examined. At the third assessment time of 13-December plantings examined in 2016, cv. Pishgam had the highest mean disease severity (P< 0.05) compared to the other cultivars studied, followed by cv. Parsi (Figure 1). At the third assessment time of 30-December planting date, cvs. Parsi, Pishgam, and Sivand had higher (P< 0.05) disease severities than the other cultivars. At the forth assessment time of October-planted plots, cv. Pishtaz indicated the greatest mean disease severity (P< 0.05) followed by cvs. Parsi and Pishgam. For the mid-December plantings at the forth assessment time, the highest level of wheat powdery mildew was developed on cv. Parsi, followed by cvs. Pishgam, Pishtaz, Baharan and Sirwan. At the forth powdery mildew assessment of 30-December plant plots, cv. Pishgam had the greatest mean value for powdery mildew severity among all the cultivars. At the fifth disease assessment of mid-December plantings, cvs. Parsi and Pishgam had greater mean values (P< 0.05) for powdery mildew severity followed by cv. Pishtaz. At the fifth assessment time of 30-December plantings, the highest powdery-mildew-severity level (P< 0.05) was detected on cv. Pishgam.

The powdery-mildew-severity-AUDPC values for the commercial wheat cultivars and planting times examined from 2013 to 2017 are presented in Table 2. The results of Kruskal-Wallis one-way ANOVA analyses evidenced the rankings of powdery-mildew-AUDPC according to wheat cultivar, disease onset, sowing time, resistance index, and year categories (Table 3). Based on H-test

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Table 1. Analysis Of Variance (ANOVA) for powdery mildew severity rated on commercial wheat cultivars planted at different sowing dates.

Factors	df	SS	*F* pr
Cultivar	6	11513.0	0.001
Date	2	5092.2	0.001
Time [a]	4	16107.2	0.001
Cultivar×Date	12	7023.4	0.001
Cultivar×Time	24	12091.2	0.001
Date×Time	8	4668.6	0.001
Cultivar×Date×Time	48	9545.2	0.001
Residual	416	18199.1	
Total	524	84747.6	

[a] Multiple-point disease assessment times.

Table 2. The Area Under Disease Progress Curve (AUDPC) for powdery mildew severity ratings on commercial wheat cultivars planted at different sowing dates.

Factors	2015-2016		
Cultivar	27-Oct	13-Dec	30-Dec
Bahar	na[a]	na	na
Baharan	0.0	216.0	81.0
Chamran	0.0	0.0	0.0
Parsi	135.0	782.0	184.5
Pishgam	108.0	830.0	621.0
Pishtaz	225.0	418.5	148.5
Sirwan	0.0	117.0	189.0
Sivand	0.0	76.5	203.5

[a] na= Not assessed.

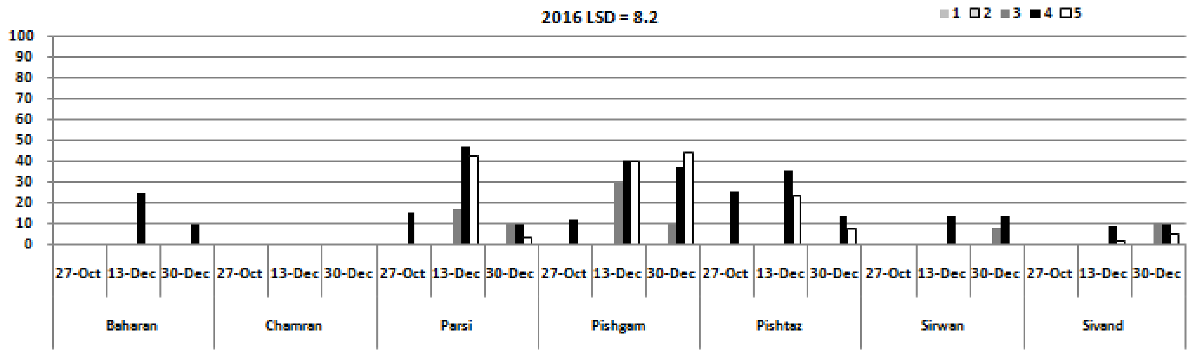

Figure 1. Mean powdery mildew severity ratings on commercial wheat cultivars planted at different sowing dates.

comparisons, the timing of powdery-mildew-onset affected (Adjusted H= 60.8; *Chi* P< 0.001) the AUDPC. The earlier onset of powdery mildew (Mean= 73.6; Rank= 1) had a significantly greater mean AUDPC value than the later disease onset (Mean= 40.0; Rank= 2). Evaluation of the four sowing dates (Adjusted H= 8.0; *Chi* P< 0.047) demonstrated higher powdery-mildew-AUDPC levels for the late (Mean= 50.7; Rank= 2) and very late (Mean= 54.0; Rank= 1) sowings in comparison with the early (Mean= 40.0; Rank= 4) and optimum (Mean= 45.0; Rank= 3) planting dates.

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Table 3. Ranks for factors' levels detected by Kruskal-Wallis one-way ANOVA according to Area Under Disease Progress Curve (AUDPC) for wheat powdery mildew severity ratings.

Factors	Factor levels							
Cultivar	Bahar	Baharan	Chamran II	Parsi	Pishgam	Pishtaz	Sirwan	Sivand
Number of samples	7	7	14	14	10	14	14	14
Mean adjusted H= 7.2	40.0	52.9	40.0	50.2	54.8	50.4	46.4	46.3
Rank *Chi* P= 0.409	7	2	7	4	1	3	5	6
Disease onset time	Early				Late			
Number of samples	21				73			
Mean adjusted H= 60.8	73.6				40.0			
Rank *Chi* P < 0.001	1				2			
Disease resistance index	20	30	40	50	80	85	100	
Number of samples	14	10	14	7	21	14	14	
Mean adjusted H= 6.6	50.2	54.8	50.4	52.9	44.3	46.3	40.0	
Rank *Chi* P= 0.364	4	1	3	2	6	5	7	
Sowing time	Early		Optimum		Late		Very late	
Number of samples	20		27		27		20	
Mean adjusted H= 8.0	40.0		45.0		50.7		54.0	
Rank *Chi* P= 0.047	4		3		2		1	
Year	2014		2015		2016		2017	
Number of samples	24		21		21		28	
Mean adjusted H= 60.8	40.0		40.0		73.6		40.0	
Rank *Chi* P< 0.001	2		2		1		2	

Comparison of the four growing seasons (Adjusted H= 60.8; *Chi* P< 0.001) indicated a greater powdery-mildew-AUDPC value for 2016 (Mean= 73.6; Rank= 1) than those for 2014, 2015 and 2017 (Mean= 40.0; Rank= 2). There were no significant effects of wheat cultivar (Adjusted H= 7.2; *Chi* P= 0.409) and resistance index (Adjusted H= 6.6; *Chi* P= 0.364) on powdery-mildew-AUDPC according to H-test evaluations.

The four principal components provided by the PCA analysis accounted for 88.0% of the total variance in powdery mildew development examined over four growing seasons in eight commercial wheat cultivars planted at different dates (Table 4). The PC1 justified 47.1% of the variance in the crop-powdery-mildew-weather data. The first PC evidenced a moderate negative loading for the timing of powdery-mildew-onset, and moderate positive loadings for the three weather indicators. The variables of mean minimum temperature in Ordibehesht, number of rainy days over Ordibehesht-Khordad months, and wind speed in Khordad corresponded with the PC1. This PC, explained the highest proportion of the variance in data-set and demonstrated that the occurrence of powdery mildew was associated significantly with the above-mentioned weather indicators.

The PC2, which accounted for 16.8% of the total variance in powdery-mildew-weather-wheat data, was linked to the maturity, six-monthly mean temperature, and sowing-time variables (Table 4). This PC provided moderate negative loading values for the sowing date and maturity indicators, and a moderate positive loading for six-monthly mean temperature. The PC2 also evidenced the indirect dependence of wheat maturity and sowing time on the

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Table 4. Principal component analysis of powdery mildew severity data on commercial wheat cultivars planted at different sowing dates (2013-2017).

Variables	Principal components			
	1	2	3	4
Disease onset date	**-0.40**[a]	-0.32	0.05	-0.07
Maturity date	0.28	**-0.47**	**-0.36**	-0.17
Mean minimum temperature in Ordibehesht	**0.39**	-0.07	0.01	0.24
Mean minimum temperature in Khordad	-0.34	0.33	**-0.44**	-0.15
Number of rainy days in Ordibehesht and Khordad	**0.44**	0.06	0.04	0.19
Six-monthly mean temperature	0.21	**0.53**	**-0.47**	0.05
Sowing time	0.23	**-0.40**	**-0.42**	**-0.41**
Resistance index[b]	-0.04	-0.17	**-0.39**	**0.74**
Wind speed in Khordad	**0.35**	0.01	**0.37**	0.02
Eigen values	4.7	1.7	1.3	1.1
Variation (%)	47.1	16.8	13.3	10.8
Accumulated variation (%)	47.1	63.9	77.2	88.0

[a] A bold number indicates a significant loading value ≥ 0.35. [b] Resistance index= 100-Greatest disease severity rating obtained for every cultivar.

weather variable and six-monthly mean temperature. For instance, this suggested that cooler autumn, winter, and early spring corresponded with later maturity of the commercial wheat cultivars studied.

The PC3, which accounted for 13.3% of the total variance in data-set, determined the significant contributions of the maturity, resistance-index, sowing-time, and the three weather descriptors in the development of powdery mildew epidemics that occurred over the four growing seasons of wheat. According to PC3 loading values, there was a moderate positive loading for the wind-speed variable. Based on the negative loading values obtained for PC3, the timing of wheat cultivars maturation was dependent on the mean minimum temperature in the month of Khordad, sowing date, resistance index, six-monthly mean temperature, and wind speed. The significant contributions of climate, maturity, sowing time and resistance index with the third principal component also demonstrated the strong association of these descriptors with the powdery mildew progression across wheat crops.

The forth PC, accounting for 10.8% of the data variance, corresponded significantly with the sowing time and resistance index determined for the eight commercial wheat cultivars during the four growing seasons (Table 4). The PC4 provided a high positive loading value for the disease resistance index and moderate negative loading values for the sowing time. Thus, the fourth PC suggested that a higher resistance level corresponded with earlier sowings of the test wheat cultivars affected by powdery mildew over the growing season. This PC evidenced sowing time and resistance index as the major descriptors of the powdery-mildew-wheat pathosystem. Based on the PCA analysis, the plot-scale progression of powdery mildew disease on various commercial wheat cultivars corresponded mainly with the climate and disease onset time (PC1), timing of maturation (PC2), sowing date (PC3), and genotypic resistance (PC4).

According to multiple linear regression analysis, the scores obtained for the PC1, PC2 and PC4 were significantly correlated with the progression of powdery mildew

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disease (AUDPC as dependent variable) examined over four growing seasons (2013-2017) for eight commercial wheat cultivars with different resistance levels and sowing times (Table 5). Based on the loading values of the crop-disease-weather descriptors on the PC1 (Table 4), earlier disease onset, greater mean minimum temperature in Ordibehesht, further rainy days in the second and third months of spring season, and more speedy winds in the month of Khordad corresponded with higher powdery mildew AUDPC levels. According to the loadings of variables on the PC2, the development of powdery mildew was associated with six-monthly mean temperature, sowing and maturity variables. The loading values of predictors on PC4 demonstrated the correspondence of more severe powdery mildew with later sowings and lower disease resistance levels. Correlation of the fitted data against calculated (response) AUDPC values (correlation coefficient = 0.82) indicated the good fitness of powdery mildew AUDPC regression involving highly relevant climate-crop-disease descriptors.

DISCUSSION

Due to the lack of thorough understanding of the planting-date-powdery-mildew-weather-wheat interaction, the inter-relationships among a reasonable number of agronomic and environmental variables, and the plot-scale disease progression were characterized during the four growing seasons. Identification of highly relevant agro-ecological predictors of powdery mildew development assists with developing more effective agronomic management programs for wheat powdery mildew and well-timed application of fungicides. Therefore, such comprehensive information on the climate-crop-disease interplay leads us to manage wheat powdery mildew more sustainably using resistant cultivars and well-timed planting optimized according to influential agro-ecological characteristics.

More susceptibility of wheat plants to powdery mildew and ten times greater sporulation were observed at 14°C compared to 7°C (Last, 1953). Then, the optimum temperature and relative humidity for germination of powdery mildew conidia was determined within the ranges of 10-22°C and 95-100%, respectively (Wiese, 1987). Elsewhere, Friedrich (1995) reported restrictions in powdery mildew development due to a high and a low vapor pressure. From April to June in the UK, the number of days with maximum temperature above 20˚C, accumulated minimum temperature > 12˚C, number of consecutive days ≥ 95% relative humidity, and accumulated rain > 10 mm were identified with higher predictive values for severe wheat powdery mildew epidemics (Te Beest *et al.*, 2008). Liu *et al.* (2015) reported significant associations of meteorological factors in March and April on wheat powdery mildew index based on a five-year study in China. Although these Chinese and British studies found no disease restrictions due to temperatures exceeding

Table 5. Multivariate regression analysis of Area Under Disease Progress Curve (AUDPC) for wheat powdery mildew severity ratings based on Principal Component (PC) analysis.

Variables	Parameter estimate	SE	t Prob	R^2
Constant	46.1	8.7	0.001	0.67
PC1	41.4	4.0	0.001	
PC2	42.9	6.8	0.001	
PC3	0.2	7.6	0.977	
PC4	-52.2	8.5	0.001	

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20˚C, Wiese (1987) reported that powdery mildew development declined at temperatures above 25°C. For the powdery-mildew-wind interaction, it is believed that wind can not only lower air moisture as an essential prerequisite for infection (Friedrich, 1995; Te Beest *et al*., 2008), but also distribute *B. graminis* f. sp. *tritici* conidia for wider powdery mildew spread (Wiese, 1987). All the above-mentioned reports differing in appropriate humidity, temperature, and wind required for the occurrence of powdery mildew epidemics encouraged us to replace hourly or daily records with monthly meteorological data and consider longer climate-disease assessment time per year for a more accurate explanation of seasonal variability in the disease intensity across experimental plots. According to PCA and regression results, the current four-year-plot-scale research described direct relationships of powdery mildew development, the number of rainy days over Ordibehesht-Khordad (the second and third Iranian spring months), the average minimum temperature for Ordibehesht, and wind speed in Khordad. Due to limited powdery mildew infection resulting from high light intensity and sunshine (Wiese, 1987), the mean minimum temperature of a designated month was considered in this study that averages the lowest daily temperatures recorded around the sunrise time. Although the infection efficiency of wheat powdery mildew decreased mainly through a washing off effect of rainfalls under field conditions (Merchan and Kranze, 1986), further number of rainy days corresponded with a more intensified disease during the growing season in the present research. Because most of the available predicting models have evaluated climatic conditions over the disease cycle, the association of wheat powdery mildew progression with environmental variables for longer seasonal periods involving autumn, winter and spring is still little understood. Therefore, the present model evidenced the remarkable association of powdery mildew development with the mean minimum temperature and number of rainy days for Khordad covering the disease cycle in the study area and for the previous month, i.e. Ordibehesht, as well as the six-monthly mean minimum temperature. This time period of the climate-disease assessment, which covered the entire growing season of wheat, appears to be a new valuable record for the powdery mildew epidemiology and predicting models. The magnitude of prediction value of this linear regression model, which involved winter months' minimum temperatures, might be partially attributed to the additional evaluation of the inhibitory effect of cold winters on *B. graminis* f. sp. *tritici* overwintering and epidemic occurrence as reported earlier (Wiese, 1987).

The Italian model to predict wheat powdery mildew epidemics involved 31 variables describing detailed stages of the disease cycle, plant susceptibility, leaf position, and hourly records of air temperature, relative humidity, rain and wind (Rossi and Giosuè, 2003). Thus, the prediction of severe epidemics using this Italian model requires much sophisticated work, thus, simplified wheat-powdery-mildew predicting models based on fewer variables with a reasonable accuracy are still highly desired. The Chinese model (Zhang *et al.***,** 2017), which used only climatic descriptors (air humidity, rainfall, temperature and wind speed) to predict wheat powdery mildew epidemics, suggested a reduction of model predictive value over a 30-year period presumably due to increasing impacts of non-climatic predictors like genotypic resistance. Therefore, it appears that wheat-powdery-mildew predicting models would benefit from adding efficient agronomic predictors to climatic variables. To improve accuracy of estimating powdery mildew intensity, the present plot-scale study involved cultivar resistance, sowing date, and wheat maturity as well as weather descriptors that this multivariate selection significantly contributed in the variability of AUDPC values based on disease severity ratings.

Although wind factor from December to February indicated the greatest relevance to the occurrence of severe wheat powdery mildew epidemics in the UK (Te Beest *et al.*, 2008), wind speed over the disease cycle (in Khordad) was ranked as the third most relevant weather variable describing the disease onset and intensity across wheat cultivars sown at different times. The dominance of negative effect of wind on powdery mildew in the British model (Te Beest *et al.*, 2008), which involved only climatic variables, might have been weakened and turned to positive impact by adding significant agronomic predictors to temperature, rain and wind in the present Iranian study. Of course, differences in host plant and pathogen genotypes, environmental conditions, and methodology used might have partially caused such discrepancies between the British and Iranian findings.

Moreover, the remarkable contribution of sowing date in combination with cultivar resistance, disease onset, rain, air temperature, wind and maturity in estimating wheat powdery mildew intensity in the present research appears to be a new scientific report. The wisely timed sowing as a potential disease management tool developed for a large number of crop-disease pathosystems (Jones and Hayes, 1971; Naseri and Mousavi, 2013; Naseri, 2013, 2014a, b; Naseri and Marefat, 2019; Naseri and Sasani 2020; Younesi *et al.*, 2019) appears to restrict the progression of powdery mildew in wheat crops under environmental conditions encountered in the current study. In addition, the present PCA results evidenced a greater contribution of maturity and sowing time linked significantly to PC2 when compared to cultivar resistance linked to PC4, based on the proportions of data variance explained by each PC. To the best of our knowledge, this is the first evidence of a more important role of sowing and maturation date than cultivar resistance in the powdery-mildew-wheat interaction. From a sustainable disease management viewpoint, such information suggests involvement of sowing-time and early-maturation assessments in future attempts to improve wheat resistance to powdery mildew.

In China, Ge *et al.* (1998) found different reactions of temperature-sensitivity among *B. graminis* f. sp. *tritici* genes or among wheat genotypes. The present study added the evidence of remarkable associations of cultivar resistance with sowing date, wheat maturation and wind speed to the current knowledge. Thus, the present research recommends the involvement of powdery-mildew-onset, maturity, and sowing time, cultivar resistance, temperature, rainfall, and wind speed variables to improve the accuracy of wheat-powdery-mildew epidemics predictions. Furthermore, the significant interaction of wheat powdery mildew with agro-ecosystem determined in the present research merits continued investigation in different geographical regions.

CONCLUSIONS

The present findings evidenced that timely sown wheat cultivars may improve the resistance level and durability against powdery mildew disease under diverse climatic conditions. Such novel information encourages wheat growers and pathologists to minimize fungicide applications according to well-timed sowing of resistant cultivars for sustainable wheat production purposes.

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گسترش سفیدک پودری با آمیخته‌ای از تاریخ کاشت، هوا، نژاد گندم و رسیدگی همبستگی دارد

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چکیده

با رویداد ویژگی‌های هواشناسی و کشاورزی سازگار، سفیدک پودری بیماری زیان‌آوری برای گندم می‌گردد. کارآیی بیشتر روش‌های پرکاربرد مهار سفیدک پودری گندم (کاربرد قارچکش و مقاومت گیاه) با کمک شناخت بهتر از وابستگی گسترش بیماری به روش‌های کشاورزی و ویژگی‌های آب و هوایی بهبود می‌یابد. درصد برگ آلوده (شدت بیماری) در کرت‌های آزمایشی برپایه چند ویژگی هواشناسی و کشاورزی در سال‌های 1396-1392 در استان کرمانشاه ارزیابی شد. درصد برگ آلوده با رقم، زمان ارزیابی بیماری و زمان کاشت بستگی داشت. روش تجزیه واریانس یک سویه والیس سطح زیر منحنی بیماری (AUDPC) بالاتری را در سال 1395 برپایه درصد برگ آلوده نشان داد. در واکاوی نمودار زیر منحنی بیماری، رخداد زودهنگام بیماری AUDPC بالاتری از رخداد دیرهنگام داشت. کشت دیرهنگام نیز AUDPC بالاتری از کشت زودهنگام نشان داد. در روش تجزیه مولفه چهار مولفه اصلی 88٪ واریانس داده را دربر گرفتند. در رگرسیون برپایه روش تجزیه مولفه، رخداد زودهنگام سفیدک پودری با روزهای بارانی بیشتر و بادهای تندتر بهاری، کشت و رسیدگی دیرهنگام، مقاومت پایین‌تر، و دوره رویشی گرمتر ارقام بازاری گندم همبستگی داشت. این یافته‌ها نمایانگر کارآمدی برابر زمان کاشت با مقاومت رقم در مدیریت پایدار سفیدک پودری گندم است و داده ارزشمندی در زمینه برهمکنش رقم-بیماری-رسیدگی-زمان کاشت-آب و هوا را فراهم ساخت.

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