Australian Journal of Crop Science AJCS
AJCS 16(05):587-595 (2022) ISSN:1835-2707
doi: 10.21475/ajcs.22.16.05.p3558

Evaluation of Kenyan wheat (*Triticum aestivum* L.) cultivars for rust resistance, yield and yield components

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Abstract

Stem rust (*Puccinia graminis* f. sp. *tritici*) is an important fungal disease of wheat (*Triticum aestivum*) due to its ability to cause severe yield losses on susceptible cultivars grown under conducive conditions. The objective of this study was to evaluate 81 Kenyan wheat cultivars for yield, agronomic traits and resistance to rust. A 3-season field experiment was conducted in a 9 × 9 partially balanced lattice design at KALRO, Njoro (0˚ 20'S and 35˚ 56'E) under stem rust (*Sr*) and yellow rust (*Yr*) pressure. The results from this study showed that effects due to season, cultivar and cultivar × season interaction were significant (p≤0.001) for number of kernels spike^{-1}, Area Under Disease Progress Curve for stem rust ($AUDPC_{\_SR}$), Area Under Disease Progress Curve for yellow rust ($AUDPC_{\_YR}$), yield, 1000-kernel weight (TKW), biomass and days to heading. Principal component analysis showed AUDPC was the most effective disease parameter for determining rust resistance and biplot analysis identified cultivars *K. Fahari*, *K. Kingbird*, *K. Songbird* and *K. Pelican* with desirable traits for yield, TKW, biomass and kernels spike $^{-1}$. Stem rust contributed to the highest in reduction of yield and TKW accounting for 12.87% and 21.95% variation, respectively while *Yr* contributed the most to biomass reduction accounting for 25.65% variation. From this study, cultivars *Bounty*, *Lenana*, and *K. Leopard* which produced high yield, low $AUDPC_{\_SR}$ and $AUDPC_{\_YR}$ values ranging from 3.5- 32.2 and 15.6-80.4, respectively can be used as valuable genetic stocks for improvement of rust resistance in wheat cultivars in Kenya.

Keywords: AUDPC; Biplot; Principal component analysis; Stem rust; *Triticum aestivum*; Yellow rust.
Abbreviations: $AUDPC_{\_SR}$ _Area Under Disease Progress Curve stem rust; $AUDPC_{\_YR}$ _Area Under Disease Progress Curve yellow rust; GS_ Growth stage; TKW_ 1000 kernel weight.

Introduction

Stem rust (*Puccinia graminis* f. sp. *tritici*), leaf rust (*Puccinia triticina*) and yellow rust (*Puccinia striiformis* f. sp. *tritici*) are important fungal diseases of wheat (*Triticum aestivum* L.) which causes significant yield losses on susceptible cultivars worldwide. Stem rust has continued to cause significant yield losses in wheat production because of constant change in virulence of the races due to emergences of new races in *P. graminis* populations (Soko et al., 2018). A study conducted on wheat in Kenya, determined that *Sr* caused yield loss ranging between 32-57% and reduced kernel weight by 24% (Wanyera et al., 2010). Although, use of fungicides to control rust is a short term strategy, incorporation of major and minor resistant genes into appropriate wheat cultivar backgrounds restrict development of urediniospores that cause rust infection (Singh et al., 2013; Wanyera et al., 2016). Apart from the effects of rust on growth and productivity of wheat, yield is a quantitative trait affected by environmental conditions. Therefore, it is necessary for wheat breeders to develop stable high yielding, adapted and resistant cultivars suitable for different environments (Ali et al., 2017). Principal component analysis (PCA) have been used to give an understanding of agronomic traits of a crop which contribute most to yield, subsequently, these agronomic traits should be emphasized in breeding programs (Al-Saady et al., 2018). In a study conducted to determine the effects of agronomic traits on yield of wheat and analyzing data using principal component analysis, the result revealed that PC1 which was due to TKW and test weight accounted for 42.5% of the total variation (Spanic et al., 2021). However, a study conducted on wheat by Adilova et al. (2020) revealed that heads plant^{-1}, spikelets spike^{-1}, and TKW contributed to yield. PCA analysis has also been used to detect the effects of disease variables to allow the identification of resistant wheat lines. In an experiment on 1,357 barley (*Hordeum vulgare*) lines in Toluca, Mexico showed that PC1 is useful for evaluating yellow rust reaction (Xi et al., 2013).
Screening for disease resistance is a primary step for identifying potential wheat cultivars that are resistant to rust. In Kenya, extensive screening of global wheat cultivars

for rust resistance has been undertaken at hot-spot sites to characterize stem rust races, track its spread and find sources of resistance to rust diseases (Bhavani et al., 2019). Due to the prevalent *Sr* and *Yr* races in Kenya it is important to develop high yielding and rust resistant wheat cultivars. Therefore, the objective of this study was to evaluate Kenyan wheat cultivars for rust resistance, yield and yield components.

Results

Combined analysis of variance and means of main effects

In this study, effects due to season, cultivar and cultivar × season interaction were significant ($p \leq 0.001$) for plant height, spike length, days to heading, 1000-kernel weight (TKW), yield, biomass, number of kernels spike^{-1}, AUDPC$_{SR}$ and AUDPC$_{YR}$ (Table 1). Differential seasonal effects were observed on cultivars tested for yield and yield components. Plants evaluated during off season 2019 (OS 2019) took 73 days to head and attained highest mean plant height of 107.10 cm compared to those evaluated during off season of 2020 (OS 2020) (Table 2). Wheat plants evaluated during OS 2019 produced spikes that attained mean length of 10.89 cm with kernel weight heavier by 38.5% compared to the kernels obtained from wheat tested during OS 2020. In comparison of seasonal effects, 13.43% of kernels spike^{-1} were produced on wheat tested during MS 2019 more than kernels from OS 2019. The results from this study also showed that the mean yield of each cultivar ranged from 0.07 - 2.49 tonnes ha^{-1}. Generally, mean yield of 1.86 tonnes ha^{-1} and 13.90 tonnes ha^{-1} for biomass were observed during MS 2019. In this study, 17 % of the cultivars which included cultivars *Goblet*, *Regent*, *Lenana*, *Token*, *Trophy*, *Bounty*, *K. Cheetah*, *Gem*, *K. Nyati*, *Tama*, *K. Kongoni*, *K. Leopard*, *Beacon-Ken* and *K. Kingbird* produced mean yield of >1.9 tonnes ha^{-1} (Table 3). In regard to mean weight of kernels, a range of 12.7 g as observed on cultivar *Morris* to 25.7 g on cultivar *Lenana* was observed (Table 2).

Classification of cultivars based on AUDPC

Response of test cultivars to *Sr* and *Yr* infection varied with the seasons (Fig.1). Wheat cultivars with AUDPC_$_{SR}$ and AUDPC_$_{YR}$ values of 0-150, 151-300, 301-500 and > 500 were considered R, MR, MS and S, respectively. In this study, 65.4% of cultivars tested were resistant and showed mean AUDPC_$_{SR}$ ranging from 0 to 150 during OS 2020. However, between the seasons, 24 cultivars responded to stem rust infection with highest AUDPC_$_{SR}$ of > 500 during MS 2019, compared to 9 cultivars noted in OS 2020 (Fig. 1a). The severity of stem rust infection was higher by 44.6% on the wheat evaluated during MS 2019 than on wheat planted during OS 2020 (Table 2). However, translating severity of infection to AUDPC, 70.1% exhibited high AUDPC_$_{YR}$ on test cultivars planted in OS 2020. Of the 81 cultivars, 20 (24.6%) showed low AUDPC_$_{SR}$, values ranging from 3.5 - 108.8 and AUDPC_$_{YR}$ ranging from 48.6 – 343. Cultivars, *K. Cheetah*, *Goblet*, *K. Civet*, *Beacon-Ken* and *Morris* exhibited low AUDPC_$_{SR}$ value of < 20 and rAUDPC of 1.1 - 3.6 for stem rust while cultivars *K. Leopard*, *K. Civet*, *Bounty*, *K. Kingbird*, *Kongoni* and *Sungura* exhibited lowest AUDPC_$_{YR}$ value of 15.6-80.4, rAUDPC of 3.9 - 25.7 and rFDS of 5.5 - 27.1 for yellow rust (Table 4). Over the 3 seasons, cultivar *Sungura* displayed the lowest AUDPC_$_{SR}$ of 3.5 and AUDPC_$_{YR}$ of 48.6. Cultivars, *K. Nyati*, *Trophy*, *Token*, *K. Swara* and *K. Zabadi* showed high AUDPC_$_{YR}$ values ranging from 222.8-339.7 but low AUDPC_$_{SR}$ values (Table 3).

Pearson correlation

Relationship between yield and yield components in wheat is important in determining association between the traits (Table 4). In this study, there were significant negative correlations between the days plants took to head and thousand kernel weight (r= -0.55***), yield (r= -0.64***) kernel spike^{-1} (r= -0.57***). A negative correlation was also observed between biomass and AUDPC $_{YR}$ (r= -0.41***) and between plant height and kernels spike^{-1} (r=- 0.42***) (Table 4). However, a significant correlation (r= 0.76***) was observed between thousand kernel weight and yield. Yield was positively correlated with biomass (r= 0.57***) and kernels spike^{-1} (r= 0.62***).

Principal component analysis (PCA) and Biplot analysis of Cultivar × Trait

Principal component analysis was performed to depict the proportion of variance contributed by each disease variate. In this study, the first principal components (PC1) cumulatively accounted for 99.18% total variance, with the highest contribution from AUDPC with a loading of 1.2 followed by relative Final Disease Severity (rFDS) with a loading of 0.65 while PC2 was highly influenced by rAUDPC with loading of 0.09 (Table 5). The Cultivar × trait biplot and trait relationship revealed that the first 3PCs showed Eigen values >1 and cumulatively accounted for 77.62% of total variation (Fig.2). The first PC explained 42.28% of the total variation with the highest contribution from yield (loading=0.89) followed by TKW (loading=0.80) and kernel spike^{-1} (loading=0.72) while the second and third PCs accounted for 19.35% and 15.98% of the variation, respectively. A vector was drawn from the biplot origin to show the relationship among the measured traits. An acute angle among biomass, TKW and yield showed positive association among the traits. Cultivars on the right side of the biplot are associated with traits located on the right side and vice versa. High yielding cultivars *Fahari* (75), *K. Kingbird* (68), *K. Songbird* (71), *K. Pelican* (70), *Nyangumi* (46), *K. Cheetah* (78), *Lenana* (15), *Nyoka* (39), *Gabrino* (14), *Tembo* (40), *K. Weaverbird* (73), *Sunbird* (65), *Ngiri* (44), *Paka* (41) and *Romany* (22) showed high values for TKW, biomass and kernels spike^{-1} while low yielding cultivars were tall, with long spikes and took long days to attain heading (Fig.2).

Stepwise regression analysis

Wheat is normally infected by stem rust, leaf rust and yellow rust. In some cases, infection of these rust usually occur on at the same time. Therefore, in this study, stepwise multiple regression showed that a unit increase in AUDPC_$_{SR}$ accounted for 12.87% (Cp of 2.29), 4.2% (Cp 1.04) and 25.63% (Cp of 2.35) reduction for yield, TKW and biomass, respectively, in OS 2019 (Table 6). This study demonstrated that during main season of 2019, an increase in AUDPC_$_{SR}$ resulted in a decrease in yield by 4.79% (Cp of 3.00) while TKW decreased by magnitude of 21.95% (1.59). In addition, biomass was decreased by 6.69% (Table 6). In contrast, effects of yellow rust on wheat, showed that AUDPC_$_{YR}$ accounted for 6.01% reduction in yield with Cp of 5.19, 5.9% for TKW and relatively high magnitude of reduction of 25.65% for biomass with Cp of 8.70 during MS 2019 (Table 6). During OS 2020, it was clear that increase in AUDPC_$_{SR}$ resulted into decrease of 2.13% for yield (Cp=2.19), 4.32%

Table 1. Analysis of variance of wheat cultivars for grain yield and yield components, AUDPC_SR and AUDPC_YR during OS 2019, MS 2019 and OS 2020 at KALRO, Njoro.

Source of variation	df	Expected mean squares	Plant height	Spike length	TKW	Yield	Biomass
			cm		g	tonnes ha^{-1}	
Season	2	$\sigma_e^2 + 243\sigma_B^2 + 2187\sigma_R^2 + 6561\sigma_S^2$	583.05***	54.96***	4555.85***	105.51***	1430.41***
Rep within Season	6	$\sigma_e^2 + 243\sigma_B^2 + 2187\sigma_R^2$	307.35	1.97	37.76	0.58	94.10
Block (Rep × Season)	72	$\sigma_e^2 + 243\sigma_B^2$	78.27	0.50	14.05	0.36	16.31
Cultivar	80	$\sigma_e^2 + 81\sigma_{cs}^2 + 243\sigma_c^2$	1051.07***	7.23***	139.73***	3.41***	85.42***
Cultivar ×Season	160	$\sigma_e^2 + 81\sigma_{cs}^2$	101.73***	1.45***	27.98***	1.02***	23.70***
Error	408	σ_e^2	36.88	0.47	7.24	0.07	9.55
R^2			0.90	0.84	0.90	0.96	0.80
CV %			5.73	6.65	14.57	21.99	27.83

Source of variation	df	Expected mean squares	Kernels spike^{-1}	Days to Heading	AUDPC_SR	AUDPC_YR
Season	2	$\sigma_e^2 + 243\sigma_B^2 + 2187\sigma_R^2 + 6561\sigma_S^2$	1659.66***	2431.31***	1855.20***	2370.49***
Rep within Season	6	$\sigma_e^2 + 243\sigma_B^2 + 2187\sigma_R^2$	594.25	49.79	7.38	8.85
Block (Rep× Season)	72	$\sigma_e^2 + 243\sigma_B^2$	39.29	17.46	14.90	5.42
Cultivars	80	$\sigma_e^2 + 81\sigma_{cs}^2 + 243\sigma_c^2$	495.47***	997.52***	477.04***	157.40***
Cultivar× Season	160	$\sigma_e^2 + 81\sigma_{cs}^2$	77.78***	50.00***	24.28***	18.87***
Error	408	σ_e^2	35.43	10.07	8.70	5.16
R^2			0.83	0.96	0.93	0.91
CV %			18.50	4.14	19.70	20.62

*** Significant at *P*≤ 0.001df: degree of freedom; CV: Coefficient of variation; TKW: 1000- Kernel weight; AUDPC: Area Under Disease Progress Curve Test H=Cultivar × Season and Block within season and replicates E=Random error; Test H=cultivar E= Cultivar× Season; Test H = Replicate within season E=Block within seasons and replicates.

Table 2. Mean of grain yield and yield components, AUDPC_SR and AUDPC_YR evaluated over three seasons at KALRO, Njoro.

Season	Plant height	Spike length	TKW	Yield	Biomass	Days to heading	Kernels spike^{-1}	AUDPC_SR	AUDPC_YR
	cm		g	tonnes ha^{-1}					
OS 2019	107.10a	10.89a	22.30a	1.23b	9.73b	73.38c	29.62c	320.89b	61.44c
MS 2019	106.53a	10.21b	19.31b	1.86a	13.90a	76.83b	34.84a	362.11a	170.59b
OS 2020	104.18b	9.98c	13.77c	0.54c	9.67b	79.69a	32.06b	200.25c	205.52a
$MSD_{(0.05)}$	1.08	0.12	0.57	0.05	0.65	0.67	1.27	19.13	12.27

OS: Off season; MS: Main season; TKW: 1000- Kernel weight; AUDPC_SR: Area under Disease Progress Curve stem rust; AUDPC_YR: Area under disease progress curve yellow rust; MSD: Tukey's minimum significance difference.

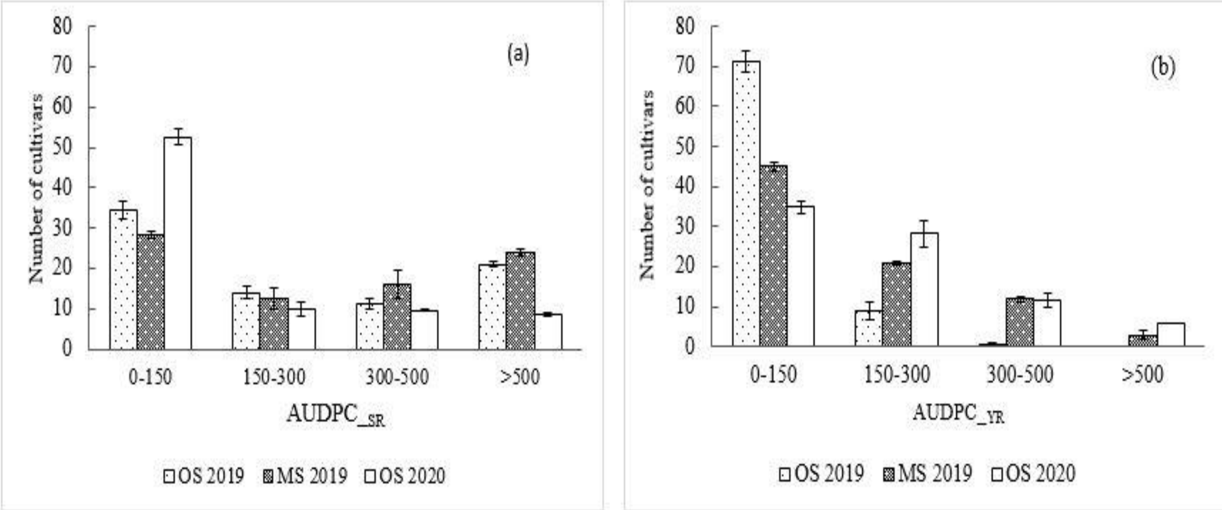

Fig 1. Distribution of 81 Kenyan wheat cultivars for (a) stem rust and (b) yellow rust AUDPC values evaluated over 3 seasons.

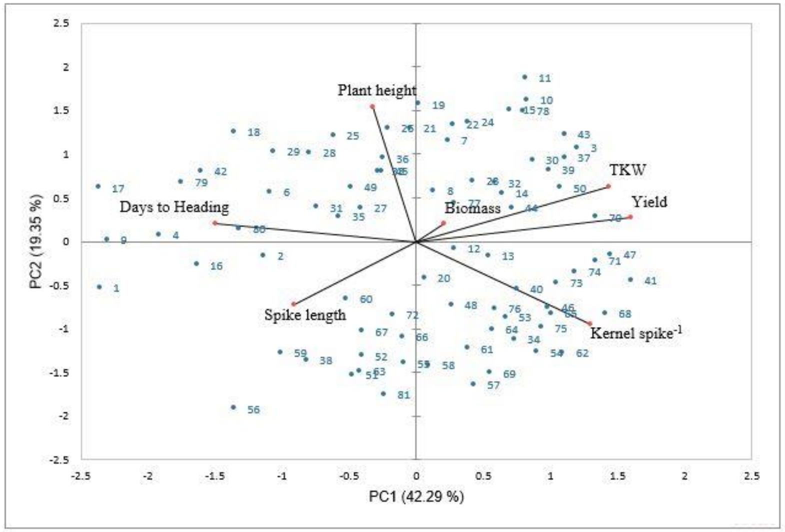

Figure 2. A cultivar by trait (CT) biplot representing 81 wheat cultivars measured for seven traits across three cropping seasons. The black line represents trait projections on 2 axes, the greater the projection, higher the contribution to total variations in a given axis. TKW: 1000-kernel weight. The cultivars are coded based on the supplementary table 1.

Table 3. Mean of 20 resistant Kenyan bread wheat cultivars for 1000- kernel weight, yield, $AUDPC_{\_SR}$ and $AUDPC_{\_YR}$.

		TKW	Yield	Stem rust			Yellow rust		
Cultivar[a]	Pedigree	g	t ha^{-1}	AUDPC	rAUDPC	rFDS	AUDPC	rAUDPC	rFDS
Lenana	Yaqui- 48/Kentana-48	25.7	1.8	26.7	2.6	3.7	114.0	31.4	29.8
Gem	BT908/Frontana//Cajeme 54	23.2	1.4	42.0	3.7	4.3	135.9	37.0	35.7
K. Nyati	Africa Mayo/2*Romany	22.5	1.7	63.3	5.4	6.8	222.8	56.1	51.9
K. Cheetah	Warigo/Sterling	22.9	1.9	18.3	1.8	3.6	186.3	46.2	40.7
Leopard	Lageadinho/3*Kenya-354-P//CI-12632/3*Kenya-354-P	22.4	1.1	21.8	1.9	3.7	15.6	3.9	5.5
Trophy	Timstein/2*Kenya-RF-342//2*Yaqui-50	20.2	1.6	55.8	4.9	8.3	343.0	90.5	92.9
Bounty	Timstein/2*Kenya-RF-324//Bonza-55	21.3	1.9	32.2	2.7	4.2	76.7	19.6	19.1
K. Kingbird	TAM-200/TUI/6/PAVON-76//CAR-422/Anahuac-75/5/Bobwhite/Crow//Buckbuck/Pavon-76/3/Yecora-70/4/Trap-1	22.0	1.8	108.8	10.0	17.2	80.1	24.1	25.4
Goblet	Gabo-54/Lerma-52//Gabo/3/Kenya/General-Urquiza	20.2	2.1	3.8	0.2	1.1	204.7	59.6	60.7
K. Swara	CI-8154/2*FROCOR/3/TIMSTEIN/ 2*KENYA//Y-59.2.B	19.2	0.9	19.8	1.7	3.1	260.8	67.6	72.4
K. Civet	CI-12632/3*Kenya-354-P	21.7	0.8	12.7	1.1	2.4	56.7	16.3	13.8
Regent	H44/Reward	22.1	2.2	33.7	2.9	6.4	203.0	51.6	45.7
Token	Timstein/2*Kenya-RF-342//2*Yaqui-50	18.8	1.5	51.7	4.6	6.4	339.7	82.7	79.9
Tama	Yaktana-54/Lerma-52	20.0	1.8	32.6	3.0	4.7	174.2	43.7	41.1
K. Kongoni	CI-8154/2*Frocor//3*Romany/4/Wisconsin-245/II-50-17/CI-8154//2*Frocor/3/Tobari-66	17.2	1.6	92.7	8.1	13.5	80.4	25.9	27.1
K. Zabadi	Correcaminos/Inia-67//K-4500-2/3/Kenya-Swara//Tobari-66/Ciano-67	17.7	0.8	34.5	2.9	4.6	263.6	65.4	57.9
Mentor	NA	21.9	0.2	29.7	2.9	4.2	186.3	52.4	50.5
Beacon-Ken	Frontana//Kenya-58//Newthatch/3/3*Bonza	15.1	1.1	18.5	1.6	7.1	178.4	50.0	48.4
Sungura	ID-1877/Morris,Kenya-4365-B4D5	14.5	0.8	3.5	0.3	0.7	48.6	12.6	12.2
Morris	Thatcher//Kenya117a/Mida/3/Frontana/4*Thatcher/4/Thatcher/5/Frontana/4*Thatcher	12.7	0.3	9.4	0.8	1.4	178.8	45.7	47.3
Cacuke [b]	Canadian/Cunningham//Kennedy	17.4	0.6	1186.1	100.0	100.0	325.8	100.0	100.0

[a]K = Kenya; [b]Cacuke = susceptible control.; g: grams; TKW: 1000- Kernel weight; $AUDPC_{\_SR}$: Area under Disease Progress Curve stem rust; $AUDPC_{\_YR}$: Area under disease progress curve yellow rust; rAUDPC: relative area under disease progress curve; rFDS : relative final disease severity.

Table 4. Correlation coefficients among Yield, Yield components and $AUDPC_{\_SR}$ and $AUDPC_{\_YR}$.

	Days to heading	TKW	Yield	Biomass	Kernels $spike^{-1}$	Plant height	$AUDPC_{\_YR}$	$AUDPC_{\_SR}$
Days to heading		-0.55***	-0.64***	-0.06	-0.57***	0.16	-0.22	-0.26
TKW			0.76***	0.33	0.28	0.07	0.08	-0.33
Yield				0.57***	0.62***	0.01	-0.12	-0.25
Biomass					-0.27	0.32	-0.41***	-0.35
Kernel $spike^{-1}$						-0.42***	0.18	-0.35
Plant height							-0.32	-0.43
$AUDPC_{\_SR}$								
$AUDPC_{\_YR}$								

***, significant at $P \leq 0.001$: DH: days to heading; TKW: 1000- Kernel weight; $AUDPC_{\_SR}$: Area under Disease Progress curve stem rust; $AUDPC_{\_YR}$: Area under Disease Progress Curve yellow rust.

Table 5. Principal components and contribution of three disease components in evaluation of wheat cultivars.

PC	Eigen values	Individual contribution	Cumulative contribution	Disease variates	loadings		Contribution of the variates(%)	
					PC1	PC2	PC1	PC2
1	2.39	99.18	99.18	AUDPC	1.24	-0.07	65.15	32.98
2	0.01	0.76	99.94	rAUDPC	0.63	0.09	17.05	51.05
				rFDS	0.65	0.05	17.79	15.96

PC; Principal component; AUDPC: Area under Disease Progress Curve stem rust; rAUDPC: relative area under disease progress curve; rFDS: relative final disease severity.

Table 6. Multiple regression analysis showing effects of stem rust and yellow rust infection on yield, TKW and biomass of the tested cultivars evaluated in 2019 and 2020 cropping season.

	Variable	Parameter Estimate	Standard Error	C_p	Partial R^2	Model R^2	*P*
OS 2019							
Yield	Intercept	6.0693	0.3456				
	AUDPC $_{SR}$	-0.0021	0.0006	2.29	0.1287	0.1261	0.0010
	AUDPC $_{YR}$	-0.0041	0.0036	3.00	0.0142	0.1429	0.2590
	Yield=6.06 - 0.0021(AUDPC$_{SR}$) - 0.0041(AUDPC$_{YR}$)						
TKW	Intercept	23.5630	0.8835				
	AUDPC $_{SR}$	-0.0036	0.0019	1.04	0.0420	0.0420	0.0665
	TKW= 23.56 - 0.0036 (AUDPC $_{SR}$)						
Biomass	Intercept	24.3806	1.0963				
	AUDPC $_{SR}$	-0.0124	0.0024	2.35	0.2563	0.2563	<0.0001
	AUDPC $_{YR}$	-0.0160	0.0138	3.00	0.0127	0.2690	0.2484
	Biomass= 24.38 - 0.0124(AUDPC $_{SR}$) - 0.0160 (AUDPC $_{YR}$)						
MS 2019							
Yield	Intercept	7.8401	0.5221				
	AUDPC $_{SR}$	-0.0018	0.0008	3.00	0.0479	0.0479	0.0440
	AUDPC $_{YR}$	-0.0043	0.0017	5.19	0.0601	0.0601	0.0274
	Yield= 7.84 – 0.0018(AUDPC $_{SR}$)– 0.0043(AUDPC $_{YR}$)						
TKW	Intercept	22.4759	0.9538				
	AUDPC $_{SR}$	-0.0076	0.0016	1.59	0.2195	0.2195	<0.0001
	AUDPC $_{YR}$	-0.0024	0.0031	3.00	0.0059	0.2254	0.4447
	TKW= 22.47– 0.0076 (AUDPC$_{SR}$) – 0.0024 (AUDPC$_{YR}$)						
Biomass	Intercept	37.4297	1.8888				
	AUDPC $_{SR}$	-0.0088	0.0031	3.00	0.0669	0.3234	0.0069
	AUDPC $_{YR}$	-0.0335	0.0062	8.70	0.2565	0.2565	<0.0001
	Biomass= 37.42= -0.0088(AUDPC $_{SR}$)- 0.0335 (AUDPC $_{YR}$)						
OS 2020							
Yield	Intercept	3.6749	0.2526				
	AUDPC $_{SR}$	-0.0009	0.0005	2.19	0.0213	0.0213	0.1938
	AUDPC $_{YR}$	0.0010	0.0009	3.00	0.0148	0.0361	0.2772
	Yield= 3.67= -0.0009(AUDPC $_{SR}$)- 0.0010 (AUDPC $_{YR}$)						
TKW	Intercept	13.8251	0.7164				
	AUDPC $_{SR}$	-0.0035	0.0016	2.28	0.0432	0.0432	0.0626
	AUDPC $_{YR}$	0.0032	0.0028	3.00	0.0155	0.0587	0.2609
	TKW= 13.82- 0.0035 (AUDPC $_{SR}$)- 0.0032 (AUDPC $_{YR}$)						
Biomass	Intercept	22.9706	1.1887				
	AUDPC $_{SR}$	-0.0083	0.0027	3.59	0.1472	0.1472	0.0004
	AUDPC $_{YR}$	-0.0075	0.0047	3.00	0.0275	0.1747	0.1111
	Biomass= 22.97- 0.0083(AUDPC $_{SR}$) – 0.0075 (AUDPC $_{YR}$)						

OS: Off season; MS: Main season; TKW: 1000- Kernel weight; AUDPC$_{SR}$: Area under disease progress curve stem rust; AUDPC$_{YR}$: Area under disease progress curve yellow rust.

for TKW (Cp=2.28) and 14.72% biomass (Cp=3.59) while high AUDPC$_{YR}$ accounted for 2.75% less biomass (Table 6).

Discussion

In this study, significant variation due to season for AUDPC$_{SR}$, AUDPC$_{YR}$, yield and yield components could be attributed to differences in variability of temperature and moisture. Mideksa et al. (2018) reported that an increase of rainfall during wheat growing periods led to surge in severity of stem rust on wheat. In this study, significant effects due to cultivar for agronomic traits, yield and rust diseases could be due to variation of genetic and background effects. Genotypic effects have been observed on wheat for plant height, biomass, TKW and yield by Alemu et al. (2018). In this study, season × cultivar interaction suggests that rust infection, yield and yield components among the cultivars varied with seasons. It has been shown that significant season × cultivar interaction indicates variable response of cultivars to the season for yield, days to heading, plant height, TKW and test weight in durum wheat (*Triticum turgidum*) (Sakin et al., 2011). The high mean yield obtained during the MS 2019 was attributed to high precipitation and probably long spike length which bore feretile florets with high number of kernels spike^{-1}. It has been observed that long spike length bear high number of kernels spike^{-1} that contributes to yield (Assefa and Kassaye, 2017). During OS 2019, high temperatures might have reduced fertile florests on the spikelets. In this study, genetic constitution of the cultivars contributed immensely to the rust reaction observed as translated into AUDPC. Stem rust infection was high during MS 2019 due to warm humid weather experienced. Normally, stem rust infection is favoured by day temperatures ranging between 23 - 30 ˚C, night temperatures of <15 ˚C and high relative humidity at night during the main wheat growing season in Njoro (Wanyera et al., 2016). Infection of yellow rust on wheat occurs when temperatures ranges 2 - 15 ˚C (Shrestha et al., 2021). Therefore, in this study, infection of *Yr* on wheat was high during OS 2020 because of frequent precipitation and cool weather that prevailed. Cultivars that exhibited a high AUDPC$_{_YR}$ with low AUDPC$_{_SR}$ was due to the reduction on photosynthetic area which is important for stem rust infection and spread. Correlation observed between yield, TKW and kernels spike^{-1} suggested an association between TKW and kernels spike^{-1} with yield. Other studies have reported improving number of kernels spike^{-1} and TKW will result in high yields (Kashif and Khaliq, 2004; Pal et al., 2010). A positive correlation was observed between biomass and yield and this was attributed to a high biomass which resulting to an increase in yield. Budak and Yıldırım, (1999) found similar correlation between biomass and yield in wheat and ascribed it to the total proportion of available assimilates which are translocated into the kernels. Days to heading showed a significant negative association with TKW suggesting that wheat plants took longer days to head hence reducing the grain filling period. This was consistent with findings of Khan et al. (2013) who reported negative correlation between days to heading and TKW. The PC analysis of the disease parameters showed the total variation in PC1 was due to AUDPC suggesting that it is the most effective parameter to identify resistant cultivars against *Sr* and *Yr*. This is in line with Singh et al. (2015) who reported that AUDPC showed a positive factor loading of 0.93 indicating it is more precise for evaluating partial resistance. This study showed that rFDS is also an important parameter to determine rust resistance. Contrary Abu et al. (2017) reported final disease severity was more appropriate for evaluating large number of genotype. Based on the findings of this study PC2 exhibited rAUDPC to be an important component for determining rust resistance, it compares the severity of each cultivar to severity of susceptible check. However, in a different study on evaluation of potato (*Solanum tubersome*) genotypes revealed that rAUDPC of the same cultivar varied among trials and thus it was limited in quantifying susceptibility (Yuen and Forbes, 2009). The biplot showed that variation due to PC1 and PC2 accounted for high proportion of the variations on yield and yield components due to cultivar and cultivar by trait interactions. This finding is in agreement with Ali et al. (2021), who found out PC1 and PC2 accounted for 52.77% of total variation of plant height, yield, days to he and TKW in wheat advanced lines. Traits such as plant height, TKW, yield, kernels spike^{-1}, days to heading and spike length had long vectors and were the most responsive traits in discriminating between the cultivars that performed well for those traits. Positive correlation between yield, TKW, kernels spike^{-1} and biomass as shown by the acute angles imply that cultivars plotted along these vectors possess multiple desirable traits that can be used for development of high yielding cultivars with good agronomic attributes. Gholizadeh and Dehghani (2018) used a graphical representation of a genotype × trait biplot in a study on wheat to select promising genotypes for plant height, kernels spike^{-1}, yield, spike length and days to heading.

From the stepwise regression analysis, *Sr* was observed to be an important disease in reducing yield and TKW. Stem rust fungus infects the leaves and awns of wheat which are the source of photosynthetic activities, destroys the xylem and phloem therefore interfering with with nutrient flow to developing kernels resulting to shriveled kernel (Mitiku et al., 2018). Yellow rust reduced biomass due to its earlier occurrence than *Sr* resulting in chlorosis and necrosis which affected photosynthesis in the tested cultivars. Abdennour et al. (2018) found that yellow rust is associated with a reduced capacity of the canopy to absorb solar radiation hence affecting the photosynthetic activity of the leaves.

Materials and methods

Experimental site

A field experiment was conducted during OS 2019 (January-May), MS 2019 (June-November) and OS 2020 (January - May) at Kenya Agricultural and Livestock Research Organization (KALRO), Njoro (0˚ 20'S and 35˚56'E). The site receives annual rainfall of 931 mm, altitude is 2160 m above the sea level and the temperature ranges from 15.7-17.5 ˚C (Jaetzold et al., 2012). The soil is predominantly *Mollic Andosols* that is well drained. The experimental site is situated in the main wheat production areas of the Central Rift Valley regions of Kenya.

Cultivars

A set of 81 Kenyan wheat cultivars released between 1920 and 2016 were used in this study. The cultivars were selected based on performance on yield and yield components. Wheat line Cacuke was included in the study as a susceptible check (Supplementary Table 1).

Experimental procedure

The field trial was planted in a field that was previously under canola (*Brassica napus*). The land was disc ploughed and harrowed to a fine tilth suitable for wheat growing. While making furrows, Di-ammonium Phosphate, (DAP) fertilizer was applied at 125 kg ha^{-1} to supply an equivalent of 22.5 kg N ha^{-1} and 57.5 kg P ha^{-1}. Each cultivar was sown in a 2-row experimental unit measuring 0.7 × 0.2 m with an equivalent seed rate of 125 Kg ha^{-1}. Irrigation using sprinklers was done after planting to initiate uniform germination and growth of seedling. When the plants attained growth stage GS20 (Zadoks et al.,1974) the plots were top dressed with urea at 100 kg ha^{-1} to supply an equivalent of 27 kg N ha^{-1}. In this study a 9 × 9 partially balanced lattice design with 3 replications was used. Plots within blocks and blocks within replicates were separated by 0.3 m wide alleyway. A spreader mixture of susceptible stem rust wheat lines; six-*Sr24* carrying lines (CIMMYT Germplasm Identification, 5391050, 5391052, 5391056, 5391057, 5391059 and 5391061), susceptible line Cacuke#1 (GID 7400914) was planted in an alley of 0.5 m between replicates. Post-emergence herbicide Buctril MC® at GS13-30 to control broad leaf weeds (Zadoks et al., 1974) was applied after sowing. A systemic insecticide Thunder OD® 145 was applied at tillering (GS20-29) and ear emergence (GS50-59) stages at rate of 6 kg ha^{-1} to control Russian wheat aphid (*Diuraphis noxia*).

Data collection

Stem rust and yellow rust severity were visually assessed as percentage of the stem and leaf area covered by pustules per plot, respectively based on modified Cobb Scale ranging from 0 to 100% (Peterson et al., 1948). Plant response was based on type of uredinia pustules with presence or absence of necrosis and/or chlorosis (Roelfs et al., 1992). Each cultivar was considered to have attained 50% of spikes emerged completely from the boot. The plant height was determined by measuring from the base of the plant to the tip of the spike excluding awns from a random sample of 5 plants. Spike length was measured from the first node where the first spikelet emerged to the spike tip excluding awns. The kernels spike^{-1} was an average of 5 randomly selected spikes per cultivar. Thereafter, at physiological maturity plants in each plot were harvested by cutting the plants at the base, thereafter, threshed by a stationary thresher (Model LPTD, serial no. T09235 ALMACO USA, NEVADA Iowa, USA) and winnowed. Individual plots were cut close to the ground level, air-dried in the sun and then weighed to determine biomass. Yield was estimated from each plot after cleaning and drying to approximate 12% moisture content and later converted to tonnes ha^{-1}. The 1000-kernels were obtained from each cultivar using a seed counter (CONTADOR; serial no. 14176107 Pfeuffer) and weighed to determine 1000-kernel weight (TKW).

Data analyses

The disease severity readings of both stem rust and yellow rust were used to compute AUDPC as described by Wilcoxson et al. (1975). Wheat line Cacuke was used as susceptible check as a reference to obtain the relative area under disease progress curve (rAUDPC) and relative final disease severity (rFDS) (Milus and Line, 1986).

Combined analysis of variance (ANOVA) was done to determine the significant differences among the wheat cultivars for multiple agronomic traits using *PROC GLM* in Statistical Analysis System version 8.2 (SAS, Institute, Cary NC, 2001) using the following statistical model.

$$Y_{ijklm} = \mu + S_i + R_{j(i)} + B_{K(IJ)} + C_l + CS_{il} + \varepsilon_{ijklm}$$

Where Y_{ijklm}= Observation of the experimental units, μ =Overall mean; S_i= Effect due to i^{th} season, $R_{j(i)}$ =Effect due to j^{th} replicate within the i^{th}season, $B_{K(IJ)}$=Effect due to k^{th} block within the i^{th} season and the j^{th} replicate, C_l = effect due to the l^{th} cultivars, CS_{il}= Effect due to interaction between the i^{th} season and the l^{th} cultivar, ε_{ijklm} = Random error component.

Cultivars were considered as fixed factors while blocks, seasons, replicates and the interaction of cultivars and season were considered as random factors. Means of wheat cultivars were separated using Tukey Studentized Range procedure at $p \leq 0.05$. A Pearson correlation coefficient test was calculated using SAS *PROC CORR*. The contributions of disease parameters in evaluating the wheat cultivars for rust resistance was done using principal component analysis (PCA) procedure. The biplot was performed in XLSTAT to show the proportion of variance explained by each yield component and identify cultivars with several desirable traits. Stepwise multiple regression was conducted using SAS *PROC REG* forward elimination method to determine effect of stem rust and yellow rust on yield, biomass and TKW.

Conclusion

The study found significant variation for *Sr* and *Yr* reaction and agronomic traits among 81 wheat cultivars. Cultivars Bounty, *Leopard*, *Lenana*, *Gem* and *K. Kongoni* were identified as high yielding with low AUDPC values for *Sr* and *Yr*. These cultivars could be exploited in breeding programs as sources of resistance.

Acknowledgements

This research was supported by the Delivering Genetic Gain in Wheat (DGGW) project #OPP133199 (funded by the Bill and Melinda Gates Foundation and the United Kingdom Department for International Development (DFID), Accelerating Genetic Gain (AGG) in Maize and Wheat Project Grant (Grant INV-003439) funded by the Bill and Melinda Gates Foundation (BMGF), the Foreign and Commonwealth Development Office (FCDO) and Foundation for Food and Agriculture Research (FFAR).

References

Abdennour S, Sahbi F, Houcine B (2018) Yellow rust effects on grain yield, and yield components of some spring bread wheat cultivars under rainfed conditions. World J Agri Res. 6: 65-69.

Abu AAM, Omara RI, El-Malik A, Nagwa I (2017) Evaluation of new sources of resistance to wheat stripe rust (*Puccinia striiformis* f. sp. *tritici*), under Egyptian field conditions. J Plant Prot Pathol. 8: 181-188.

Addinsoft (2022) XLSTAT statistical and data analysis solution. New York, USA. https://www.xlstat.com/en.

Adilova SS, Qulmamatova DE, Baboev SK, Bozorov TA, Morgunov AI (2020) Multivariate cluster and principle component analyses of selected yield traits in Uzbek bread wheat cultivars. Am J Plant Sci. 11: 903.

Alemu G, Mohammed H, Asnake D (2018) Analysis of genotype by environment interaction for agronomic traits of bread wheat (*Triticum aestivum* L.) genotype in Ethiopia. J Agric Res. 3: 1-11.

Ali N, Hussain I, Ali S, Khan NU, Hussain I (2021) Multivariate analysis for various quantitative traits in wheat advanced lines. Saudi J Biol Sci. 28: 347–352.

Ali S, Liu Y, Ishaq M, Shah T, Abdullah Ilyas A, Din I (2017) Climate change and its impact on the yield of major food crops: evidence from Pakistan. Foods. 39: 1-19.

Al-Saady NAB, Nadaf SK, Al-Lawati AH, Al-Hinai SA (2018) Genetic diversity of indigenous mungbean (*Vigna radiata* L. Wilczek) germplasm collection in Oman. Agric For Fish. 7: 113-120.

Assefa A, Kassaye M (2017) Response of bread wheat (*Triticum aestivum* L.) varieties to different seeding rate for growth, yield and yield components in Kombolcha district, North-Eastern Ethiopia. J Biol Agr Healthc 7: 79-91.

Bhavani S, Hodson DP, Huerta-Espino J, Randhawa MS, Singh RP (2019) Progress in breeding for resistance to *Ug99* and other races of the stem rust fungus in CIMMYT wheat germplasm. Front Agr Sci Eng. 6: 210-224.

Budak N, Yıldırım MB (1999) Correlations among the yield and yield components at segregating populations derived from selection based on harvest index in bread wheat. Cereal Res Commun. 27: 267-272.

Gholizadeh A, Dehghani H (2016) Graphic analysis of trait relations of Iranian bread wheat germplasm under non-saline and saline conditions using the biplot method. Genetika+. 48: 473-486.

Jaetzold R, Schmidt H, Hornetz B, Shisany CA (Eds.) (2012) Farm management handbook of Kenya vol. I-IV (Western Central Eastern Nyanza Southern Rift Valley Northern Rift Valley Coast); Government Printers: Nairobi, Kenya, 2012.

Kashif M, Khaliq IH (2004) Heritability, correlation and path coefficient analysis for some metric traits in wheat. Inter J Agric Bio. 6: 138-142.

Khan AA, Alam MA, Alam MK, Alam MJ, Sarker ZI (2013) Genotypic and phenotypic correlation and path analysis in durum wheat (*Triticum turgidum* L. var. durum). Bangl J Agric Res. 38: 219-225.

Mideksa T, Fininsa C, Hundie B (2018) Analysis of climate variability effects on wheat stem rust (*Puccinia graminis* f. sp *tritici*) epidemics in Bale and Arsi Zones of Oromia Regional State, Ethiopia. Am J Bio Envt Stat. 4: 49-65.

Milus EA, Line RF (1986) Gene action for inheritance of durable, high-temperature, adult-plant resistance to stripe rust in wheat. Phytopathology. 76: 435-411.

Mitiku M, Hei NB, Abera M (2018) Characterization of slow rusting resistance against stem rust (*Puccinia graminis* f. sp. *tritici*) in selected bread wheat cultivars of Ethiopia. Adv Crop Sci Tech. 6: 3-8.

Pal S, Singh T, Ramesh B (2010) Estimation of genetic parameters in barley (*Hordeum vulgare* L.). Crop Improv. 37:52-56.

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

Roelfs AP, Singh RP, Saari EE (1992) Rust diseases of wheat: Concepts and methods of disease management. CIMMYT, Mexico, DF. pp. 46.

Sakin MA, Akinci C, Duzdemir O, Donmez E (2011) Assessment of genotype x environment interaction on yield and yield components of durum wheat genotypes by multivariate analyses. Afr J Biotechnol. 10: 2875-2885.

SAS Institute (2002) SAS user's guide: Statistics version 9.2 for windows. SAS Institute, Carry NC.

Shrestha R, Mahto BN (2021) Screening of wheat (*Triticum aestivum* L.) genotypes for rust-resistance and assessment on prevalence and distribution of the rust diseases in wheat production fields. J Agr Nat Resour. 4: 186-200.

Singh AK, Singh VK, Chand R, Kushwaha C, Srivastava CP (2015) Evaluation of slow rusting components in pea. J Plant Pathol. 97: 87-92.

Singh S, Singh RP, Bhavani S, Huerta-Espino J, Eugenio LVE (2013) QTL mapping of slow-rusting, adult plant resistance to race *Ug99* of stem rust fungus in PBW343/Muu RIL population. Theor Appl Genet 126: 1367-1375.

Soko T, Cornelia MB, Prins B, Pretorius ZA (2018) Yield loss associated with different levels of stem rust resistance in bread wheat. Plant Dis. 102: 2531-2538.

Spanic V, Cosic J, Zdunic Z, Drezner G (2021) Characterization of agronomical and quality traits of winter wheat (*Triticum aestivum* L.) for fusarium head blight pressure in different environments. Agron. 11: 213.

Wanyera R, Macharia JK, Kilonzo S (2010) Challenges of fungicide control on wheat rusts in Kenya. Intech. 124-138.

Wanyera R, Wamalwa M, Odemba M, Wanga H, Kinyanjui P, Onyango V, Owuoche J (2016) Management of wheat rusts at different growth stages using Nativo 300 SC (*trifloxystrobin* 100g/L+ *tebuconazole* 200g/L) fungicide. Aust J Crop Sci. 10: 1273-1280.

Wilcoxson RD, Skovmand B, Atif AH (1975) Evaluation of wheat cultivars for ability to retard development of stem rust. Ann appl biol. 80: 275-281.

Xi K, Chen XM, Capettini F, Falconi E, Yang RC, Helm JH, Turkington TK (2013) Multivariate analysis of stripe rust assessment and reactions of barley in multi-location nurseries. Can J Plant Sci. 93: 209-219.

Yuen JE, Forbes GA (2009) Estimating the level of susceptibility to *Phytophthora infestans* in potato genotypes. Phytopathology. 99: 782-786.

Zadoks JC, Chang TT, Konzak CF (1974) A decimal code for the growth stages of cereals. Weed Res. 14: 415-421.