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ORIGINAL PAPER

Determining the impact of stripe rust and leaf rust on grain yield and yield components' losses in Indian wheat cultivars

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Abstract

Rust diseases continue to cause economic losses to wheat production worldwide. Host-plant resistance significantly non-race-specific or combining race-specific and non-race-specific resistance is the most efficient, economic and ecofriendly way to control wheat rusts, besides eliminating the use of fungicides. Evidence on the effects of race-specific and non-race-specific resistance categories on stripe rust caused by *Puccinia striiformis* Westend. f. sp. *tritici* Eriks. and Henn and leaf rust (*Puccinia triticina*) development and in defending yield component losses in Indian wheat cultivars is still limited. Experiment was conducted to study the impacts of stripe rust and leaf rust on grain yield and yield components of some Indian wheat cultivars under artificial epiphytotic conditions. Cultivars with highly effective adult plant resistance to stripe rust viz. HD 2733, HD 2967, HD 3263, HS 562, NIAW 34, HI 1621, DBW 187, HD 3226, VL 829, VL 829, C 306, HD 3086, and NI 5439, and HD 3086, HD 3226, HI 1620, DBW 187, WH 1124, HI 1628, HS 562, RAJ 4496, MACS 6222, and VL 907 for resistance to leaf rust exhibited low values of epidemiological parameters as well as low yield components' losses despite moderate disease levels might possessing APR gene(s). In this study, cultivars having slow rusting resistance with low values of epidemiological parameters were identified. These cultivars can be best utilized in varietal development programs to get improved varieties with high levels of durable resistance against novel virulent races of leaf rust.

Keywords Durable resistance · Epidemiological parameters · *Yr* · *Lr* genes · Pathotypes

Introduction

The rusts are historical yield constraints in wheat in Asia and elsewhere (Sendhil et al. 2022). Through the emergence of newer and more virulent race of rust pathogens, the prevalent pathotypes are being substituted with the existing pathotypes, which may result in extensive and widespread epidemics (Rahmatov et al. 2017; Ali et al. 2022). Among the three rusts, a significantly higher yield reduction is currently caused by stripe rust or yellow rust caused by *Puccinia striiformis* Westend. f. sp. *tritici* Eriks. and Henn (Chen et al. 2014; Chen 2020). Leaf rust caused by *Puccinia triticina* is the most widely distributed of the rusts also causes significant losses (Huerta-Espino et al. 2011; Singh et al. 2014; Bhavani et al. 2022). Losses due leaf rust and stripe rust are largely due to infection of the flag leaf, which contributes most to grain formation and grain filling. Yield losses caused by these diseases have been estimated at 10–70% in individual fields, but in exceptional cases, grain loss can be as high as 100% (Chen 2005, 2020; Ordonez et al. 2010). Global wheat yield losses due to stripe rust of about 5.5 mt per year were estimated (Beddow et al. 2015).

In recent past, localized stripe rust epidemics with significant crop losses were reported from different major wheat growing areas of the world, in addition to African and Central Asian regions (Ezzahiri et al. 2009; Rahmatov

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et al. 2012; Singh et al. 2016; Chen 2020). In the past few years, increased incidences of stripe rust have been reported with greater reoccurrence (Wellings 2007; Hovmøller et al. 2008, 2016; Chen 2020), which was mainly due to the higher and faster growth rates in the population of rust pathogens (Hovmøller and Justesen 2007), long-distance spore spreading (Zadoks 1961; Brown and Hovmøller 2002) and development of novel pathotypes (Rodriguez-Algaba et al. 2014; Rahmatov et al. 2017; Gangwar et al. 2019). In India, stripe rust has gained importance in recent past especially in cooler parts and is a threat in 10 mha area under Northern parts (Prashar et al. 2015; Bhardwaj et al. 2019). Occurrence of stripe rust in severe form was due to evolution of new and virulent pathotypes, which were able to overcome widely used resistance in wheat (Prashar et al. 2007; Gangwar et al. 2019; Srinivas et al. 2021). During the emergence of virulence (46S119) for *Yr*9, and virulence (78S84) for *Yr*9 and *Yr*27 in year 1960 and 2001, respectively led to susceptibility of the widely grown cultivar PBW 343 (Prashar et al. 2007).

Stripe rust in severe form has been reported from plains of Jammu and Kashmir, foothills of Punjab, Himachal Pradesh and tarai of Uttarakhand (Sharma and Saharan 2011). In 2014–15, yellow rust was noticed on some popular wheat cultivars grown under plains of J and K, foothills of HP, Haryana, Punjab, tarai of UK and western UP, but the incidence was quite low (Saharan et al. 2015). Recently, five new *P. striiformis tritici* pathotypes, 46S117, 110S119, 238S119, 110S247 and 110S84 were identified in India, which showed virulence on lines with genes *Yr*11, *Yr*12 and *Yr*24 gene (Gangwar et al. 2016). Race 110S119 is considered the most dominant, aggressive and rapid population builds up ability (Gangwar et al. 2016). Similarly, the present *Puccinia triticina* pathotypes, 77-9 (121R60-1), 77-5 (121R63-1), and 104-2 (21R55) are most prevalent and widely virulent variants isolated from the present-day Indian wheat cultivars (Bhardwaj et al. 2019).

Although various strategies are available to combat rust pathogens, host resistance is considered the most economic method to curb wheat rusts (Singh et al. 2005; Van der Plank 1963; Bhardwaj et al. 2021). Fast evolution of new virulences of the pathogen due to mutation and somatic recombination makes cultivars with all-stage resistance become susceptible very rapidly (Line and Qayoum 1992a, b; McIntosh et al. 1998; Wan and Chen 2012; Bhardwaj et al. 2019). In India, it has been observed that the commercially grown rust resistant wheat varieties loses their effectiveness just after 3–5 years of their release (Rao et al. 1981). In recent past, most of the cultivars deployed with major gene for rust resistance have frequently become ineffective, because seedling resistance is mainly governed by single *R*-genes based resistance. On the contrary, non-race-specific is mainly polygenic, durable, often quantitatively inherited (Singh et al. 2004; Herrera-Foessel et al. 2011; Bhardwaj et al. 2021). 83 officially named genes, 67 temporarily designated resistance genes, and over 300 quantitative trait loci (QTL) for stripe rust resistance have been reported So far, out of these, only nine genes *Yr*18, *Yr*29, *Yr*30, *Yr*36, *Yr*39, *Yr*46, *Yr*48, *Yr*49 and *Yr*52 are associated with non-race-specific/adult plant resistance (McIntosh et al. 2012; Chen and Kang 2017). Nearly 100 genes including alleles conferring leaf rust resistance genes have been known and defined (McIntosh et al. 2017). Majority of the designated *Lr* genes are conferring race-specific resistance (seedling stage) and stay operative across the adult plant stage. Among the race-specific genes, some genes, *Lr*12, *Lr*13, *Lr*21, *Lr*22, *Lr*35, *Lr*37, *Lr*48, *Lr*49, *Lr*74, *Lr*75 and *Lr*77 are race-specific APR genes. Only four *Lr* genes, *Lr*34, *Lr*46, *Lr*67 and *Lr*68 are reported to confer adult plant resistance.

To characterize and identify effective resistant sources which are more suitable to cultivate in the disease prone areas of the country, screening and phenotyping genotypes for rust resistance is considered the finest and inexpensive way. In many cereals-rust pathosystems, the quantitative aspects of host resistance have been described and estimated by means of host response and different epidemiological parameters (FRS, CI, AUDPC and r) and values of other slow rusting parameters at a particular crop growth stage (Pathan and Park 2006; Shah et al. 2014; Singh et al. 2015, 2017). Currently, major emphasis is given to develop cultivars with non-race-specific or by combining race-specific and non-race-specific resistance that offers more effective and durable control against rust pathogens. Also, evidence on the influence of above two dissimilar resistance categories on rust development and in defending yield components in Indian wheat material is still limited. Therefore, the association among rust diseases, crop yield and resulting losses in relation with cultivars having different types of rust resistance needs to be studied.

Materials and methods

Field trials were carried out to study the impact of stripe and leaf rust on grain yield and yield component of some Indian wheat cultivars having different resistance types (race-specific and non-race-specific) in the field under artificial epiphytotic conditions at wheat rusts experiment farm of ICAR-IARI, New Delhi. Two separate sets of 21 Indian wheat cultivars including two susceptible checks were used for each rust used (Table 1). The individual variety per set were considered based on their genetic background and seedling response with six virulent and most predominant pathotypes, viz. 47S103, 46S119, 110S119, 78S84, 110S84 and 238S119 of *P. striiformis tritici*, and four virulent and most prevalent pathotypes, viz. 12-5 (29R45), 77-5

Table 1 Genotypes used for yield loss studies and postulated *Yr* and *Lr* genes

Entry no	Cultivar	*Yr* gene(s)	Cultivar	*Yr* gene(s)
1	HS 628	*R*	HI 1531	*Lr*24+*R*
2	PBW 725	*R*	HI 1544	*Lr*24+*R*
3	PBW 752	*R*	HW 2040	*Lr*24+*R*
4	PBW 756	*R*	MACS 6222	*R*−
5	HD 3086	*Yr*9+A+	HD 2733	*Lr*26+34+
6	HD 3226	*Yr*2+	HD 2967	*Lr*23+1+
7	HI 1620	*Yr*A+	HD 3263	*Lr*13+
8	DBW 187	*Yr*2+	HS 562	*Lr*23+10+
9	WH 1124	*Yr*2+	NIAW 34	*Lr*34+
10	HI 1628	*Yr*2+	HI 1621	*Lr*13+1+
12	HS 562	*Yr*A+	DBW 187	*Lr*23+10+
13	RAJ 4496	*Yr*A+	HD 3226	*Lr*23+10+
14	MACS 6222	*Yr*9+27+	VL 829	*Lr*26+34+
15	VL 907	*Yr*9+18+	C 306	*Lr*34+
16	NIAW 34	*Yr*18+	HD 3086	*Lr*23+10+3+
17	NIAW 1415	*Yr*9+	NI 5439	*Lr*34+
18	NI 5439	*Yr*2+18+	WH 1124	*Lr*13+10+
19	HD 2967	*Yr*2+	VL 907	*Lr*26+34+
20	C 306	*Yr*18+	HD 3043	*Lr*26+23+1+
21	Local Red	*S*	Local Red	*S*
22	A-9-30-1	*S*	Agra Local	*S*

Stakman et al. (1962), with modifications (Bhardwaj et al. 2010) Resistant (*R*), Susceptible (*S*)

(121R63-1), 77-9 (121R60-1) and 104-2 (21R55) of *P. triticina*, respectively. The inferred presence of *Yr* and *Lr* gene(s) and seedling response of cultivars with above mentioned rust pathotypes were taken into consideration from the seedling stage resistance evaluation tests conducted in the present investigations (ST 3 and 5).

They were divided into two groups, viz. protected (disease free) and infected (diseased) in randomized block design (RBD) with three replications. Sowing took place on 24th of and 25th November 2018 and 2019, respectively. Plot size of 7.5 m^2 (3×2.5 m) was sown with row-to-row distance of 25 cm. Plots were spaced at 50 cm. The irrigation channels were made in space between replicates. The recommended agronomic package and practices were strictly followed to maintain the uniform stand of crop.

In Infected (diseased) conditions, the experimental block was surrounded by 2 rows of the mixture of highly susceptible wheat cultivars (Local Red, Agra Local, A-9-30-1) to provide high and uniform disease pressure in field. The urediniospores inoculum comprised mixtures of the above Pst. *striiformis tritici*, and Pt. The susceptible infection rows were injected with urediniospores suspended in water (106 spores/ml). The disease free plots were protected by 0.1% Difenoconazole 25EC applied four times at 15 days intervals, starting 24th of December 2018 and 25th of December 2019 in each year.

Disease severity was recorded six times at weekly intervals and final disease severity (FDS) was taken for stripe rust on 5th and 7th of March in each year 2018–19 and 2019–20, and for leaf rust on 28th and 31st of March in each year 2018–19 and 2019–20. Recording of disease severity was started when susceptible checks reached 25–30% severity from individual cultivar/plot in all the replications according to the modified Cobb scale (Peterson et al. 1948), and the response of individual cultivar referred to the adult plant infection types (ITs) were categorized as resistant (*R*), moderately resistant (MR), moderately susceptible (MS) and susceptible (*S*) reactions based on Roelfs et al. (1992). Coefficient of infection (CI) was calculated by multiplying disease severity and constant values of infection type, which was used for estimating AUDPC and apparent infection rate (r). The constant values for infection types were used based on, Immune = 0, $R = 0.2$, MR = 0.4, $M = 0.6$, MS = 0.8, $S = 1$ (Stubbs 1986). Area under the disease progress curve (AUDPC) and relative area under the disease progress curve (rAUDPC) for rust development on each cultivar/plot was calculated from multiple disease severity readings using the following formula (Milus and Line 1986). Apparent infection rate (r) was also estimated in terms of disease severity recorded on cultivar at different times by using the following formula (Van der Plank 1963).

$$\text{AUDPC} = \frac{N_1\left(X_1 + X_2\right)}{2} + \frac{N_2\left(X_2 + X_3\right)}{2}$$

where X_1, X_2 and X_3 = disease severity recorded on the first, second and third scoring dates, respectively. N_1 = the interval day between X_1, X_2 and N_2 = the interval day between X_2, X_3.

$$\text{rAUDPC} = \frac{\text{line/genotype AUDPC}}{\text{susceptible AUDPC}} \times 100$$

$$r = \frac{1}{t_2 - t_1}\left(\log_e \frac{X_2}{1 - X_2} - \log_e \frac{X_1}{1 - X_1}\right)$$

where X_1 = the rust disease severity recorded at date t_1, X_2 = the rust disease severity recorded at date t_2 and $t_2 - t_1$ = the interval in days between these dates.

After maturity of crop, the individual cultivar per plot from both infected and protected conditions was harvested separately and spike was threshed separately by using electric operated plot thresher in the month of April each year. Grain weight from threshed spikes was measured with an electronic balance to calculate grain yield per plot for each cultivar. As this disease result into shrivelling of grains also, therefore randomly selected 1000 grains from each cultivar was also counted with a seed counter and weighed with an electronic balance to calculate thousand grain weight (TGW) (Herrera-Foessel et al. 2006, Shehab-Eldeen and Abou Zeid 2020). Yield loss assessment was made by comparing the yield difference of each cultivar in infected (diseased) and protected (disease-free) conditions.

Statistical data analysis was done to determine the significance of the differences among the cultivars for adult plant resistance parameters and grain yield and yield components' losses. Duncan's post-hoc tests were performed to make multiple correlation comparisons. In addition, Pearson correlation coefficient matrices were also calculated to look at the multiple bivariate correlations between different adult plant slow rusting resistance parameters and grain yield and yield components' losses using SPSS software (version 16.0).

Results

Stripe rust

Impact of stripe rust infection on yield and grain yield components in 21 Indian wheat cultivars with different resistance types were studied in field conditions. Data analysis and mean comparison evidently showed that different groups of cultivars (different resistance types) were significantly different based on adult plant slow rusting resistance parameters during both 2018–19 and 2019–20 (Tables 2). The analysis of variance revealed that cultivars had significant difference in terms of all the adult plant slow rusting resistance parameters (FDS, CI, rAUDPC and *r*), 1000-grain weight (gm) and grain yield (kg/plot) in protected and infected plots (Table 2). The analysis of data and comparison of mean values also revealed that stripe rust infection significantly affected yield and grain yield components of all groups/categories/types of resistance in Indian wheat cultivars (Table 3) that are described in the following sections:

Group with race-specific seedling resistance

This group comprised of four cultivars HS 628, PBW 725, PBW 752 and PBW 756 possessing race-specific seedling resistance to stripe rust. (Supplementary table 1) During *rabi* season 2018–19, this group of cultivars, namely HS 628, PBW 725, PBW 752 and PBW 756 showed the least values of different adult plant slow rusting resistance parameters (Supplementary table 3). Cultivars in this group exhibited resistant '*R*' infection type at adult plant stage with least stripe rust infection (0.66–6.66%). The yield components were the least in this group in comparison with other groups having adult plant slow rusting resistance and susceptible '*S*' reaction to stripe rust (Figs. 1, 2). Mean losses of 1000-grain weight (gm) and grain yield (kg/plot) for this race-specific seedling resistance group of cultivars were 2.49 and 3.83%, respectively. During *rabi* season 2019–20, similar pattern was observed, as this group showed least values of APR parameters and resistant '*R*' adult plant infection type with lowest disease (0.66–3.33%) (Supplementary table 3). The yield components' losses were the least in this group in comparison with other groups having APR and susceptible '*S*' reaction to stripe rust (Figs. 1, 2). Mean losses of 1000-grain weight (gm) and grain yield (kg/plot) for this group were 1.95 and 3.24%, respectively.

Table 2 Analysis of variance for APR parameters and grain yield components in infected and protected plots of 21 wheat cultivars to stripe rust (*rabi* 2018–19)

Source of variation	D.f	Mean squares for adult plant slow rusting resistance parameters and grain yield components*							
		Protected plots						Infected plots	
		FDS	CI	rAUDPC	*r*	TKW	Yield	TKW	Yield
Cultivars	20	2624.61**	2961.54**	3015.38**	0.045**	11.58**	1.54**	120.05**	3.46**
Replications	2	71.04	55.98	2.44	0.004	8.05	0.42	18.36	0.54
Cultivars × Replications	40	27.48	20.34	9.00	0.001	6.16	0.10	5.13	0.10
Error	62	866.67	970.26	978.58	0.014	7.97	0.45	42.62	1.20
Analysis of variance for APR parameters and grain yield components in infected and protected plots of 21 wheat cultivars to stripe rust (2019–20)									
Cultivars	20	2527.27**	2721.56**	2893.34**	0.043**	11.96**	1.15**	115.53**	3.44**
Replications	2	58.85	44.29	3.10	0.003	33.08	0.42	13.16	0.39
Cultivars × Replications	40	26.19	20.15	8.65	0.003	4.91	0.10	5.39	0.10
Error	62	834.04	892.58	939.02	0.015	8.09	0.45	41.17	1.19

FDS = final disease severity; CI = coefficient of infection; rAUDPC = relative Area under the disease progress curve; *r* = Apparent infection rate; TKW = thousand grain weight (gm); Yield, grain yield (kg/plot), D.f. = degrees of freedom; **, * $P < 0.01$, $P < 0.05$

Table 3 Correlation coefficients between different APR parameters and yield components losses for stripe rust across 21 Indian wheat cultivars (*rabi* 2018–19)

Parameter*	Parameter*					
	FDS	CI	rAUDPC	*r*	TGW (% loss)	Grain yield (% loss)
FDS	–					
CI	0.994**	–				
rAUDPC	0.981**	0.979**	–			
R	0.927**	0.911**	0.976**	–		
TGW (% loss)	0.833**	0.843**	0.884**	0.854**	–	
Grain yield (% loss)	0.837**	0.859**	0.913**	0.857**	0.998**	–
Correlation coefficients between different APR parameters and yield components losses for stripe rust across 21 Indian wheat cultivars (*rabi* 2019–20)						
FDS	–					
CI	0.997**	–				
rAUDPC	0.986**	0.979**	–			
R	0.929**	0.913**	0.925**	–		
TGW (% loss)	0.866**	0.876**	0.895**	0.816**	–	
Grain yield (% loss)	0.868**	0.884**	0.918**	0.818**	0.998**	–

*FDS = final disease severity; CI = coefficient of infection; rAUDPC = relative Area under the disease progress curve; *r* = Apparent infection rate; TKW = thousand grain weight (gm); Yield, grain yield (kg/plot), D.f. = degrees of freedom; **, * $P<0.01$, $P<0.05$

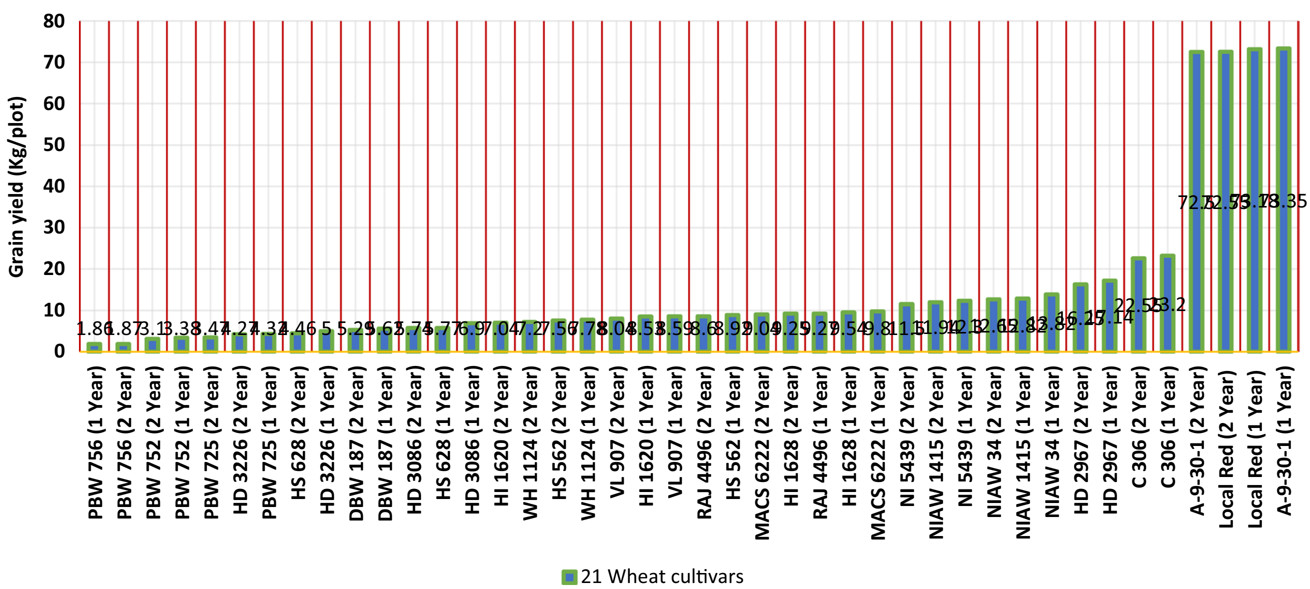

Fig. 1 Comparison of losses for grain yield components in infected and protected conditions of 21 Indian wheat cultivars having different resistance types to stripe rust (2018–20)

Groups with non-race-specific/adult plant slow rusting resistance

Based on the statistical data analysis, susceptibility levels of different Indian wheat cultivars showed significant differences during both 2018–19 and 2019–20. The analysis of data indicated that cultivars were grouped into three categories based on the values of adult plant resistance parameters (FDS, CI, rAUDPC and *r*). The effect of these three groups on yield and grain yield components were significantly different during both years (Tables 2,3).

Category 1: high level of adult plant slow rusting resistance This group comprised of seven cultivars, viz. HD 3086, HD 3226, HI 1620, DBW 187, WH 1124, HI 1628 and HS 562. This group of cultivars were susceptible at seedling

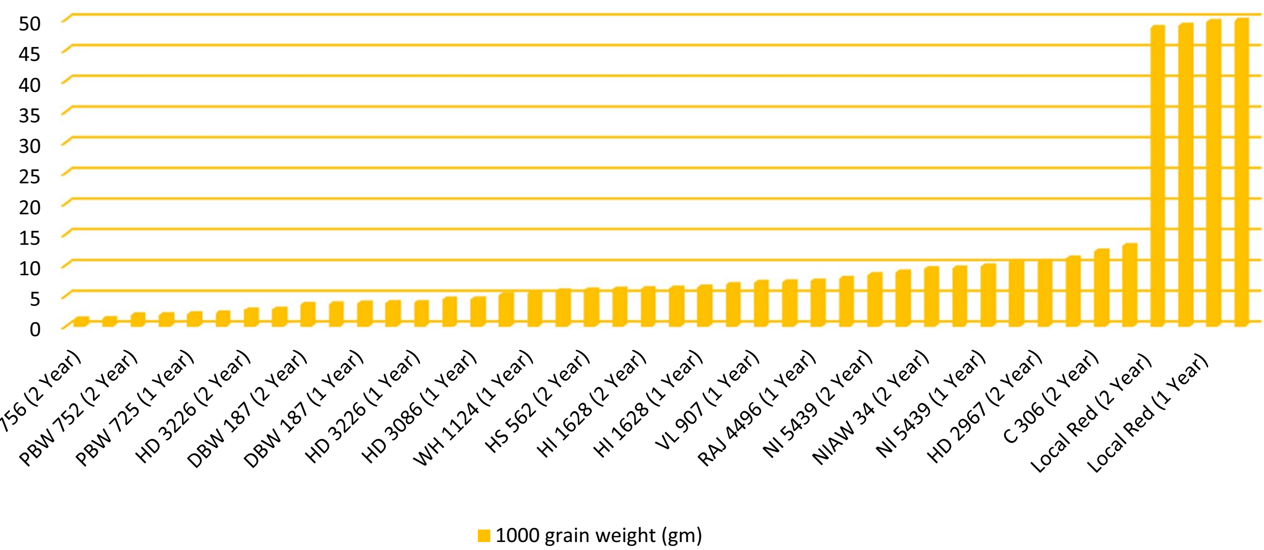

Fig. 2 Comparison of losses for grain yield components in infected and protected conditions of 21 Indian wheat cultivars having different resistance types to stripe rust (2018–20)

stage evaluation tests against six most prevalent and virulent stripe rust pathotypes (Supplementary table 3). According to Pathan and Park (2006), cultivars with CI values of 0–20 are regarded as possessing high levels of adult plant slow rusting resistance. During *rabi* 2018–19, cultivars in this group exhibited moderately resistant 'MR' to moderately susceptible 'MS' infection types at adult plant stage with FDS up to 23.33%, CI values up to 18.66 and *r* values up to 0.07. This group had rAUDPC values up to 13.19% of the susceptible check (Fig. 1 and Supplementary table 3). On the basis of rAUDPC values, cultivars were categorized into two distinct groups according to (Ali et al. 2007). The first group included the cultivars exhibiting rAUDPC values up to 30% of the susceptible check, while the cultivars showing rAUDPC values up to 60% of susceptible check were placed in another group. The cultivars in first group were marked as having high level of APR and that of another group were marked as having moderate level of APR. Mean losses of TGW (gm) and grain yield (kg/plot) in this group were 5.22 and 7.59%, respectively (Figs. 1, 2 and Supplementary table 4). During *rabi* season 2019–20, similar pattern was observed, as values of all adult plant slow rusting resistance parameters were at low level compared to other groups/categories, viz. category-2 and 3 (Figs. 1, 2 and Supplementary table 3, 4).

Category 2: moderate/medium level of adult plant slow rusting resistance This category comprised of 3 cultivars RAJ 4496, MACS 6222 and VL 907. During 2018–19, this group of cultivars exhibited CI values of 24–32, FDS values of 30–40%, rAUDPC values of 16.16–21.7% of susceptible check and *r* values of 0.08–0.09, which were marked as having moderate/medium level of adult plant slow rusting resistance (Supplementary table 3). In this group, values of all APR parameters were more than category-1, but it was less than category-3 compared to the susceptible checks. Mean losses of TGW (gm) and grain yield (kg/plot) were 9.98 and 13.19%, respectively (Figs. 1, 2 and Supplementary table 4). Similar pattern was also observed during second year (2019–20) of field experiment (Figs. 1, 2 and Supplementary table 4).

Category 3: low level of adult plant slow rusting resistance The cultivars NIAW 34, NIAW 1415 and NI 5439 are included in this group. This group of cultivars was susceptible at seedling stage against six most prevalent and virulent stripe rust pathotypes (Table 1, Supplementary table 1). During *rabi* season 2018–19, cultivars in this group showed susceptible infection types at adult plant stage with high level of FDS up to 53.33%, CI values up to 53.33, rAUDPC values up to 48.4 and *r* values up to 0.19, and the highest reductions for TGW and yield compared with the other cultivars of category-1 & 2 (Supplementary table 3). This group showed high level of epidemiological parameters and were marked as having low level of adult plant slow rusting resistance. Mean losses of 1000-grain weight (gm) and grain yield (kg/plot) were 9.98 and 13.19%, respectively, which was high than the above two categories and less than the susceptible group and susceptible checks (Figs. 1, 2 and Supplementary table 4). During *rabi* season 2019–20, similar pattern was also observed, as the values of all the adult plant slow rusting resistance parameters were at high level compared to other two categories (category-1 and category-2), but at low level than susceptible group and susceptible checks (Figs. 1, 2 and Supplementary table 4).

Susceptible group The cultivars HD 2967 and C 306 are included in this group. These cultivars were susceptible at the seedling stage against six most prevalent and virulent stripe rust pathotypes (Table 1, Supplementary table 1). During *rabi* 2018–19, cultivars in this group exhibited high values of epidemiological parameters, FDS up to 73.33%, CI values up to 73.33, rAUDPC values up to 65.98 and *r* values up to 0.24. In this group, the values of all adult plant slow rusting resistance parameters were high than the above three categories, but low than the susceptible checks. During *rabi* 2019–20, the similar pattern of epidemiological parameters was observed on the cultivars in this susceptible group (Figs. 1, 2 and Supplementary table 4).

Association between APR parameter and yield components

In this present investigation, the relationship between different adult plant slow rusting resistance parameters and yield components' losses for stripe rust across 21 Indian wheat cultivars/varieties including two susceptible checks was studied. During *rabi* season 2018–19, positive correlation of FDS was observed with CI, rAUDPC and *r* with a strong R^2 value that was 0.994, 0.981 and 0.927, respectively (Table 3). The highest correlation coefficient was accomplished between FDS, rAUDPC and CI ($R^2=0.994$) and the lowest R^2 value was between CI and *r* ($R^2=0.911$). Positive correlation was also observed between adult plant slow rusting resistance parameters and grain yield components' losses. The highest correlation coefficient was observed between rAUDPC and grain yield losses ($R^2=0.913$) and the lowest correlation was between FDS and TGW losses ($R^2=0.833$). The correlation coefficient between grain yield components' losses was also significant. During *rabi* season 2019–20, similar pattern of positive correlation coefficient was also observed (Table 3).

Leaf (brown) rust

The effect of leaf rust disease on yield and grain yield components' losses in 21 Indian wheat cultivars/varieties having different resistance types (race-specific and non-race-specific) were studied in field conditions. Data analysis and mean comparison clearly indicated that different groups of cultivars (different resistance types) were significantly different based on all the adult plant slow rusting resistance parameters during both *rabi* seasons, 2018–19 and 2019–20 (Tables 4, 5). The analysis of variance revealed that cultivars had significant difference in terms of all the adult plant slow rusting resistance parameters (FDS, CI, rAUDPC and *r*), 1000-grain weight (gm) and grain yield (kg/plot) in protected and infected conditions. (Tables 4). The analysis of data and comparison of mean values also revealed that leaf rust infection significantly affected the yield and grain yield components of all groups/categories/types of resistance in Indian wheat cultivars (Table 5) that are described in the following sections:

Table 4 Analysis of variance for APR parameters and grain yield components in infected and protected plots of 21 wheat cultivars to leaf rust (2018–19)

Source of variation	D.f	Mean square value for adult plant slow rusting resistance parameters and grain yield components*							
		Protected plots						Infected plots	
		FDS	CI	rAUDPC	*r*	TKW	Yield	TKW	Yield
Cultivars	20	2351.06**	2619.39**	2662.04**	0.042**	10.12**	1.11**	109.96**	3.05**
Replications	2	22.68	6.06	16.73	0.001	11.79	0.26	3.57	0.81
Cultivars × Replications	40	29.08	21.24	3.58	0.003	5.45	0.12	5.86	0.08
Error	62	777.90	858.86	861.57	0.015	7.16	0.43	39.37	1.06
Analysis of variance for APR parameters and grain yield components in infected and protected plots of 21 wheat cultivars to leaf rust (*rabi* 2019–20)									
Cultivars	20	2341.81**	2520.16**	2717.23**	0.040**	11.71**	1.25**	107.79**	3.13**
Replications	2	30.61	21.74	4.36	0.004	13.44	0.26	26.60	0.17
Cultivars × Replications	40	30.38	21.92	2.71	0.002	5.37	0.10	4.71	0.11
Total error	62	776.01	827.80	878.41	0.014	7.68	0.48	38.67	1.09

*FDS = final disease severity; CI = coefficient of infection; rAUDPC = relative Area under the disease progress curve; *r* = Apparent infection rate; TKW = thousand grain weight (gm); Yield, grain yield (kg/plot), D.f. = degrees of freedom; **, *$P<0.01$, $P<0.05$

Table 5 Correlation coefficients between different APR parameters and yield components losses for leaf rust across 21 Indian wheat cultivars (*rabi* 2018–19)

Parameters*	Parameters*					
	FDS	CI	rAUDPC	*r*	TGW (% loss)	Grain yield (% loss)
FDS	–					
CI	0.991**	–				
rAUDPC	0.982**	0.981**	–			
R	0.918**	0.908**	0.934**	–		
TGW (% loss)	0.881**	0.888**	0.828**	0.835**	–	
Grain yield (% loss)	0.881**	0.889**	0.931**	0.838**	0.999**	–
Correlation coefficients between different APR parameters and yield components losses for leaf rust across 21 Indian wheat cultivars (*rabi* 2019–20)						
FDS	–					
CI	0.993**	–				
rAUDPC	0.984**	0.982**	–			
R	0.921**	0.915**	0.946**	–		
TGW (% loss)	0.885**	0.887**	0.831**	0.859**	–	
Grain yield (% loss)	0.882**	0.889**	0.934**	0.864**	0.998**	–

*FDS = final disease severity; CI = coefficient of infection; rAUDPC = relative Area under the disease progress curve; *r* = Apparent infection rate; TKW = thousand grain weight (gm); Yield, grain yield (kg/plot), D.f. = degrees of freedom; **,* $P < 0.01$, $P < 0.05$

Group with race-specific seedling resistance

This group included of four cultivars HI 1531, HI 1544, HW 2040 and MACS 6222 having race-specific seedling resistance to leaf rust pathogen. This group of cultivars were resistant to all four most virulent and prevalent pathotypes of *P. triticina* at seedling stage resistance evaluation tests conducted in the present investigations (Table 1, Supplementary table 2).

During *rabi* season 2018–19, this group of cultivars, HI 1531, HI 1544, HW 2040 and MACS 6222 showed the least values of all the adult plant also rusting resistance parameters (Supplementary table 5). The cultivars in this group exhibited resistant '*R*' infection type at adult plant stage with lowest leaf rust severity (1–6.66%) (Appendix-XI). The least reduction in grain yield components were observed in this group compared with other groups having different level of adult plant slow rusting resistance and susceptible '*S*' reaction to leaf rust (Supplementary table 6). Mean losses of 1000-grain weight (gm) and grain yield (kg/plot) for this race-specific seedling resistance group of cultivars were 2.58 and 3.78%, respectively. During *rabi* season 2019–20, similar pattern was also observed, as this group showed least values of APR parameters and resistant '*R*' adult plant infection type with lowest disease (0.66–3.33%) (Supplementary table 5). The yield components' losses were the least in this group in comparison with other groups having different levels of APR and susceptible '*S*' reaction to stripe rust (Figs. 3, 4 and Supplementary table 6). Mean losses of TGW and grain yield for this group were 1.99 and 3.15%, respectively.

Group with non-race-specific/adult plant slow rusting resistance

Based on the statistical data analysis, susceptibility levels of different Indian wheat cultivars/varieties showed significant differences during both *rabi* season 2018–19 and 2019–20 (Tables 4, 5). The analysis of data indicated that cultivars were grouped into three categories based on the values of adult plant resistance parameters (FDS, CI, rAUDPC and *r*). The effect of these three categories on yield and grain yield components' losses was significantly different during both years of experiment (Tables 4, 5).

Category 1: high level of adult plant slow rusting resistance This group comprised of eight cultivars HD 2733, HD 2967, HD 3263, HS 562, NIAW 34, HI 1621, DBW 187 and HD 3226. This group of cultivars was susceptible at seedling stage evaluation tests against four most prevalent and virulent pathotypes of *P. triticina* (Supplementary table 2). According to Pathan and Park (2006), cultivars with CI values of 0–30 are regarded as possessing high levels of adult plant slow rusting resistance. During 2018–19, cultivars in this group exhibited moderately resistant 'MR' to moderately susceptible 'MS' infection types at adult plant stage with CI values up to 12, FDS up to 30% and *r* values up to 0.05. This group had rAUDPC values up to 7.23% of the susceptible check (Fig. 3 and

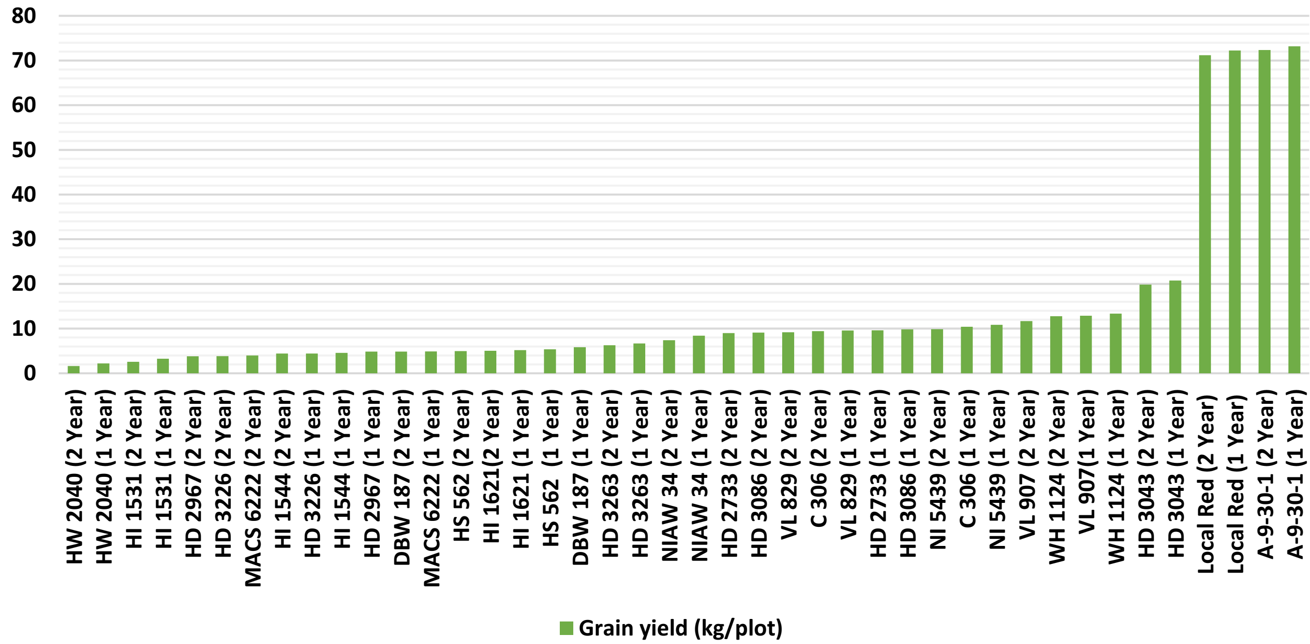

Fig. 3 Comparison of losses for grain yield components in infected and protected conditions of 21 Indian wheat cultivars having different resistance types to leaf rust (2018–20)

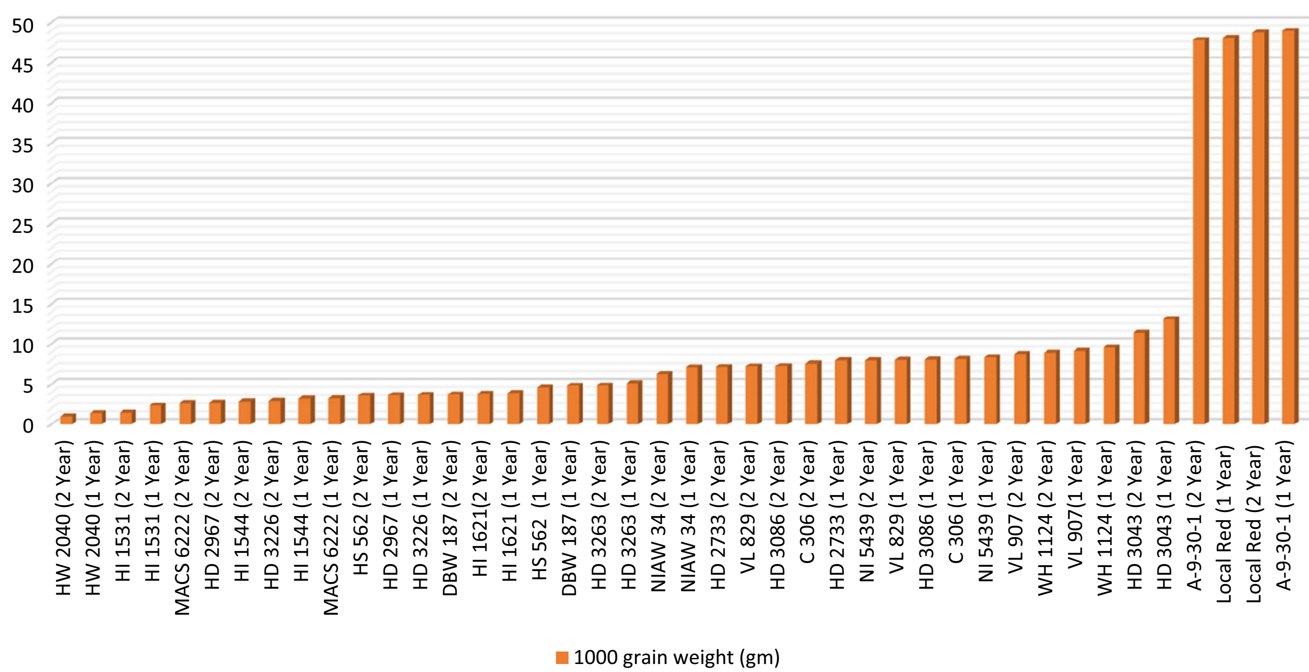

Fig. 4 Comparison of losses for grain yield components in infected and protected conditions of 21 Indian wheat cultivars having different resistance types to leaf rust (2018–20)

Supplementary table 5). According to Ali et al. (2007), cultivars were categorized into two distinct groups on the basis of rAUDPC values. The first group included the cultivars exhibiting rAUDPC values up to 30% of the susceptible check, while the cultivars showing rAUDPC values up to 60% of susceptible check were placed in another group. The cultivars in first group were marked as having high level of APR and that of another group were marked as having moderate level of APR. Mean losses of TGW (gm) and grain yield (kg/plot) in this group were 5.11 and 6.30%, respectively (Fig. 4 and Supplementary table 6). During *rabi* 2019–20, similar pattern was also observed, as the values of all adult plant slow rusting resistance parameters were at low level in comparison to other two groups/categories (category-2 and 3) (Figs. 2, 3 and Supplementary table 5, 6).

Category 2: moderate/medium level of adult plant slow rusting resistance This category comprised of four cultivars VL 829, C 306, HD 3086 and NI 5439. This group of cultivars were susceptible at seedling stage against four most prevalent and virulent leaf rust pathotypes. In this group of cultivars, by applying gene-matching techniques using multi-pathotype data, the presence of *Lr*23, *Lr*26 and APR gene *Lr*34 were postulated singly or in combination with gene *Lr*3, *Lr*10 and *Lr*23 (Table 2). During *rabi* 2018–19, this group of cultivars exhibited CI values of 24–37.5, FDS values of 30–43.33%, rAUDPC values of 19.89–26.19% of susceptible check and *r* values of 0.07–0.13, which were marked as having moderate level of APR (Fig. 2 and Supplementary table 5). In this category, values of all APR parameters were more than category-1, but it was less than category-3 compared to the susceptible checks. Mean losses of TGW (gm) and grain yield (kg/plot) were 8.13 and 10.16%, respectively (Fig. 3 and Supplementary table 6). Similar pattern was also observed during second year (2019–20) of field experiment (Figs. 2, 3 and Supplementary table 5, 6).

Category 3: Low level of adult plant slow rusting resistance The cultivars WH 1124 and VL 907 are included in this group. This group of cultivars was susceptible at seedling stage against four most prevalent and virulent leaf rust pathotypes (Table 2 and Supplementary table 2). During season 2018–19, cultivars in this group showed susceptible infection types at adult plant stage with high level of FDS up to 43.33%, CI values up to 43.33, rAUDPC values up to 34.74 and *r* values up to 0.19, and the highest reductions for TGW and yield compared with the other cultivars of category-1 and category-2 (Fig. 3 and Supplementary table 5). As this group showed high level of epidemiological parameters and were marked as having low level of adult plant slow rusting resistance. Mean losses of 1000-grain weight (gm) and grain yield (kg/plot) were 9.36 and 13.11%, respectively, which was high than the above two categories and less than the susceptible group and susceptible checks (Figs. 3 and Supplementary table 6). During *rabi* 2019–20, similar pattern was also observed, as the values of all the adult plant slow rusting resistance parameters were at high level compared to other two categories (category-1 and category-2), but at low level than susceptible group and susceptible checks (Figs. 2, 3 and Supplementary table 5, 6).

Susceptible group The cultivar HD 3043 are included in this group. This cultivar was susceptible at seedling stage against four most prevalent and virulent leaf rust pathotypes (Table 1). During *rabi* season 2018–19, cultivar in this group exhibited high values of epidemiological parameters FDS, CI, rAUDPC and *r* with 66.66%, 66.66, 62.14% and 0.27, respectively. In this group, the values of all adult plant slow rusting resistance parameters were higher than the above three categories, but lower than the susceptible checks. During *rabi* 2019–20, the similar pattern of epidemiological parameters was observed on the cultivars in this susceptible group (Figs. 2, 3 and Supplementary table 4, 5).

Association between APR parameter and yield components' losses

In this present investigation, the relationship between different adult plant slow rusting resistance parameters and yield components' losses for stripe rust across 21 Indian wheat cultivars/varieties including two susceptible checks was studied. During *rabi* season 2018–19, positive correlation of FDS was observed with CI, rAUDPC and *r* with a strong R^2 value that was 0.991, 0.982 and 0.918, respectively (Table 5). The highest correlation coefficient was accomplished between FDS, rAUDPC and CI ($R^2=0.991$) and the lowest R^2 value was between CI and *r* ($R^2=0.908$). Positive correlation was also observed between adult plant slow rusting resistance parameters and grain yield components' losses. The highest correlation coefficient was observed between rAUDPC and grain and the lowest correlation was between FDS and TGW losses ($R^2=0.881$). The correlation coefficient between grain yield components' losses was also significant. During season 2019–20, similar pattern of positive correlation coefficient was also observed (Table 5).

Discussion

Rust diseases are considered one of the most serious biotic constraints inflecting high economic yield losses in wheat worldwide (Chen 2020; Bhardwaj et al. 2021). Impacts of stripe and leaf rust infection on yield and grain yield components' losses in 21 diverse Indian wheat cultivars/varieties with different resistance types (race-specific and non-race-specific) were studied in field conditions. Results of the study showed that the different groups of cultivars having different resistance types were significantly different based on adult plant slow rusting resistance parameters consistently during *rabi* seasons 2018–20. The analysis of variance revealed that cultivars had significant diversity in terms of all the adult plant slow rusting resistance parameters (FDS, CI, rAUDPC and *r*), 1000-grain weight (gm) and grain yield (kg/plot) in protected and infected plots.

Comparison of the mean values also revealed that stripe and leaf rust infection significantly affected yield and grain yield components' losses of all groups/categories/types of resistance in Indian wheat cultivars (Safavi 2015; Mabrouk et al. 2022; Dinglasan et al. 2022).

The cultivars with race-specific group resistant at seedling stage exhibited resistant '*R*' infection type at adult plant stage along with the least values of different adult plant resistance parameters. Yield component losses were the least in this group compared to other groups with different adult plant resistance and susceptible '*S*' reaction. Similar results were described by various workers (Hailu and Fininsa 2009; Herrera-Foessel et al. 2006; Safavi 2015; Mabrouk et al. 2021; Dinglasan et al. 2022) as they reported that the resistant cultivars have the least losses in yield components under high disease pressure. Although, cultivars in this group have resistant reaction with no pustulation, however, they showed minimum losses under high disease pressure. Because, plants challenges to rust infection with energy demanding physiological processes, possibly defense reactions, using stored host energy which else would go to the growth and development of grains. In addition, a reduction in photosynthetic leaf area due to hypersensitive flecking also can contribute in yield reductions (Herrera-Foessel et al. 2006). Application of systemic fungicides with triazole (to which group difenoconazole belongs) have been shown for a beneficial impact on plants by delaying senescence, thus extending the duration of green leaf area and increasing the yield (Bertelsen et al. 2001). As per the findings of other researchers (Johnson 1988; Ali et al. 2007; Dadrezaei et al. 2013) and in terms of disease response at seedling as well as adult plant stages, cultivars in this group may probably have major gene or combination of major and minor gene(s), effective against all the virulences of rusts used in the study. However, cultivars with race-specific resistance are short-lived and lost their popularity just after few years of release due to fast emergence of new rust virulences (Line and Qayoum 1992a, b; Wan and Chen 2012; Gangwar et al. 2019). In India, it has been experienced in rust resistant wheat cultivars that losses their status/effectiveness within 3–5 years after their release (Rao et al. 1981; Chen 2020). Many cultivars with race-specific resistance have been rendered in recent years, because of having single *R*-genes based resistance. In light of potential change in virulence of rust pathogens by several means like mutation, migration in long distances and selection pressure of cultivars on pathogen populations (Hovmøller et al. 2011; Ben Yehuda et al. 2004; Chen 2020) wheat researchers should be emphasis on deployment of non-race-specific or combination of race-specific and non-race-specific resistance sources instead on using only race-specific/single *R*-gene based resistance (Dinglasan et al. 2022).

Besides race-specific resistance group, the cultivars were also grouped into three categories based on the values of different adult plant slow rusting parameters (FDS, CI, rAUDPC and *r*) in the study. The cultivars susceptible at seedling stage and exhibited MR to MS reaction at adult plant stage under high disease pressure shown by susceptible checks were included in category-1. In this category, cultivars exhibited low values of APR parameters as well as low yield components' losses despite moderate disease levels as compared to other categories (category-2 and 3). (Hailu and Fininsa 2009; Herrera-Foessel et al. 2006; Safavi 2015) also concluded that the moderately resistant wheat and barley cultivars had low reduction in yield against rusts. Cultivars which had MS or MR infection type may be carrying durable resistance genes (Brown et al. 2001; Singh et al. 2005; Randhawa et al. 2019). Subsequently, cultivars with low levels of CI and other APR parameters might have APR/durable resistance genes, and their resistance can be effective for a long period.

Cultivars exhibited more values of all APR parameters than category-1, but less than category-3 compared to the susceptible checks were included in category-2. Based on the APR parameters, cultivars in this category were marked as having moderate level of APR. Cultivars/lines with different levels of partial resistance are advocated to be more effective and durable (Singh et al. 2004; Bhardwaj et al. 2021). Besides, cultivars/lines with acceptable degree of slow rusting restrict evolution of new virulent pathotypes of rust pathogens.

Cultivars in the catgory-3 were showed high level of APR parameters and marked as having low APR level. Mean losses of TGW and grain yield was higher than the above two categories and less than the susceptible group and susceptible checks. Likewise, other researchers (Hailu and Fininsa 2009; Herrera-Foessel et al. 2006; Safavi 2015) also reported that the cultivars exhibited high level of rust severity and moderately susceptible to susceptible infection types at adult plant stage suffer greater losses than other slow rusting category.

Cultivars with high values of APR parameters compared to susceptible checks were included in susceptible group. In this group, the values of all APR parameters and mean losses of yield components were higher than the above three categories, but lower than the susceptible checks. Salman et al. (2006) and Safavi (2015) reported that the yield losses rise consistently with the increase in rust severity. They also reported that the susceptible cultivars exhibited maximum losses (52–57%) due to leaf rust. Other researchers also concluded in the same way that the cultivars having slow rusting resistance usually suffer less yield losses compared to fast rusting cultivars like Morocco, etc., in which losses were as high as 52–57% (Afzal et al. 2008; Bhardwaj et al. 2021). Considering the facts of above results, it is apparent that there is a dire need to avoid fast rusting and susceptible cultivars. Besides, wheat improvement and protection program should be focused on regular monitoring of rust situation and development of durable rust resistance cultivars in the way to effectively control the rust problem and ultimately safeguarding sustainable wheat production.

In this investigation, relationship between different APR parameters and yield components' losses for stripe and leaf rust pathogens across 21 different Indian wheat cultivars/varieties including two susceptible checks were also studied. A positive correlation of FDS was observed with CI, rAUDPC and *r* with a strong R^2 value that was 0.994, 0.981 and 0.927, respectively. The highest correlation coefficient was accomplished between FDS, rAUDPC and CI ($R^2 = 0.994$) and the lowest R^2 value was between CI and *r* ($R^2 = 0.911$). Positive correlation was also observed between APR parameters and grain yield components' losses. The highest correlation coefficient was observed between rAUDPC and grain yield losses ($R^2 = 0.913$) and the lowest correlation was between FDS and TGW losses ($R^2 = 0.833$). The correlation coefficient between grain yield components' losses was also significant. This strong positive correlation is in agreement with the findings of other researchers (Shah et al. 2010; Sandoval-Islas et al. 2007; Safavi 2012). Earlier Sandoval-Islas et al. (2007) found a good correlation of rAUDPC with quantitative resistance components (latent period and infection frequency). Positive correlation coefficient between rAUDPC and yield losses were also reported by several workers (Hailu and Fininsa 2009; Herrera-Foessel et al. 2006; Ochoa and Parlevliet 2007; Afzal et al. 2008; Safavi 2015).

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Author contributions KS performed the work and wrote the manuscript. VKS validated the results, contributed to the interpretation of the results, provided the laboratory facilities, and approved the final version of the article. BS, KKS and LP revised the paper. GPS provided the resources.

Declarations

Competing interests The authors have no competing interests to declare relevant to this article's content.

References

Afzal SN, Haque MI, Ahmedani MS, Rauf A, Muhammad M, Firdous SS, Rattu AR, Ahmad I (2008) Impact of stripe rust on kernel weight of wheat varieties sown in rainfed areas of Pakistan. Pak J Bot 40:923–929

Ali S, Shah SJA, Ibrahim M (2007) Assessment of wheat breeding lines for slow yellow rusting. Pak J Biol Sci 10:3440–3444

Ali Y, Raza A, Iqbal S, Khan AA, Aatif HM, Hassan Z, Hanif CMS, Ali HM, Mosa WF, Mubeen I, Sas-Paszt L (2022) Stepwise regression models-based prediction for leaf rust severity and yield loss in wheat. Sustainability 14(21):13893

Beddow JM, Pardey PG, Chai Y, Hurley TM, Kriticos DJ, Braun JC et al (2015) Research investment implications of shifts in the global geography of wheat stripe rust. Nat Plants 1:15132

Bertelsen JR, de Neergaard E, Smedegaard-Ptersen V (2001) Fungicide effects of azoxystrobin and poxiconazole on phylosphere fungi, senescence and yield of winter wheat. Plant Pathol 50:190–205

Bhardwaj SC, Prashar M, Jain SK, Kumar S, Datta D (2010) Adult plant resistance in some Indian wheat genotypes and postulation of leaf rust resistance genes. Indian Phytopathol 63(2):174–180

Bhardwaj SC, Singh GP, Gangwar OP, Prasad P, Kumar S (2019) Status of wheat rust research and progress in rust management. Agronomy 9(12):892

Bhardwaj SC, Gangwar OP, Prasad P, Kumar S, Pal D (2021) Immunity to rusts in wheat: theory, fact and practice. Indian Phytopathol 74(2):355–363

Bhavani S, Singh RP, Hodson DP, Huerta-Espino J, Randhawa MS (2022) Wheat rusts: current status, prospects of genetic control and integrated approaches to enhance resistance durability. In: Wheat Improvement, Springer, Cham, pp 125–141

Brown JKM, Hovmøller MS (2002) Aerial dispersal of fungi on the global and continental scales and its consequences for plant disease. Science 297:537–541

Brown WMJ, Hill JP, Velasco VR (2001) Barley yellow rust in North America. Ann Rev Phytopathol 39:367–384

Chen X (2020) Pathogens which threaten food security: *Puccinia striiformis*, the wheat stripe rust pathogen. Food Secur 12(2):239–251

Chen XM (2005) Epidemiology and control of stripe rust (*Puccinia striiformis* f. sp. *tritici*) on wheat. Can J Plant Pathol 27:314–337

Chen XM (2014) Integration of cultivar resistance and fungicide application for control of wheat stripe rust. Can J Plant Pathol 36(3):311–326

Chen XM, Kang ZS (eds) (2017) Stripe rust. Springer, Dordrecht, 719 p

Dadrezaei ST, Nazari K, Afshari F, Mohamadi-Goltapeh E (2013) Phenotypic and molecular characterization of wheat leaf rust resistance gene *Lr*34 in Iranian wheat cultivars and advanced lines. Am J Plant Sci 4:1821–1833

Dinglasan E, Periyannan S, Hickey LT (2022) Harnessing adult-plant resistance genes to deploy durable disease resistance in crops. Essays Biochem 66(5):571–580

Ezzahiri B, Yahyaoui A, Hovmøller MS (2009) An analysis of the 2009 Epidemic of yellow rust on wheat in Morocco. In The 4th Regional Yellow Rust Conference for Central and West Asia and North Africa (Antalya: Turkish Ministry of Agriculture and Rural Affairs, ICARDA, CIMMYT, FAO of the United Nations)

Gangwar OP, Kumar S, Prasad P, Bhardwaj SC, Hanif K, Verma H (2016) Virulence pattern and emergence of new pathotypes in *Puccinia striiformis tritici* during 2011–15 in India. Indian Phytopathol 69:178–185

Gangwar OP, Kumar S, Bhardwaj SC, Prasad P, Kashyap PL, Khan H, Singh GP, Savadi S (2019) Virulence and molecular diversity among *Puccinia striiformis* f. sp. *tritici* pathotypes identified in India between 2015 and 2019. Crop Prot 48:105717

Hailu D, Fininsa C (2009) Relationship between stripe rust (*Puccinia striiformis*) and common wheat (*Triticum aestivum*) yield loss in the highlands of Bale, southeastern Ethiopia. Arch Phytopathol Plant Prot 42(6):508–523

Herrera-Foessel SA, Singh RP, Huerta-Espino J, Crossa J, Yuen J, Djurle A (2006) Effect of leaf rust on grain yield and yield traits of durum wheats with race-specific and slow-rusting resistance to leaf rust. Plant Dis 90(8):1065–1072

Herrera-Foessel SA, Lagudah ES, Huerta-Espino J, Hayden MJ et al (2011) New slow rusting leaf rust and stripe rust resistance genes Lr67 and Yr46 in wheat are pleiotropic or closely linked. Theor Appl Genet 122:239–249

Hovmøller MS, Justesen AF (2007) Rates of evolution of avirulence phenotypes and DNA markers in a northwest European population of *Puccinia striiformis* f.sp. *tritici*. Mol Ecol 16:4637–4647

Hovmøller MS, Walter S, Bayles R, Hubbard A, Flath K, Sommerfeldt N et al (2016) Replacement of the European wheat yellow rust population by new races from the centre of diversity in the near-Himalayan region. Plant Pathol 65:402–411

Hovmøller MS, Yahyaoui AH, Milus EA, Justesen AF (2008) Rapid global spread of two aggressive strains of a wheat rust fungus. Mol Ecol 17:3818–3826

Hovmøller S, Sørense CK, Walter S, Justesen AF (2011) Diversity of *P. striiformis* on cereals and grasses. Ann Rev Phytopathol 49:197–217

Huerta-Espino J, Singh RP, German S, McCallum BD, Park RF, Chen WQ, Bhardwaj SC, Goyeau H (2011) Global status of wheat leaf rust caused by *Puccinia triticina*. Euphytica 179(1):143–160

Johnson R (1988) Durable resistance to yellow (stripe) rust in wheat and its implications in plant breeding. In: Simmonds NW, Rajaram S (eds) Breeding strategies for resistance to the rusts of wheat. CIMMYT, Mexico, pp 63–75

Line RF, Qayoum A (1992a) Virulence, aggressiveness, evolution, and distribution of races of *Puccinia striiformis* (the cause of stripe rust of wheat) in North America, 1968–87. Technical bulletin-United States Department of Agriculture (1788)

Line RF, Qayoum A (1992b) Virulence, aggressiveness, evolution, and distribution of races of Puccinia striiformis (the cause of stripe rust of wheat) in North America, 1968–87. Technical bulletin-United States Department of Agriculture (1788).

Mabrouk OI, EL-Hawary MN, Gad KI (2021) Disease incidence and genetic analysis of adult plant resistance to leaf rust in some Egyptian wheat cultivars. Egypt J Phytopathol 49(2):54–67

Mabrouk OI, Fahim MA, Omara RI (2022) The impact of wheat yellow rust on quantitative and qualitative grain yield losses under Egyptian field conditions. Egypt J Phytopathol 50(1):1–19

McIntosh RA, Dubcovsky J, Rogers WJ, Morris C, Appels R, Xia XC (2012) Catalogue of gene symbols. KOMUGI Integrated Wheat Science Database. http://www.shigen.nig.

McIntosh RA, Dubcovsky J, Rogers WJ, Morris CF, Appels R, Xia XC (2017) Catalogue of gene symbols for wheat 2017 (supplement):1–20

McIntosh RA, Hart GE, Davos KM, Gale MD, Roger WJ (1998) Catalogue of gene symbols for wheat. In: Slinkard AE (ed) Proceedings of the International wheat genetics symposium, vol 5. University of Saskatchewan Extension Press, Saskatoon

Milus EA, Line RF (1986) Gene action for inheritance of durable, high-temperature, adult-plant resistance to stripe rust in wheat. Phytopathology 76(4):435–511

Ochoa J, Parlevliet JE (2007) Effect of partial resistance to barley leaf rust Puccinia hordei, on the yield three barley cultivars. Euphytica 153:309–312

Ordonez ME, German SE, Kolmer JA (2010) Genetic differentiation within the *Puccinia triticina* population in South America and comparison with the North American population suggests common ancestry and intercontinental migration. Phytopathology 100:376–383

Pathan AK, Park RF (2006) Evaluation of seedling and adult plant resistance to leaf rust in European wheat cultivars. Euphytica 149(3):327–342

Peterson RF, Campbell AB, Hannah AE (1948) A diagrammatic scale for estimating rust intensity on leaves and stem of cereals. Can J Res Sect C 26:496–500

Prashar M, Bhardwaj SC, Jain SK, Dutta D (2007) Pathotypic evolution in *P. striiformis* in India during 1995–2004. Aust J Agric Res 58:602–604

Prashar M, Bhardwaj SC, Jain SK, Gangwar OP (2015) Virulence diversity in *P. striiformis tritici* causing yellow rust on wheat (*Triticum aestivum*). Indian Phytopathol 68(2):129–133

Rahmatov M, Eshonova Z, Ibrogimov A, Otambekova M, Khuseinov B, Muminjanov H et al (2012) Monitoring and evaluation of yellow rust for breeding resistant varieties of wheat in Tajikistan. In Meeting the Challenge of Yellow Rust in Cereal Crops Proceedings of the 2nd, 3rd and 4th Regional Conferences on Yellow Rust in Central and West Asia and North Africa (CWANA) Region, Yahyaoui A, Rajaram S (eds) International Center for Agricultural Research in the Dry Areas, Alnarp.

Rahmatov M, Hovmøller MS, Nazari K, Andersson SC, Steffenson BJ, Johansson E (2017) Seedling and adult plant stripe rust resistance in diverse wheat-alien introgression lines. Crop Sci 57(4):2032–2042

Randhawa M, Bains N, Sohu V, Chhuneja P, Trethowan R, Bariana H, Bansal U (2019) Marker assisted transfer of stripe rust and stem rust resistance genes into four wheat cultivars. Agronomy 9:497. https://doi.org/10.3390/agronomy9090497

Rao MV, Naque SMA, Luthra JK (1981) Mlks-11/A wheat multiline variety for the north and north western plains of India. In: Borlaug NE (ed) Indian multiline. CIMMYT, Mexico, pp 7–9

Rodriguez-Algaba J, Walter S, Sørensen CK, Hovmøller MS, Justesen AF (2014) Sexual structures and recombination of the wheat rust fungus *Puccinia striiformis* on *Berberis vulgaris*. Fungal Genet Biol 70:77–85

Roelfs AP, Singh RP, Saari EE (1992) Rust diseases of wheat: concepts and methods of disease management. CIMMYT, Mexico

Safavi SA (2012) Field based assessment of partial resistance in dry land wheat lines to stripe rust. Int J Agric Res Rev 2(3):291–297

Safavi SA (2015) Effects of yellow rust on yield of race-specific and slow rusting resistant wheat genotypes. J Crop Prot 4(3):395–408

Saharan MS, Kumar S, Selvakumar R, Sharma I (2015) Wheat crop health report of February–March 2013. directorate of wheat research, Karnal. Wheat Crop Health Newsl 20(3):1–7

Salman A, Khan MA, Hussain M (2006) Prediction of yield losses in wheat varieties. Pak J Phytopathol 18:178–182

Sandoval-Islas JS, Broers LHM, Mora-Aguilera G, Parlevliet JE, Osada-Kawasoe S, Vivar HE (2007) Quantitative resistance and its components in 16 barley cultivars to yellow rust *Puccinia striiformis* f. sp. *hordei*. Euphytica 153(3):295–308

Sendhil R, Kumari B, Khandoker S, Jalali S, Acharya KK, Gopalareddy K, Singh GP, Joshi AK (2022) Wheat in Asia: trends, challenges and research priorities. In: New Horizons in Wheat and Barley Research, Springer, Singapore, pp 33–61

Shah SJA, Hussain S, Ahmad M, Farhatullah and Ibrahim M (2014) Characterization of slow rusting resistance against *P. striiformis* tritici in candidate & released bread wheat cvs. of Pakistan. J. Plant Pathol. Microbiol 5:1–9

Shah SJA, Muhmmad M, Hussain S (2010) Phenotypic and molecular characterization of wheat for slow rusting resistance against *Puccinia Striiformis* f. sp. *tritici*. J Phytopathol 158:393–402

Sharma I, Saharan MS (2011) Status of wheat disease in India with a special reference to stripe rust. Plant Dis Res 26(2):156

Shehab-Eldeen MT, Abou-Zeid MA (2020) Quantitative studies on resistance to stripe and stem rust diseases and on grain yield of bread wheat. J Plant Prod 1(11):1071–1075

Singh A, Knox RE, DePauw RM, Singh AK, Cuthbert RD et al (2014) Stripe rust and leaf rust resistance QTL mapping, epistatic interactions and co-localization with stem rust resistance loci in spring wheat evaluated over three continents. Theor Appl Genet 127:2465–2477

Singh RP, Huerta-Espino J, William HM (2005) Genetics and breeding for durable resistance to leaf and stripe rusts in wheat. Turk J Agric for 29:121–127

Singh RP, Huerta-Espino J, Pfeiffer W, Figueroa-Lopez P (2004) Occurrence and impact of a new leaf rust race on durum wheat in north western Mexico from 2001 to 2003. Plant Dis 88:703–708

Singh VK, Mathuria RC, Singh GP, Singh PK, Singh S, Gogoi R, Aggarwal R (2015) Characterization of yellow rust resistance genes by using gene postulation and assessment of adult plant resistance in some Indian wheat genotypes. Res Crops 16(4):742–751

Singh VK, Singh GP, Singh PK, Harikrishna MRC, Gogoi R, Aggarwal R (2017) Assessment of slow rusting resistance components to stripe rust in some exotic wheat germplasm. Indian Phytopathol 70(1):52–57

Singh VK, Mathuria RC, Gogoi R, Aggarwal R (2016) Impact of different fungicides & bioagents, and fungicidal spray timing on wheat stripe rust development and grain yield. Indian Phytopath 69(4):357–362

Srinivas K, Moizur Rahman S, Yadav M, Sharma M (2021) Brown and yellow rust of wheat in india-significance of climate on its races and resistance. Int J Environ Climate Change 11(11):72–91

Stakman EC, Stewart DM, Loegering WQ (1962) Identification of physiologic races of Puccinia graminis tritici. USDA-ARS. E6 17:1–53

Stubs RW, Prescot JM, Saari EE, Dubi HJ (1986) Cereal disease methodology manual. CIMMYT, Mexico, pp 46

Van der Plank JE (1963) Plant diseases. Elsevier Science

Wan AM, Chen XM (2012) Virulence, frequency and distribution of races of P. striiformis f.sp. tritici and P. striiformis f.sp. hordei identified in the United States in 2008 and 2009. Plant Dis 96:67–74

Wellings CR (2007) *Puccinia striiformis* f.sp. *tritici* in Australia: a review of the incursion, evolution and adaptation of stripe rust in the period 1979–2006. Aust J Agric Res 58:567–575

Yehuda PB, Eilam T, Manisterski J, Shimoni A, Anikster Y (2004) Leaf rust on *Aegilops speltoides* caused by a new forma specialis of *Puccinia triticina*. Phytopathology 94(1):94–101

Zadoks JC (1961) Yellow rust on wheat, studies in epidemiology and physiologic specialization. Tijdschrift over Plantenziekten 67:256–269