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Modeling Wheat Yield Based on Brown Rust, Cultivar Resistance, Weather Conditions, Maturity, and Planting Date

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ABSTRACT

Background and Objective: Estimation of wheat yield based on specific brown rust descriptors is little understood. This four-growing-season study attempted to predict yield in brown-rust-affected cultivars of wheat differing in maturity and planting date, and resistance index. **Materials and Methods:** Experimental plots were prepared to assess specific descriptors of brown rust progress across wheat cultivars and planting dates considered as treatments. A significance level of 5% was considered in the H-test and correlations to examine associations of treatments with disease, maturity, cultivar resistance, and yield. Weather data was also considered in the data analyses. **Results:** Highest ranking of yield was detected for early plantings in October, with yield being increased by 185% compared to late plantings in early January. Factor analysis accounting for 76% of data variance demonstrated significant associations of brown rust progress variables (first principal factor), wheat yield with environment, maturity and planting date (second principal factor), brown rust progress with resistance index (third principal factor), and environment with brown rust progress (fourth principal factor). Yield model describing 94% data variability revealed that a greater productivity of wheat corresponded with an earlier planting date, a greater resistance index, fewer moist and temperate days in spring, and a longer maturity period. **Conclusion:** This is the first report on the joint analysis of wheat yield, cultivar resistance, maturity duration, planting date, and weather. This new information helps with predicting future brown rust epidemics and estimating wheat yield in conjunction with breeding efforts for more resistant cultivars.

KEYWORDS

Cereals, climate, joint analyses, *Puccinia recondita*, leaf rust

INTRODUCTION

Brown (leaf) rust, caused by *Puccinia recondita* f. sp. *tritici*, has been found as a destructive biotic stress under conducive conditions in wheat fields worldwide. Recent reports from Iranian field studies showed that the Area under Brown Rust Progress Curve (AUBRPC) was linked to the disease onset, cultivar maturity, average monthly minimum temperature from October 23 to April 20, number of days with minimum temperature 5-25°C and maximum relative humidity (RH) above 60% over the first and second

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months of spring, resistance index and planting date[1]. This suggested that the progression of brown rust in susceptible wheat cultivars could be hastened by early disease onset, late planting and maturity, moderate autumn and winter seasons, and rainy spring. The next attempt tried to examine the seasonal progression of wheat brown rust based on the following specific disease predictors: AUBRPC, disease-onset, Gaussian parameters, and maximum disease severity. These specific predictors explained 75% of disease variations across commercial cultivars planted at different dates[2]. However, still need to unravel the strength of associations of wheat yield with such effective agro-ecological and pathological predictors, specifically developed for brown rust disease.

Early onset brown rust epidemics reduced wheat yield up to 40% according to a significant regression between tiller grain weight and the AUBRPC[3]. Herrera-Foessel *et al.*[4] examined simple correlations of AUBRPC and final brown rust severity ratings to yield variables in wheat genotypes with different resistance levels planted at normal and late dates. The other studies on adult plant resistance to brown rust have also used general disease progress predictors[5]. Mabrouk *et al.*[6] studied brown rust progress descriptors for slow rusting under greenhouse conditions in 12 promising lines and varieties of wheat. They compared brown rust progress curves according to incubation period, latent period, pustule density and size, and AUBRPC. Although Mabrouk *et al.*[6] focused on the associations among descriptors of brown rust progress, they ignored associations of agro-ecological parameters with yield. All previous studies modeled wheat yield according to general predictors of brown rust seasonal patterns. Therefore, attempts were made to predict wheat yield based on specific predictors of brown rust progress in conjunction with yellow and black rusts and powdery mildew progress[7]. The progression of these four major diseases was studied together to model wheat yield more accurately and realistically. In the next step, the agronomic and weather factors associated with brown rust progress[1,2] and wheat yield[7] were still needed. However, due to differences in associations of the mildew and rust diseases with various weather variables, it is needed to examine the crop-disease-weather-yield interaction for each pathosystem individually. Furthermore, it was unreliable to determine interrelationships between a large number of predictors defined for mildew and rusts progress, cultivar resistance, maturity duration, planting date, and weather to model wheat yield. Thus, a more concise simulation of wheat yield based on the influential agro-ecological and specific brown rust progress predictors is highly desired. To meet this requirement, the current study aimed to examine the descriptive values of wisely-selected variables of air temperature and RH, brown rust progress, cultivar resistance, maturity duration and planting date; and more accurate estimation of wheat yield based on considered agro-ecological and brown rust descriptors at plot scale under agro-ecological conditions encountered in Kermanshah.

MATERIALS AND METHODS

Study area: Experimental fields were located at Islamabad Research Station, Latitude 34°7'N, Longitude 46°28′E, which is a major site for performing cereals breeding programs in Iran. During four growing seasons from early autumn in 2013 to the end of spring in 2017, the characterization of brown rust progress in eight commercial winter cultivars of bread wheat was performed across 282 plots. The treatments of cultivars and planting dates, timing and type of field assessments in this study have been summarized in Table 1.

Trials were designed as a split-plot with three replicates per experimental treatment. The eight wheat cultivars (Table 1) originated from the breeding program conducted by the seed and plant improvement institute. Various levels of planting dates, cultivars of wheat, and seasons were used as effective factors to maximize heterogeneity in the progression of brown rust across field trials. Such high heterogeneity in the disease intensity and yield datasets improves the predictability of regression modeling[7,8]. Experimental plots were not treated with fungicides to allow natural infections of wheat brown rust to develop. Based on the highest severity rating of brown rust determined over this four-season investigation, the eight wheat cultivars were grouped as resistant for cvs., Parsi, Pishtaz, and Sirwan, partially resistant to cvs., Bahar, Baharan, and Pishgam and susceptible to cvs., Chamran II and Sivand[2].

Table 1: Properties of 282 plots, treatments, and 1701 measurements performed at the field scale

	Treatments			
Measurements	Years	Planting dates (main plot)	Cultivars (subplot)	
Brown rust	2013-2014	October 10, November 7, December 3 and 31	a	Pishgam
Yield (kg/ha)	2014-2015	October 12, November 14 and December 19	Baharan	Pishtaz
	2015-2016	October 27, December 13 and 30	Chamran II	Sirwan
	2016-2017	October 11, November 15, December 11 and January 5	Parsi	Sivand

Plot properties: Fertilized with 225 kg/ha urea and 50 kg/ha superphosphate, No fungicide applied to maximize brown rust development, Pesticide Deci's (180 kg/ha) applied to manage pests; Irrigated with sprinkler system every 7-10 days. Study site properties: Annual average temperature 13.7°C and 479.8 mm rainfall, Latitude 34°7' North and Longitude 46°28' East; Weather data collected from the adjacent meteorological station during the study, 2013-2017

Data collection: The brown rust severity was determined every week from mid-spring (early May) to early summer (mid-June) as the percentage of leaf area covered with brown pustules for the three youngest leaves of 3-5 randomly observed plants per plot. Then, the progression of brown rust during the four growth seasons of wheat was modeled based on brown rust severity ratings[2] using the following criteria: (1) Disease onset defined the duration of time (in days) from planting to the occurrence of first brown rust pustules assessed every season, (2) AUBRPC according to disease severity ratings, (3) Maximum disease severity recorded over the four growing seasons, (4) Gaussian curve elements, b, m and s, determined based on severity ratings[2]. The GENSTAT (VSN International, Oxford, UK) was used for all the statistical analyses. The Gaussian model estimated the following parameters: b for the height of the curve's peak, m for the central point of the curve's peak, s (considered as the standard deviation) for the width of the Gaussian bell, and x for time intervals between disease assessment times. At harvest, when all wheat plants across plots were physiologically mature, the whole wheat grains obtained per plot were weighed. Then, the data obtained for wheat grain yield g/plot was converted to the yield kg/ha data.

Data analysis: Using the Kruskal-Wallis One-way ANOVA (H-test), the effects of cultivar, disease onset, maturity duration, planting date, resistance index, and growing season on brown rust progress and wheat yield were ranked. The test revealed statistically significant differences ($p<0.05$) among these factors, indicating that each contributed variably to disease development and yield variation across treatments.

For the H-test ranking of brown rust progress, the Gaussian parameter (m) and maximum disease severity with the greatest contributions to the brown rust dataset[2] were considered. This H-test provided a preliminary examination of brown rust onset, cultivar, growing season, planting date, and resistance index ranked according to the disease severity ratings, Gaussian parameter (m), and wheat yield. Such information, which advanced our understanding on the importance of each treatment or factor in interaction with either brown rust or wheat yield, was unclear when subjecting the datasets to a simple ANOVA earlier[2,7]. Furthermore, the H-test results confirmed variations in the disease development and the subsequent yield levels across plots, which were required in this study as mentioned above. Thus, more sophisticated statistical methods were used in the next steps to unravel associations among the different disease-environment-plant indicators.

To examine predictive values of the disease and agro-ecological variables, a factor analysis (FA) determine the contributions of 11 agronomic, disease progress, environmental, and yield descriptors based on the loading values. A greater value of significant loading (if $\geq$0.35) defines a stronger contribution of that variable to the principal factor. Those factors were considered for statistical interpretations because their eigenvalues or data variance proportions were greater than 1.0. The examination of collinear variables to be removed from modeling analyses was conducted with the help of FA as recommended by Naseri[7] and

Kranz[8]. This statistical methodology has highly improved the accuracy of selecting variables to be involved in the yield predicting model. To meet this requirement, an accurate evaluation of the percentage of data variations (eigenvalues) explained by principal factors, along with the magnitude (loading value) of those predictors contributing to principal factors, was needed based on the FA result. In addition to considering T-test results for the disease and agro-ecological variables, the graphical appraisal of normal distribution of residuals, F-test, and R^2 was examined to fit the linear multiple regression involving the five FA-selected predictors to the yield dataset[7]. After fitting the multivariate regression model, the observed data for wheat yield (kg/ha) was regressed to the fitted data in the eight commercial wheat cultivars differing in brown rust progress, maturity duration, and resistance index. Mean values of wheat yield for three replicate plots (in total 282 experimental plots) for each cultivar and planting date were obtained earlier[7].

RESULTS

The two weather variables, air temperature and mean six-monthly temperature, were used to model wheat yield (Table 2). Further to weather variables, the duration of maturity, which varied by the cultivar and planting date, was included in the remainder of the statistical analysis. The planting date, resistance index, and brown rust variables were also considered in the analysis of the yield dataset as characterized in Table 2. Table 2 outlines the key variables used in the study to model wheat yield based on agro-ecological and pathological factors. Environmental variables included the number of days with minimum temperatures between 5-25°C and relative humidity ≥60%, as well as the mean autumn-winter temperature over six months. Maturity duration varied among eight wheat cultivars, ranging from 247 to 270 days depending on the trial. Planting dates were categorized into early (October), optimum (November), late (early to mid-December), and very late (late December to early January). The resistance index, calculated as 100 minus the maximum brown rust severity, ranged from 0 (Sivand) to 70 (Sirwan). Brown rust descriptors included the Area under the Brown Rust Progress Curve (AUBRPC), timing of rust onset (early or late), Gaussian parameters (b = curve height, m = midpoint and s = width), and maximum severity, which varied between 30 and 100% across seasons.

Table 2: Variables used in the current study varied by wheat cultivars, maturity, planting dates, resistance, and brown rust levels

Variables	Variable characterization							
Environment	Number of days with minimum temperature within 5-25°C and maximum relative humidity ≥60%							
	Mean six-monthly (autumn-winter) temperature per year							
Maturity duration in	Bahar	Baharan	Chamran II	Parsi	Pishgam	Pishtaz	Sirwan	Sivand
days varied by trials	255-267	251-267	251-268	247-268	247-266	250-268	251-269	252-270
Planting date[a]	Early	Optimum	Late			Very late		
	October	November	Early to mid-December			Late December to early January		
Resistance index[b]	Bahar	Baharan	Chamran II	Parsi	Pishgam	Pishtaz	Sirwan	Sivand
	50	50	30	60	50	60	70	0
Brown rust	Area under the brown rust progress curve				AUBRPC			
	Brown rust onset				Early and Late			
	a+b×Gauss ((x-m)/s)				Gaussian parameter (b, m and s)			
	Maximum disease over four seasons				Maximal severity ratings ranged from 30-100%			

[a]Planting dates were applied depending on environmental conditions appropriate for seeding and [b]Resistance index = 100-maximum disease severity recorded during four-year research

Table 3: Ranking the maximum severity of brown rust according to different wheat cultivars, planting dates, years, disease onset, and resistance index levels

Factors	Factor categories							
Brown rust onset	Early			Late				
Mean H = 73.46	71.13			25.80				
Chi p<0.001								
Cultivar	Bahar	Baharan	Chamran II	Parsi	Pishgam	Pishtaz	Sirwan	Sivand
Mean H = 6.45	51.00	42.64	52.00	48.43	41.55	40.79	41.29	59.93
Chi p = 0.488								
Growing season	2013-2014		2014-2015		2015-2016		2016-2017	
Mean H = 74.12	69.00		23.50		73.57		27.52	
Chi p<0.001								
Planting date	Early		Optimum		Late		Very late	
Mean H = 4.05	39.30		45.69		50.00		54.77	
Chi p = 0.056								
Resistance index	Bahar/50	Baharan/50	Chamran II/30	Parsi/60	Pishgam/50	Pishtaz/60	Sirwan/70	Sivand/0
Mean H = 5.21	44.62	44.62	52.00	44.61	44.62	44.61	41.29	59.93
Chi p = 0.266								

Rankings for maximum brown rust severity: The onset date of brown rust affected (Chi p<0.05) the maximum disease severity ratings (Table 3). The early onset of wheat brown rust intensified the disease in terms of maximum severity rating by 175.7% compared to the late disease onset (Chi p<0.001; mean H = 73.46). Cultivar, planting date, and resistance index were ineffective (Chi p>0.05) on the maximum disease severity. For the effect of growing season, rankings of maximum brown rust severity determined (Chi p<0.001 and mean H = 74.12) for 2013-2014 and 2015-2016 seasons were greater than those for 2014-2015 and 2016-2017 seasons. According to the current H-test results, such heterogeneity in the maximum disease intensity across different cultivars, planting dates, and seasons was needed to improve the predictability of the yield model.

Rankings for the Gaussian parameter (m) of brown rust progress: For the effect of brown rust onset, the ranking of Gaussian parameter (m) for the early occurrence of disease was greater (Chi p<0.001 and mean H = 78.37) than that for the late brown rust onset (Table 4). For the effect of growing season, the 2013-2014 and 2015-2016 seasons were ranked with a greater (Chi p<0.001 and mean H = 78.41) Gaussian parameter (m) compared to the remainder of the seasons. For the effect of the planting date factor, the ranking of the Gaussian parameter (m) (Chi p = 0.016 and Mean H = 10.35) increased from early planting date with the postponing of the date of planting. According to the current H-test results, such heterogeneity in the Gaussian parameter (m) of brown rust progressed across different cultivars, planting dates, and seasons was needed to improve the predictability of the yield model.

Rankings for wheat yield: Associations of wheat yield (kg/ha) with the categories of cultivar, disease onset, planting date, resistance index, and study year factors were ranked using the H-test (Table 5). For the onset of brown rust, the early disease occurrence on the cultivars improved the ranking of wheat yield by 27.0% in comparison with the late disease onset (Chi p = 0.008 and mean H = 7.02). The growing season affected (Chi p<0.001 and mean H = 36.25) the grain yield of wheat cultivars. The highest ranking of wheat yield was obtained for the first growing season (2013-14), followed by the second (2014-15), third (2015-16), and fourth (2016-17) seasons of this research. This suggested that the first year of studying the cultivars with different levels of maturity duration and disease resistance index provided the highest ranking of wheat yield, which decreased by 66.4% in the fourth year of study.

Table 4: Ranking the Gaussian parameter (m) of brown rust progress according to different wheat cultivars, planting dates, years, disease onset, and resistance index levels

Factors	Factor categories							
Brown rust onset	Early			Late				
Mean H = 78.37	71.46			25.50				
Chi p<0.001								
Cultivar	Bahar	Baharan	Chamran II	Parsi	Pishgam	Pishtaz	Sirwan	Sivand
Mean H = 2.01	49.64	46.57	47.64	51.32	38.25	46.96	46.71	50.86
Chi p = 0.959								
Growing season	2013-2014		2014-2015		2015-2S016		2016-2017	
Mean H = 78.41	70.77		25.50		72.24		25.50	
Chi p<0.001								
Planting date	Early		Optimum		Late		Very late	
Mean H = 10.35	35.12		44.06		51.44		59.20	
Chi p = 0.016								
Resistance index	Bahar/50	Baharan/50	Chamran II/30	Parsi/60	Pishgam/50	Pishtaz/60	Sirwan/70	Sivand/0
Mean H = 0.848	44.00	44.00	47.64	49.14	44.00	49.14	46.71	50.86
Chi p = 0.932								

Table 5: Ranking yield according to different wheat cultivars, planting dates, years, brown rust onset, and resistance index levels

Factors	Factor categories							
Brown rust onset	Early			Late				
Mean H = 7.02	55.28			40.36				
Chi p<0.008								
Cultivar	Bahar	Baharan	Chamran II	Parsi	Pishgam	Pishtaz	Sirwan	Sivand
Mean H = 8.97	64.29	35.57	49.21	54.43	31.30	47.21	51.50	44.29
Chi p<0.225								
Growing season	2013-2014		2014-2015		2015-2016		2016-2017	
Mean H = 36.25	67.71		59.74		41.07		25.82	
Chi p<0.001								
Planting date	Early		Optimum		Late		Very late	
Mean H = 32.93	66.67		59.30		39.33		23.43	
Chi p<0.001								
Resistance index	Bahar/50	Baharan/50	Chamran II/30	Parsi/60	Pishgam/50	Pishtaz/60	Sirwan/70	Sivand/0
Mean H = 1.88	42.17	42.17	49.21	50.82	42.17	50.82	51.50	44.29
Chi p<0.757								

Table 6: Factor analysis to characterize wheat yield in association with the progression of brown rust in different cultivars, planting date, maturity time, and resistance index

Variables	Variable categories	Principal components			
		1	2	3	4
Environment	Nd min temp 5-25°C and max RH ≥60%[a]	0.15	0.36[b]	-0.12	-0.42
	Mean six month temperature	0.26	-0.32	0.31	-0.23
Maturity duration	Nd from planting to maturity	0.29	0.44	0.13	-0.04
Planting date		0.22	0.45	0.20	0.00
Resistance index		-0.18	0.05	0.62	-0.29
Disease progress	Area under the brown rust progress curve	0.39	-0.12	-0.31	-0.12
	Brown rust onset	-0.38	0.16	-0.30	0.32
	Gaussian parameter (b)	0.07	0.07	0.40	0.56
	Gaussian parameter (m)	0.38	-0.04	0.16	0.30
	Gaussian parameters	0.35	-0.04	-0.07	0.38
	Maximum brown rust severity	0.42	-0.14	-0.23	-0.09
Yield (kg/ha)		-0.01	-0.55	0.17	-0.03
Eigenvalues		4.27	2.44	1.44	1.03
Variation (%)		35.59	20.35	12.03	8.57
Accumulated variation (%)		35.59	55.94	67.97	75.54

[a]Nd: Number of days from autumn to winter, Min temp: Minimum temperature, max RH: Maximum relative humidity and [b]Significant loadings if ≥0.35

The highest ranking of yield was obtained for early planted cultivars of wheat, followed by the optimum, late, and very late-planted cultivars (Table 5; Chi $p<0.001$ and mean H = 32.93). This observation demonstrated that the lowest ranking of wheat yield in very late planted cultivars increased by 184.6% compared to the highest ranking planted early in October over this four-season research. Very late planting of the cultivars in November reduced the ranking of wheat yield by 153.1% compared to the optimum planting date. The ranking of wheat yield was not affected (Chi $p>0.05$) by the cultivar and resistance factors (Table 5). From the present H-test results, such heterogeneity in the yield levels across different cultivars, planting dates, and seasons was needed to improve the predictability of wheat yield modeled based on the disease and agro-ecological descriptors.

Factor analysis: The four principal factors of FA accounted for 75.5% of the variance in data on cultivar resistance, maturity duration, planting date, air temperature-RH, brown rust progress and wheat yield studied at four different planting dates and years (Table 6). The first principal factor accounting for 35.6% of the data variance provided the highest loading value for maximum brown rust severity (0.42), followed by the AUBRPC variable (0.39). Furthermore, variables of brown rust onset and Gaussian parameters (m) and s contributed to the first principal factor. The yield variable was linked with the highest loading value (-0.55) to the second principal factor, which accounted for 20.4% of data variance. The temperature-RH, maturity duration, and planting date also contributed directly to this factor. The resistance index and Gaussian parameter (b) contributed directly to the third principal factor, justifying 12.0% of data variance. The fourth principal factor, accounting for 8.6% of variance, received reverse and direct contributions of the temperature-RH variable and Gaussian parameters, respectively.

Therefore, this factor analysis demonstrated the significant associations of brown rust progress variables (the first principal factor), wheat yield with environment, maturity and planting date (the second principal factor), brown rust progress with resistance index (the third principal factor), and environment with brown rust progress (the fourth principal factor). This suggested that the environment variable was linked more closely to wheat yield (the second factor) compared to the progression of brown rust (the fourth factor) in different cultivars. The two crop variables of maturity and planting date were linked significantly to wheat yield (the second factor). Furthermore, the other variable of wheat crop, which has been defined as the resistance index, was linked significantly to brown rust progress (the third factor).

Table 7: Linear regression modeling wheat yield (kg/ha) according to factor analysis of predictors of brown rust progress, cultivar resistance, environment, maturity duration, and planting date (R^2 = 94%; p<0.001)

Variables	Parameter estimates	Standard errors	t-probability
Maturity duration	42.73	3.23	<0.001
Maximum brown rust severity	32.35	7.17	<0.001
Nd min temp 5-25°C and max RH ≥60%[a]	-72.60	15.00	<0.001
Planting date	-1352.00	170.00	<0.001
Resistance index	25.73	8.51	0.003

[a]Nd: Number of days from autumn to winter, Min temp: Minimum temperature and max RH: Maximum relative humidity

Regression modeling of wheat yield: Table 7 presents the results of a linear regression model predicting wheat yield (kg/ha) based on key factors influencing brown rust development, cultivar resistance, and agronomic variables. The model shows a strong fit (R^2 = 94% and p<0.001). Wheat yield increased significantly with longer maturity duration (42.73±3.23) and higher resistance index (25.73±8.51), while it decreased with delayed planting date (-1352.00±170.00) and an increased number of days with minimum temperature between 5-25°C and maximum relative humidity ≥60% (-72.60±15.00). Maximum brown rust severity was also positively associated with yield (32.35±7.17), possibly reflecting cultivar tolerance under managed conditions.

DISCUSSION

These findings improved the accuracy of yield estimations based on a manageable number of influential properties of the wheat farming system attacked by different levels of brown rust epidemics. Furthermore, the diversity of brown rust progress curves developed across wheat cultivars with different levels of resistance index was maximized to enhance the predictability of specific disease variables. We already know it well[2,7] that such a high diversity in disease spread across experimental fields provides a more concise description of wheat damage due to brown rust development. Although our previous study explained 41% of the variability in wheat yield data according to specific predictors of powdery mildew and rusts progress, adding effective agro-ecological variables to the specific predictor of brown rust progress increased the descriptive potential of the present yield model to 94%. This remarkable improvement in estimating wheat yield might be attributed to the noticeable association of yield not only with the disease intensity but also with the cultivar resistance, maturity duration, planting date, and weather. Although some earlier reports estimated wheat yield according to brown rust besides agro-ecological predictors[4,9], this seems to be the first report of wheat yield modeled according to such a wisely selected array of epidemiological and agro-ecological variables. These variables, which represented different aspects of the wheat production system, were examined step by step for their predictive values[1,2,7]. For instance, the current H-tests provided valuable information on brown rust onset, growing season, and planting date rankings according to the disease severity, Gaussian parameter (m), and wheat yield. The current findings demonstrated the magnitude of planting date treatment, the disease onset, and growing season factors impacting brown rust and wheat yield, which were needed for performing more advanced statistical analyses, the FA, and modeling.

Considering the five epidemiological and agro-ecological variables used to model wheat yield, higher yield levels corresponded unexpectedly with more severe brown rust epidemics. This unexpected observation might be attributed to the complicated relationships among the variables of cultivar resistance, maturity duration, maximum brown rust severity, planting date, and weather. According to an earlier report by Naseri[7], the Gaussian parameters (b and s) estimated for brown rust progress were negatively linked to wheat yield. This reverse relationship between wheat yield and brown rust epidemics was determined based on the joint analysis of four major diseases, powdery mildew and black-brown-yellow rusts. Therefore, the involvement of agro-ecological variables as representing diverse aspects of this cropping system may have diverted the reverse interaction of brown rust with yield, as reported similarly for other pathosystems[2,10].

According to Sabouri *et al.*[11], brown rust progress has been associated with air temperature, high RH, initial inoculum, and susceptibility of wheat cultivar. Moreover, the progression of brown rust in wheat begins at a mild temperature ranging within 22-24°C and a high RH (70-80%). Thus, with a rising air temperature and moisture (3-4 hrs of leaf wetness), latent and infectious periods of brown rust were shortened on susceptible wheat cultivars, resulting in fast disease progress[11]. Mabrouk *et al.*[6] added brown rust progress descriptors for slow rusting in 12 promising lines and varieties. A recent finding by Naseri and Sasani[1] advanced our understanding of brown rust progress influenced by the cultivar resistance, disease onset, maturity duration, number of days with 5-25°C minimum temperature and maximum RH above 60% during the first and second months of spring, and planting date. One may conclude that air temperature and wetness affected brown rust development at all the four planting dates examined in this research. Another finding which should be noted here is the noticeable association of maturity duration with brown rust progress in wheat. However, all these earlier reports ignored a joint analysis of specific disease predictors along with agronomic and environmental variables to improve the accuracy of yield estimates. Thus, the current findings assist with breeding more stable and adaptable wheat cultivars planted at the appropriate time for more durable resistance to brown rust and high productivity in sustainable agriculture.

Wolffgang[12] found that the number of *P. recondita* f. sp. *tritici* pustules per leaf corresponded with cultivar resistance. Later, Iqbal *et al.*[13] confirmed that slow rusting of wheat cultivar resulted in smaller and lesser number of brown rust pustules. This slow rusting response to brown rust progress remained stable during all three trials[13]. Furthermore, some wheat lines/cultivars rusted fast under appropriate environmental conditions and probably lacked resistance to brown rust. Late-planted lines and varieties in the third trial with lesser units of AUBRPC produced lower yields. Thus, Mabrouk *et al.*[6] advised that slow rusting resistant lines and varieties provide a good potential for developing high-yielding varieties with more durable resistance to wheat brown rust. Recently, Mapuranga *et al.*[14] reviewed the bilateral linkages of genetic resistance to wheat rusts with planting date and environment. The current FA results added to our understanding that the linkage of brown rust progress with the resistance index (third principal factor) was more notable than that with the environment (fourth principal factor). Moreover, the resistance index was linked to the Gaussian parameter (b), which defines the height of the curve's peak, whereas the environmental variable of air temperature-RH corresponded with the Gaussian parameter (s), defining the width of the Gaussian curve. In other words, the third principal factor indicated that a greater resistance index resulted in a higher peak of the brown rust progress curve. The fourth principal factor showed that fewer temperate and moisty days during the first and second months of spring corresponded with a wider Gaussian bell. The second principal factor signified the interactions of a late planting date, long maturity period, and further temperate and moist days in spring, with a low yield of wheat.

CONCLUSION

This study presents the first integrated analysis of wheat yield about brown rust progress, cultivar resistance, maturity duration, planting date, and environmental factors. The findings highlight that early planting, longer maturity periods, fewer moist and temperate spring days, and higher resistance indices significantly enhance wheat yield. The strong relationships identified through factor and regression analyses improve our understanding of the dynamics influencing yield and rust severity. These insights are valuable for forecasting brown rust outbreaks and guiding breeding programs toward more resistant and high-yielding cultivars. The observed interactions provide a foundation for future research targeting the underlying mechanisms.

SIGNIFICANCE STATEMENT

This study identified key predictors of wheat yield, including planting date, cultivar resistance to brown rust, maturity duration, and environmental factors, which could be beneficial for improving yield forecasting, disease management strategies, and cultivar selection. This study will assist researchers in uncovering critical areas of interaction between host resistance, planting practices, and climatic variables that have remained unexplored by many. Consequently, a new theory on integrated yield-disease-environment modeling in wheat may be developed.

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