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Incorporating Yellow Rust Resistance Genes *Yr8, 15*, 27, 34 And *57* In Some Susceptible Egyptian Bread Wheat Cultivars

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ABSTRACT

Five yellow rust monogenic lines were used as donors of the genes *Yr8, Yr15, Yr27, Yr34* and *YR57* to the Egyptian bread wheat cultivars Misr-1, Misr-2, Gemmeiza-11 and Shandaweel-1 through conventional crossing during 2019/2020 to 2021/2022 seasons at Sakha Agricultural Research Station. The monogenic lines were evaluated at Sakha, Kafrelhamam and Sids Stations while parents, F$_1$ and F$_2$ were evaluated at Sakha. The results showed that genotypes carrying *Yr5, Yr8, Yr10, Yr15, Yr27, Yr33, Yr37, Yr51, Yr57, YrKK* and *YrALD* yellow rust resistance genes recorded resistance to *Puccinia striiformis tritici* pathotypes at all locations. All the crosses between the monogenic lines carrying *Yr8, Yr15* and *Yr27* genes recorded resistant field response while, most crosses including *Yr34* and *Yr57* showed susceptibility. High estimates for genetic variance and broad sense heritability were obtained for all crosses indicating that selection to yellow resistance would be practiced in segregating generations. The highest number of resistant F$_2$ plants was recorded in crosses of *Yr15* to any of the four susceptible wheat cultivars. Based on this study, the efficiency of genes can be arranged in the order of *Yr15*>*Yr8*>*Yr27*>*Yr57* with Misr-1 and Misr-2 background and *Yr15*>*Yr27*>*Yr8*>*Yr57*>*Yr34* with Gemmeiza-11 and Shandaweel-1 background. Therefore, it is recommended to introduce and pyramid *Yr8, Yr15, Yr27* and *Yr57* yellow rust resistance genes in the national wheat breeding program for yellow rust genetic control. The selected F$_2$ plants from this study can be used to create genetic diversity and obtain high yielding wheat germplasm carrying these effective genes.

Keywords: Bread wheat, breeding, rust resistance, effective *Yr* genes.

INTRODUCTION

Puccinia striiformis tritici (Pst), commonly known as yellow rust (YR), poses a significant threat to wheat production in Egypt. This biotic factor is particularly damaging due to the favorable climatic conditions prevalent in the old land of Delta and northern governorates of the Nile valley. The climate, characterized by cool and moist conditions, creates an ideal environment for the proliferation and spread of the Pst fungus, leading to severe wheat yield losses in these regions. YR poses a global threat to wheat production, affecting approximately 88% of wheat-growing areas worldwide. Each year, the disease leads to an estimated loss of 5 - 6 million tons of wheat (Beddow *et al.*, 2015), with yield reductions ranging from 10% to as high as 70% in severely affected regions (Ye *et al.*, 2022). The damaging impact of yellow rust on wheat crops stems from its interference with photosynthetic processes in the affected cells (He *et al.*, 2019). This results in reduced light interception and inefficient radiation use, ultimately leading to significant yield losses. The extent of the damage varies depending on multiple factors, including the wheat cultivar used, the timing and duration of infection, pathogenicity rate, and the overall disease duration (Xia, 2020 and Prasad *et al.*, 2020). In certain extreme situations, yellow rust outbreaks have caused complete devastation, resulting in 100% loss in specific regions (Khanfri *et al.*, 2018). For example, in the United States, there were fourteen serious outbreaks between 1958 and 2014, leading to a considerable 25% reduction in wheat yield (Chen 2005, and 2014). The spread of yellow rust is not limited to specific regions but has become a widespread problem in many parts of the world. North America, South America, northern Africa, eastern Europe, Australia, central Asia and southern Asia have all experienced new yellow rust epidemic areas. For instance, Caucasus and central Asia between 1999 and 2009 suffered four serious outbreaks, causing yield losses of 20-40%. Australia faced a dire situation in 1984 and 1986, with yellow rust outbreaks resulting in a staggering 80% reduction in wheat yields (Murray and Brennan, 2009).

The introduction of wheat yellow rust caused by *Puccinia striiformis tritici* (*Pst*) to Egypt was first documented in 1920. Over the years, researchers have observed the emergence of virulence changes and new races within Egypt in the wheat stripe rust pathogen. One notable instance was the identification of the "Warrior" race of wheat stripe rust in Egypt, which was described by Shahin (2020). This development has led to the loss of resistance, as the new races have overcome the existing resistance mechanisms. Managing the spread of yellow rust becomes a challenging task, particularly when the rust races acquire new virulence to overcome specific genetic resistance in cultivated varieties. This challenge arises when resistance is conferred by race-specific genes. Consequently, applying genetic control measures becomes a major challenge in combating the

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disease effectively. To address this issue, the most cost-efficient, productive, and environmentally friendly approach involves planting wheat cultivars that carry resistance genes of yellow rust. Research by Ren *et al.* in 2009 and Ellis *et al.* in 2014 highlights the importance of selecting resistant varieties to relieve the influence of yellow rust on wheat production. Apart from genetic control, chemical control methods also play a crucial role in managing the spread of yellow rust. Studies conducted by Chen in 2005 and 2014 emphasize the significance of using appropriate fungicides to control and contain the disease effectively.

Many yellow rust resistance genes (Yr) have been recognized and sited on different chromosomes; additionally, several Yr have been cloned. Scientists have identified > 80 officially discovered *Yr* genes, and some of them are recessive genes (*Yr 2*, *Yr 6*, *Yr 7*, *Yr 19*, *Yr 23* and *Yr 51*), while most of the others *Yr* genes are dominant. Introducing the resistance genes of wheat related species is very important to improve wheat resistance ability and increase the range of resistance genes. Yr 7, Yr 10, Yr 15, Yr AS2388, and Yr U1 are all-stage resistance genes derived from wheat lines and wild species (Xu *et al.*, 2022). Many yellow rust resistance genes have completely broken down in the field due to the changes in the prevalence of virulent pathotypes. For instance, only *Yr5*, *Yr12*, *Yr13*, *Yr14*, *Yr16*, *Yr18*, *Yr36*, *Yr41*, *Yr44*, *Yr46*, *Yr48*, *Yr50*, *Yr52*, *Yr59*, *Yr62*, *Yr69* and *Yr83* (Sharma-Poudyal *et al.*, 2013, Hou *et al.*, 2016, Jiang *et al.*, 2020, and Li *et al.*, 2020) remain resistant in China to the prevalent virulent pathotypes, *Yr5*, *Yr10, Yr15*, *YrSp* in Egypt (Ragab *et al.*, 2020). The Mendelian genetic method generally uses F_1 and F_2 of crossing between susceptible and resistant plants to analyzed whereby wheat resistance genes. The *Yr* gene is presumed to be dominant gene if the F_1 plants is similar to the resistant parent. Otherwise, the *Yr* gene is presumed to be recessive if the phenotype is susceptible. In addition, segregation ratio of the F_2 generation shows number of genes-controlled trait (Ren *et al.,* 2022). In conclusion, tackling the threat of yellow rust in Egypt requires a multifaceted approach that includes deploying resistant wheat varieties to protect the nation's wheat crops and ensure food security.

The primary goal of this study is to enhance wheat yield by incorporating resistance genes of yellow rust into the prevailing Egyptian wheat cultivars. By doing so, the research aims to develop wheat genotypes that carry specific Yr effective genes, thus equipping these varieties with robust resistance against yellow rust. This integration of resistance genes into the cultivated wheat varieties is expected to provide an effective and sustainable solution to combat the damaging effects of yellow rust and ultimately maximize wheat production in Egypt.

MATERIALS AND METHODS

Experimental site and plant materials

This investigation was carried out at the experimental farm of Sakha Agricultural Research Station, Egypt, during three wheat-growing seasons 2019/2020, 2020/2021 and 2021/2022. Four Egyptian bread wheat cultivars (provided by Wheat Research Department, Field Crops Research Institute, Agricultural Research Center (ARC), Egypt) and five yellow rust monogenic lines (obtained from the International Maize and Wheat Improvement Center, CIMMYT) were used in this study (Table 1). Yellow rust races identification was conducted in Sakha Greenhouse of Wheat Diseases Research Department, Plant Pathology Research Institute, ARC, Egypt.

Table 1. Name, pedigree and origin of the selected bread wheat genotypes.

Name	Pedigree	Yellow rust field response†	Origin
Misr 1	OASIS/SKAUZ//4*BCN/3/2*PASTOR CMSS00Y01881T-050M-030Y-030M-030WGY-33M-0Y-0S	100S	Egypt
Misr 2	SKAUZ / BAV92 CMSS96M03611S-1M-010SY-010M-010SY-8M-0Y-0S	100S	Egypt
Gemmeiza 11	BOW"S"/KVZ"S"//7C/SER182/3/GIZA168/SAKHA 61 GM7892-2GM-1GM-2GM-1GM-0GM	100S	Egypt
Shandaweel 1	SITE/MO/4/NAC/TH.AC//3*PVN/3/MIRLO/BUC CMSS93B00567S-72Y-010M-010Y-010M-3Y-0M-0HTY-0SH	100S	Egypt
Yr8	Yr8/6*AOC	0	CIMMYT
Yr15	Yr15/6*AOC	0	CIMMYT
Yr27	Yr27/6*AOC	Tr R	CIMMYT
Yr34	Yr34	50MRMS	CIMMYT
Yr57	Yr57	Tr R	CIMMYT

†0=Immune. R = resistant (necrosis with few uredinia); MR = moderately resistant (necrosis with small to moderate number of uredinia); MS = moderately susceptible (moderate number of uredinia with chlorotic areas); and S = susceptible (large number of uredinia, no necrosis but chlorosis may be evident).

Crossing and field evaluation

During 2019/2020 season, the selected four Egyptian bread wheat cultivars and the five *Yr* monogenic lines were sown in three planting dates to synchronize the differences in flowering. Each parent was represented by two rows; 2.5 m long and spaced widely at 30 cm apart on each planting date. Each of the four wheat cultivars (yellow rust susceptible parents) was crossed to the five resistance parents carrying the mono-genes *Yr8*, *Yr15*, *Yr27*, *Yr34*, and *Yr57* to produce 20 F_1 hybrids. In 2020/2021 season, the F_1 seeds were sown in rows of 2.5 m long and spaced widely at 30 cm apart of each cross to allow for the production of the largest amount of F_2 seeds. The F_1 plants of Misr 1/Yr 34 and Misr 2/Yr 34 crosses was dwarf and did not give enough seeds for F_2 generation, so it was excluded from study. In addition, the F_1 seeds of the 18 crosses (all crosses except Misr 1/Yr 34 and Misr 2/Yr 34 crosses) were reproduced by crossing the parents.

The evaluation field experiment was grown in 2021/2022 season. The nine parents, F_1's and F_2's were arranged in randomized complete block design (RCBD) with three replications. The two parents, F_1 and F_2 of each cross were planted in rows 4 m long, 30 cm apart and 20 cm between plants. Each replicate consisted of 20 rows (one for each for P_1, P_2 and F_1 and 17 for F_2). To get uniform yellow rust inoculation, the experiment was surrounded by highly susceptible yellow rust spreader wheat cultivar (Morocco). The responses of 10 plants of each parent and F_1 and about 200 plants from each F_2 to the *Pst* pathotypes, were recorded at the adult plant stage using a Modified Cobb's scale (Peterson *et al.*, 1948). Data on plant height, number of spikes per plant, number of kernels per spike, spike kernels weight, 100-kernel weight and grain yield per plant were recorded on 10 individual plants of each parent and F_1 and on 20-25 resistant F_2 plants from each cross.

Inoculation and field response to yellow rust

Fifteen *Pst* pathotypes were identified in Egypt during 2021/2022 wheat season. Virulence of these *Pst* pathotypes on *Yr* genes ranged from 3 (4E24 and 2E44) to 13 genes (174E191 and 246E175) at seedling stage in greenhouse of Wheat Disease Department at Sakha (Table 2). A mixture of the most virulent *Pst* pathotypes races were used to inoculate the plants in the field experiment. At the wheat booting stage, spreader row plants were inoculated using the technique described in (Tervet and Cassel, 1951). At the adult plant stage, the responses of each of the studied wheat genotypes to the Pst pathotypes were measured using the Modified Cobb's scale (Peterson *et al.*, 1948 and Roelfs *et al.*, 1992) techniques.

This approach used the symbols 0, R, MR, MS, and S to represent immune, resistance, moderately resistance, moderately susceptible, and susceptible (IT), respectively. Plants with infection types 0, R, and MR were grouped together and deemed resistant, whereas plants with infection types of MS and S were deemed susceptible. When the flag leaf reaction of the susceptible control rust severity reached 100S, the yellow rust reaction (severity and infection type) was noted at the adult stage of the tested plants. The method suggested by Saari and Wilcoxson (1974) was used to convert the field response into an average coefficient of infection (ACI) for quantitative analysis. ACI was calculated by multiplying infection severity by a constant value that was assigned, namely 0.0, 0.2, 0.4, 0.8, and 1 for infection types 0, R, MR, MS, and S, respectively.

Table 2. Virulence patterns of *Puccinia striiformis* f. Sp. *tritici* races detected during the 2021/2022 season in Egypt.

Pathotype[†]	Virulence formulae	New/Old	No of virulent genes	Race virulence%	Sample collected Source
134E24	7, 6,9, (3),8 /	old	5	23.52	Gemmeiza 11
134E143	7,6,9,4,(7),(6), (3),2/	new	8	41.17	Gemmeiza 11
8E62	3,(7),(6), (3),8,CV/	old	6	35.29	Misr 1
12E138	6,3 ,(7),(3),2/	new	5	29.41	Misr 1
174E191	7,6,3,SD,9,2,4,(7),(6),(3),8,CV,2/	new	13	76.47	Misr 1
78E191	7,6,3,SU,4,(7), 6, (3),8,CV, 2 /	new	11	64.70	Misr 2
6E153	7,6,4,(3),8,2/	new	6	35.29	Misr 2
6E167	7, 6,4,(7),(6),CV,2	new	7	41.14	Misr 2
78E159	7,6,3,SU,4,(7),(6),(3),8,2/	new	10	58.82	Sakha 95
246E175	7,6,10,SD,SU,9,4,(7),(6),(3),CV,SP,2/	new	13	76.47	Sakha 95
6E166	7, 6,(7),(6),CV,2/	old	6	35.29	Sdis 12
4E24	6, (3), 8/	old	3	17.64	Sdis 13
198E30	7, 6, SU, 9, (7), (6), (3), 8/	new	8	47.05	Sids 14
2E44	7, (6),(3), CV/	old	4	17.64	YR 7
132E60	6,9,(6), (3), 8, CV/	old	6	29.41	YR 9

[†] Refer to Johnson *et al.*, (1972) for pathotype nomenclature

Genetic and statistical analysis

Some genetic factors were calculated using genetic analysis based on yellow rust reaction data from the parents', F_1's, and F_2's plants. According to Little and Hills (1978), the significance of the difference between observed and expected ratios for the yellow rust reaction in F_2 populations was tested using the Chi-square test (χ^2).

The mode of inheritance and differences in resistance genes between the two parents were determined using the ratio of resistant to susceptible plants in segregating populations. For the kind and severity of yellow rust infection in F_2 plant populations, the frequency distribution values were calculated under field circumstances. The seven classes of field responses for F_2 plants were 0, 5R, 10MR, 20MS, 40MS, 40S, and 100S. According to Allard (1960), phenotypic variance (VP), environmental variation (VE), and genotypic variance (VG) were evaluated using the ACI means of the parents, F_1, and F_2 populations.

$$\boldsymbol{VE = \left[\frac{VP_1 + VP_2 + VF_1}{3}\right]}$$

$$\boldsymbol{VP = VF_2}$$

$$\boldsymbol{VG = VP - VE}$$

Additionally, the genotypic coefficient of variation (GCV), the predicted genetic advance (g%) at 5% selection intensity, and broad sense heritability (h^2b) were computed as follows:

$$\boldsymbol{h^2b = \frac{VG}{VP} x\ 100} \textbf{ following Falconer and Mackay (1996)}$$

$$\Delta \boldsymbol{g}\% = \boldsymbol{\left[k\ x\ \left(VP^{0.5}\ x\ h^2b\right)/\bar{x}\right]} \textbf{ following Allard (1960)}$$

$$\boldsymbol{GCV = \left[\left(\frac{VG^{0.5}}{F_2 mean}\right) x\ 100\right]} \textbf{ following Singh and Naraynan (2000)}$$

RESULTS AND DISCUSSION

Yellow rust wheat monogenic line`s field response

The responses of yellow rust monogenic lines at adult plant stage to *Pst* pathotypes are presented in Table 3. The wheat monogenic lines showed a wide range of rust responses under field conditions during 2019/2020, 2020/2021 and 2021/2022 growing seasons. Yellow rust severity at Sakha and Kafrelhamam was higher than that of Sids station. Morocco cultivar recorded higher yellow rust severity in 2022 than the other two seasons. Wheat genotypes carrying yellow rust resistance genes; *Yr5*, *Yr8*, *Yr10*, *Yr15*, *Yr27*, *Yr33*, *Yr37*, *Yr51*, *Yr57*, *YrKK* and *YrALD* recorded 0, R or MR reaction type to *Pst* pathotypes during the three seasons (Table 3).

Meanwhile, monogenic lines carrying *YRA*, *Yr1*, *Yr6*, *Yr 7*, *Yr9*, *Yr 17*, *Yr18*, *Yr 24*, *Yr26*, *YrSP*, *YrCV*, *Yr34*, *Yr35*, *Yr4PL,* and *Yr54* lines recorded susceptible reaction (MS & S reaction type) during the three seasons.

Sakha location has suitable environmental conditions for rust development during wheat season therefore, the national wheat research program of Egypt is using this site as a hot spot for screening against the yellow rust. This study exhibited that the five genes *Yr5*, *Yr8*, *Yr15*, *Yr57*, *YrKK* and *YrALD* conferred complete-resistance field response against the dominating *Pst* races all over the country. Therefore, wheat breeders could use them in the national breeding program for gene pyramiding in high-yielding wheat genotypes in Egypt. In a previous study in Egypt, scientists Ragab *et al.* (2020) reported that the efficiency of yellow rust resistance genes *Yr5*, *Yr10* and *Yr15* in improving resistance of Sids 12 and Gemmeiza 11 bread wheat cultivars.

Table 3. Rust severity of *Yr* genes to yellow rust in three Egyptian governorates during 2019/2020, 2020/2021 and 2021/2022 growing seasons.

YR differential	YR gene[†]	2019/2020			2020/2021			2021/2022		
		Sakha[‡]	**Kafrelhamam**	**Sids**	**Sakha**	**Kafrelhamam**	**Sids**	**Sakha**	**Kafrelhamam**	**Sids**
Morocco	-	30S	30S	10S	20S	70S	5S	90S	90S	80S
Avocet-YRA	YRA	30S	5S	10S	10S	30S	5MS	90S	20S	80S
YR1/6*AOC	YR1	20S	10S	5S	10MR	20MR	10MR	70S	50S	70S
YR5/6*AOC	YR5	0	0	0	0	0	0	0	0	0
YR6/6*AOC	YR6	30S	20S	20S	5S	10S	5S	90S	80S	80S
YR7/6*AOC	YR7	40S	5S	20S	10S	20S	5S	80S	60S	90S
YR8/6*AOC	YR8	0	0	0	0	0	0	0	0	0
YR9/6*AOC	YR9	30S	10S	20S	10S	20S	5S	90S	80S	90S
YR10/6*AOC	YR10	0	0	0	0	0	0	40MR	TRMS	10MR
YR15/6*AOC	YR15	0	0	0	0	0	0	0	0	0
YR17/6*AOC	YR17	5S	0	5MS	10MR	20MR	5MR	20S	5S	10MS
YR18/3*AOC	YR18	10S	5MR	10S	5S	0	5S	60S	10S	90S
YR24/3*AOC	YR24	30S	10S	5S	5MS	TrMR	0	60S	5MS	40S
YR26/3*AOC	YR26	20MS	10MS	5MS	TrMS	TrMR	TrMS	60MS	10MS	20MS
YR27/6*AOC	YR27	TrMR	5MS	TrMR	0	0	0	5MR	0	5MR
YRSP/6*AOC	YRSP	10S	10S	5MS	0	0	0	TRMR	TRMS	10MS
YRCV/6*AOC	YRCV	40S	30S	20S	20MS	10MS	5MS	90S	20S	90S
YR33	YR33	0	0	0	0	0	0	60S	0	10MS
YR34	YR34	50S	20S	0	10S	0	0	90S	10S	5MS
YR35 98M71	YR35	10MS	10MS	20S	5S	5S	5S	0	TRS	70S
YR37	YR37	20MR	0	0	0	0	0	90MR	0	TRMR
YR4PL	YR4PL	10MS	0	10S	0	0	0	20MS	0	50S
YR51	YR51	5MR	10MR	5MR	0	0	0	5MR	TRMS	5MS
YR54	YR54	30S	30S	20S	TrS	TrS	10S	70S	0	90S
YR57	YR57	0	0	0	0	0	0	0	0	0
YRKK	YRKK	0	0	0	0	0	0	0	TRMR	0
YRALd	YRALD	0	0	0	0	0	0	0	0	0

[†] Resistance genes based on the studies of Chen, (2005); [‡] 0=Immune. R = resistant (necrosis with few uredinia); MR = moderately resistant (necrosis with small to moderate number of uredinia); MS = moderately susceptible (moderate number of uredinia with chlorotic areas); and S = susceptible (large number of uredinia, no necrosis but chlorosis may be evident).

Yellow rust parents and F_1s' field response

The adult plant response in the field to yellow rust for the studied wheat cultivars (Misr 1, Misr 2, Gemmeiza 11 and Shandaweel 1), the yellow rust monogenic lines (*Yr8*, *Yr15*, *Yr27*, *Yr34* and *YR57*) and their eighteen crosses during 2021/2022 season are presented in Table 4. All of the examined wheat cultivars showed susceptibility reaction (100S) in the field. The resistance field response was seen in the four yellow rust monogenic lines Yr8, Yr15, Yr27, and Yr57 while *Yr34* line showed moderate response (50MR-MS). Out of the studied eighteen crosses, twelve showed resistant field response, while six recorded susceptible responses (MS or S type). It was interesting that all crosses between the monogenic lines carrying *Yr8*, *Yr15* and *Yr27* genes recorded resistant field responses. On the other hand, all crosses including *Yr34* and *Yr57* showed susceptibility field response. F_1s' field response indicated that the dominance direction was toward resistance in all crosses except that included *Yr57* gene.

Yellow rust F_2 population`s field response

Yellow rust field response for about 200 F_2 plants from each cross were scored (Table 5). In twelve out of the tested eighteen crosses, majority of the scored F_2 plants were in resistant side. F_2 plants of the crosses between *Yr8*, *Yr15* and *Yr27* monogenic lines and the four studied cultivars showed higher number of resistant plants than susceptible ones in all crosses. A chi square test of the segregation populations showed that segregation at two or one separate loci was a good fit (Table 5). In the crosses included *Yr8* monogenic line, the test confirmed the previous result from F_1 of dominating resistant reaction over susceptibility. F_2 plants of the crosses with *Yr34* of resistant plants with Shandaweel 1 and vice versa with both Gemmeiza 11 cultivar.

For crosses with *Yr57*, higher number of F_2 plants resistant were recorded for Misr 1 cross while higher number of susceptible plants were recorded for Misr 2 and Gemmeiza 11 crosses.

Chi square test showed that the segregation data gave a good fit for segregation at three, two or one independent loci for the crosses between *Yr34* and *Yr57* monogenic lines and the studied cultivars (Table 5).

Number of resistant plants and mode of inheritance obtained from F_2 populations confirmed the results of F_1 that resistance is dominating over susceptibility in most crosses. There were different types of epistatic interactions, according to F_2 segregation ratios.

This result is in harmony with that obtained by Ragab *et al.* (2020). Yellow rust resistance is governed by partial dominant or recessive genes in particular crosses (Anpilogova, 1983), or by complementing genes (Chen, 2007 and Dracatos *et al.,* 2016). Additionally, Xianming and Roland (1992) noted that some cultivars might have two genes, one dominant and one recessive for resistance to yellow rust, while Kaur and Bariana (2010) discovered three genetically distinct genes for resistance in adult plants.

Some genetic factors were estimated using the parents', F_1 and F_2 populations' mean and variance based on ACI values (Table 6). Higher the resistance level is lower the ACI values.

In general, the studied crosses recorded lower estimates of ACI in both F_1 and F_2 comparing to the commercial cultivars.

The lowest F_2 ACI mean values recorded for the crosses between cultivars and both *Yr15* and *Yr8* monogenic lines followed by that with *Yr27* and *Yr57*. Meanwhile, the highest ACI value was estimated for *Yr34* crosses. Estimates of the variance due to the environment (VE), phenotypes (VP), and genotypes (VG) ranged from 12.5 to 25; 807.33 to 1669.7; 794.83 to 1657.1, respectively.

Estimates of broad sense heritability (h2b) ranged from 97.6 for the cross Shandaweel 1/*Yr34* to 99.2 for the Misr 2 cross with *Yr27* and Gemmeiza 11 crosses with *Yr27* with *Yr57* monogenic lines. The genetic advance from selection (Δg%) ranged from 80.3 for cross Gemmeiza 11/*Yr34* to 561.7 for cross Shandaweel 1/*Yr15*. The genetic coefficient of variation estimates ranged from 0.4 to 2.8 for Gemmeiza 11/*Yr34* and Shandaweel 1/*Yr15* crosses, respectively.

The high estimates for genetic variance and heritability of broad sense indicate that yellow rust resistance in the studied crosses was a simple inherited character and suggested to practice selection for resistance in early segregating generations. Numerous investigator have looked into the variance, its components, and related characteristics; their findings are consistent with those found here (Ragab 2005, 2010; Shahin & Ragab 2015; Aglan *et al.* 2020 and Ragab *et al.* 2020).

Table 4. The adult plant field response to yellow rust under field condition for four Egyptian bread wheat cultivars, five monogenic lines and their eighteen F_1 crosses during 2020/2021 season.

Cross	Adult plant field response to yellow rust†			Dominance direction
	P_1	P_2	F_1	
Misr 1 /YR8	100S	0	Tr R	Resistance
Misr 2 /VR8	100S	0	0	Resistance
Gemmeiza 11 /YR8	100S	0	10 MR-MS	Resistance
Shandaweel 1 /YR8	100S	0	0	Resistance
Misr 1 /YR15	100S	0	Tr R	Resistance
Misr 2 /YR15	100S	0	0	Resistance
Gemmeiza 11 /YR15	100S	0	0	Resistance
Shandaweel 1 /YR15	100S	0	0	Resistance
Misr 1 /YR27	100S	Tr R	20 MR	Resistance
Misr 2 /YR27	100S	Tr R	30MR	Resistance
Gemmeiza 11 /YR27	100S	Tr R	20 MR-MS	Resistance
Shandaweel 1 /YR27	100S	Tr R	5MR	Resistance
Gemmeiza 11 /YR34	100S	50MRMS	40S	-
Shandaweel 1 /YR34	100S	50MRMS	30MS	-
Misr 1 /YR57	100S	Tr R	30S	Susceptibility
Misr 2 /YR57	100S	Tr R	20MS	Susceptibility
Gemmeiza 11 /YR57	100S	Tr R	30S	Susceptibility
Shandaweel 1 /YR57	100S	Tr R	40S	Susceptibility

†Resistance genes based on the studies of Chen, (2005); ‡ 0=Immune. R = resistant (necrosis with few uredinia); MR = moderately resistant (necrosis with small to moderate number of uredinia); MS = moderately susceptible (moderate number of uredinia with chlorotic areas); and S = susceptible (large number of uredinia, no necrosis but chlorosis may be evident).

Table 5. Adult plant field response for yellow rust, observed hypothetical ratios, chi-square (χ^2) and probability values for 18 wheat F_2 populations inoculated with *Pst* under field conditions during 2021/2022 season.

Cross	No. of plants			Ratio	χ^2	*P.* value	Number of genes and mode of inheritance†
	Resistant	Susceptible	Total				
Misr 1 /Yr8	152	44	196	3:1	0.005	0.998	1D
Misr 2 /Yr8	135	66	201	11:5	0.001	1.000	1R, 1D
Gemmeiza 11 /Yr8	152	54	206	3:1	0.001	0.999	1D
Shandaweel 1 /Yr8	170	38	208	13:3	0.000	1.000	1R, 1D
Misr 1 /Yr15	151	51	202	3:1	0.000	1.000	1D
Misr 2 /Yr15	154	48	202	3:1	0.001	0.999	1D
Gemmeiza 11 /Yr15	169	37	206	13:3	0.001	0.999	1R, 1D
Shandaweel 1 /Yr15	175	27	202	9:7	0.024	0.988	2D
Misr 1 /Yr27	148	54	202	3:1	0.002	0.999	1D
Misr 2 /Yr27	147	55	202	3:1	0.004	0.998	1D
Gemmeiza 11 /Yr27	130	71	201	9:7	0.002	0.999	2D
Shandaweel 1 /Yr27	124	77	201	9:7	0.001	1.000	2D
Gemmeiza 11 /Yr34	21	182	203	7:57	0.005	0.998	3R
Shandaweel 1 /Yr34	34	170	204	3:13	0.007	0.996	2R
Misr 1 /Yr57	123	95	218	9:7	0.000	1.000	2D
Misr 2 /Yr57	89	114	203	7:9	0.000	1.000	2R
Gemmeiza 11 /Yr57	95	106	201	7:9	0.000	1.000	2R
Shandaweel 1 /Yr57	99	104	203	7:9	0.001	1.000	2R

†D = dominant and R = recessive. Interpretation for some ratios can be found in Fasoulas (1980).

Table 6. Genetic parameters based on average coefficient of infection (ACI) for yellow rust of 18 wheat crosses.

Cross	ACI Mean				Variance			h^2_b %	Δg %	GCV
	P_1	P_2	F_1	F_2	VP	VE	VG			
Misr 1 /*Yr8*	100	0.01	0.6	16.34	1182.2	12.67	1169.48	98.9	428.8	2.1
Misr 2 /*Yr8*	100	0.01	0.0	23.11	1408.9	12.67	1396.27	99.1	331.6	1.6
Gemmeiza 11 /*Yr8*	100	0.01	6.0	20.21	1372.4	12.5	1359.89	99.1	374.2	1.8
Shandaweel 1 /*Yr8*	100	0.01	0.0	13.49	968.82	12.5	956.32	98.7	469.2	2.3
Average	100	0.01	1.65	18.3	1233.1	12.6	1220.5	98.9	400.9	1.95
Misr 1 /*Yr15*	100	0.01	0.6	19.14	1343.1	12.67	1330.45	99.1	390.7	1.9
Misr 2 /*Yr15*	100	0.01	0.0	15.42	1021.8	12.67	1009.16	98.8	421.7	2.1
Gemmeiza 11 /*Yr15*	100	0.01	0.0	15.66	1226.1	12.5	1213.61	99	455.9	2.2
Shandaweel 1 /*Yr15*	100	0.01	0.0	10.26	807.33	12.5	794.83	98.5	561.7	2.8
Average	100	0.01	0.5	15.4	1096.3	12.1	1084.2	98.9	448.0	2.2
Misr 1 /*Yr27*	100	0.6	8.0	21.76	1360	12.67	1347.29	99.1	345.9	1.7
Misr 2 /*Yr27*	100	0.6	12.0	25.23	1662.4	12.67	1649.71	99.2	330.4	1.6
Gemmeiza 11 /*Yr27*	100	0.6	12.0	28.17	1637.6	12.51	1625.05	99.2	293.7	1.4
Shandaweel 1 /*Yr27*	100	0.6	2.0	29.6	1669.7	12.51	1657.16	99.3	282.2	1.4
Average	100	0.60	8.5	26.2	1582.4	12.6	1569.8	99.2	313.0	1.53
Gemmeiza 11 /*Yr34*	100	30.0	40.0	82.99	1094.7	25	1069.72	97.7	80.3	0.4
Shandaweel 1 /*Yr34*	100	30.0	24.0	57.62	1027.1	25	1002.13	97.6	111.8	0.6
Average	100	30.00	32.0	70.3	1060.9	25.0	1035.9	97.7	96.05	0.5
Misr 1 /*Yr57*	100	0.6	30.0	25.33	1175.7	12.67	1162.99	98.9	275.8	1.4
Misr 2 /*Yr57*	100	0.6	16.0	31.42	1305.6	12.67	1292.91	99	234.6	1.1
Gemmeiza 11 /*Yr57*	100	0.6	30.0	35.1	1558.8	12.51	1546.31	99.2	229.9	1.1
Shandaweel 1 /*Yr57*	100	0.6	40.0	28.3	1127.6	12.51	1115.05	98.9	241.7	1.2
Average	100	0.60	29.0	30.0	1291.9	12.6	1279.3	99.0	245.5	1.2

† P_1= Susceptible cultivar P_2= *Yr* monogenic line, VP, VE and VG = Phenotypic, environment and genetic variance, respectively, h^2b = Broad sense heritability, Δg% = the expected genetic advance under selection, GCV = genotypic coefficient of variation.

Efficiency of the used Yr genes

Distribution of yellow rust reaction frequency as infection type and severity in the F_2 populations of the investigated crosses illustrated that introducing *Yr15* to any of the four susceptible Egyptian wheat cultivars produced the highest number of F_2 plants expressing the monogenic line field response (0 type). The percentage was 81, 76, 72 and 70% for *Yr15* combinations with Shandaweel 1, Gemmeiza 11, Misr 2 and Misr 1, respectively (Figure 1).

On the other hand, efficiency of *Yr8*, *Yr27*, *Yr57* and *Yr34* to produce F_2 plants expressing their field response differed based on the background of the cultivar. Efficiency of the genes found in the order of *Yr8* > *Yr27* >*Yr57* with Misr 1 and Misr 2 background and of *Yr27* >*Yr8* >*Yr57* >*Yr34* with Gemmeiza 11 and Shandaweel 1 background. In general, average percentage of F_2 plants that have the same field response as the monogenic line in the studied crosses were 75, 46, 43, 32 and 28% for the crosses with *Yr15*, *Yr27*, *Yr8*, *Yr57* and *Yr34* monogenic lines, respectively (Figure 1).

Therefore, the average observed order for the four genes was *Yr15* > *Yr27* > *Yr8* > *Yr57* > *Yr34*. The two Egyptian bread wheat cultivars Sids 12 and Gemmeiza 11 were improved by the yellow rust resistance genes Yr5, Yr10, Yr15, and YrSp, according to research by Ragab *et al.* (2020). They reported that *Yr15* crosses produced more than 80% resistance in F_2 populations. According to Abu Aly *et al.* (2014), the seven monogenic lines Yr1, Yr5, Yr10, Yr15, Yr17, Yr32, and YrSp displayed adult plant resistance under field conditions as well as high levels of resistance to the 198E56 and 128E28 races at the seedling stage. As opposed to those with Yr17 and YrSP, who displayed disease severity ranging from 5 to 10MR. On the other hand, the wheat yellow rust pathogen's pathogenicity for the resistance genes YrSp, Yr1, and Yr3 was first described in North Africa (Hovmoller *et al.*, 2016) and some Asian countries (Mert *et al.*, 2016 and Hovmoller *et al.*, 2017). These results concur with those published by Zhang *et al.* (2001), Ragab 2005, Kokhmetova *et al.* (2010), Shahin & Ragab (2015), and Kokhmetova *et al.* (2017).

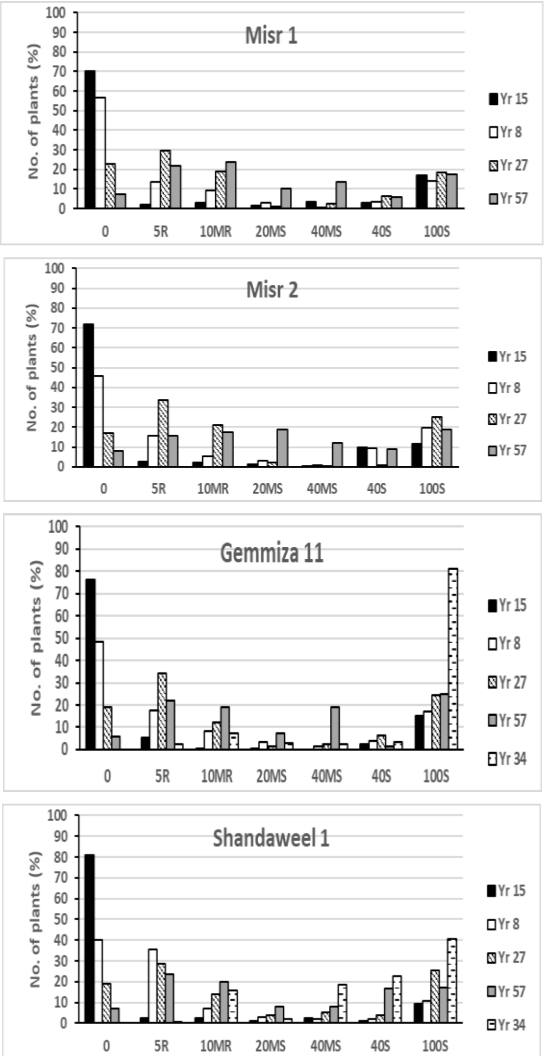

Figure 1. Adult plant yellow rust reaction of F_2 plants derived from the crosses between four Egyptian bread wheat cultivars and each of the five-yellow rust monogenic lines *Yr8, Yr15, Yr37, Yr34* and *Yr57* during 2021/2022 growing season.

Agronomic character improvement

Mean values and change percentage of commercial bread wheat cultivar`s parent and F2 strip rust resistant plants for agronomic characteristics are presented in Table 7 and Table 8. Shandaweel 1 cultivar had the highest plant height, number of spikes per plant, 100 kernels weight, number of spikes per spike, and spike kernels weight recorded among the selected F_2 yellow rust resistant plants for commercial cultivars. Meanwhile, the highest grain yield per plant were recorded for Misr 1 cultivar. Average change percentage of the selected F_2 plants from their corresponding commercial cultivar exceeded 100% in grain yield and spike kernels weight in most crosses. Where, the best improvement was recorded for Gemmeiza 11 followed by Misr 2 crosses. It was noticed that most crosses between the commercial cultivars and *Yr15*, *Yr27* and *Yr57* monogenic lines recorded the highest improvement percentage comparing to that of Yr8 and *Yr34* lines.

Table 7. Mean and change percentage of grain yield per plant, number of spikes per plant and 100 kernels weight of commercial bread wheat cultivar`s parent and F_2 strip rust resistant plants selected from 18 studied crosses.

Cross	Grain yield/plant (g/plant)			No. of spikes/plant			100 Kernels weight (g)		
	Commercial cultivar	Selected F_2 plants mean	Change %	Commercial cultivar	Selected F_2 plants mean	Change %	Commercial cultivar	Selected F_2 plants mean	Change %
Misr 1 /*Yr8*	22.2±1.31	50.7±2.93	128.4	18.4±2.14	25.6±1.47	41.3	2.63±0.24	4.11±0.11	56.3
Misr 1 /*Yr15*	22.2±1.31	55.6±3.78	150.5	18.4±2.14	30.5±1.79	68.5	2.63±0.24	4.07±0.06	54.8
Misr 1 /*Yr27*	22.2±1.31	57.3±3.21	158.1	18.4±2.14	29.1±1.29	57.6	2.63±0.24	4.22±0.08	60.5
Misr 1 /*Yr57*	22.2±1.31	44.7±2.52	101.4	18.4±2.14	23.0±1.43	25.0	2.63±0.24	3.92±0.10	49.0
Average	22.2	52.1	134.6	18.4	27.0	48.1	2.63	4.08	55.1
Misr 2 /*Yr8*	12.7±0.54	46.2±1.81	263.8	19.2±2.71	24.6±1.28	30.2	2.83±0.25	4.32±0.07	52.7
Misr 2 /*Yr15*	12.7±0.54	50.3±2.42	296.1	19.2±2.71	26.2±1.05	35.4	2.83±0.25	3.78±0.09	33.6
Misr 2 /*Yr27*	12.7±0.54	51.9±2.79	308.7	19.2±2.71	26.6±1.53	40.6	2.83±0.25	4.14±0.09	46.3
Misr 2 /*Yr57*	12.7±0.54	43.4±2.89	241.7	19.2±2.71	24.3±1.69	25.0	2.83±0.25	4.11±0.16	45.2
Average	12.7	48.0	277.6	19.2	25.0	32.8	2.83	4.09	44.4
Gemmeiza 11 /*Yr8*	7.9±0.77	45.9±2.59	479.5	11.4±0.81	18.1±0.85	57.9	0.75±0.33	4.73±0.11	530.7
Gemmeiza 11 /*Yr15*	7.9±0.77	47.4±3.06	498.5	11.4±0.81	16.7±1.23	49.1	0.75±0.33	5.05±0.12	573.3
Gemmeiza 11 /*Yr27*	7.9±0.77	52.4±3.19	561.6	11.4±0.81	22.8±1.42	101.8	0.75±0.33	4.51±0.09	501.3
Gemmeiza 11 /*Yr34*	7.9±0.77	NA	NA	11.4±0.81	NA	NA	0.75±0.33	NA	NA
Gemmeiza 11 /*Yr57*	7.9±0.77	54.5±7.95	588.1	11.4±0.81	22.3±2.20	93.0	0.75±0.33	4.53±0.13	504.0
Average	7.9	50.1	531.9	11.4	20.0	75.4	0.75	4.71	527.3
Shandaweel 1 /*Yr8*	16.6±0.95	53.6±3.49	223.7	20±1.41	23.9±1.91	20.0	4.7±0.06	4.78±0.15	1.7
Shandaweel 1 /*Yr15*	16.6±0.95	48.5±5.58	192.9	20±1.41	23.4±2.45	15.0	4.7±0.06	4.00±0.13	-14.9
Shandaweel 1 /*Yr27*	16.6±0.95	46.2±2.55	179.0	20±1.41	20.7±1.03	5.0	4.7±0.06	4.31±0.13	-8.3
Shandaweel 1 /*Yr34*	16.6±0.95	36.0±2.42	117.4	20±1.41	19.0±0.84	-5.0	4.7±0.06	NA	NA
Shandaweel 1 /*Yr57*	16.6±0.95	43.2±3.47	160.9	20±1.41	22.4±1.71	10.0	4.7±0.06	3.81±0.18	-18.9
Average	16.6	45.5	174.8	20.0	22.0	9.0	4.7	4.23	-10.1

Average increase of selected F_2 populations ranged from 101.4% (Misr 1 /*Yr57*) to 588% (Gemmeiza 11/*Yr57*) in grain yield, from 5% (Shandaweel 1/*Yr27*) to 101.8% (Gemmeiza 11/*Yr27*) in number of spikes per plant, from 1.7% (Shandaweel 1/*Yr8*) to 573.3% (Gemmeiza 11/*Yr15*) in 100 kernels weight, from 10.8% (Shandaweel 1/ *Yr15*) to 337.9% (Gemmeiza 11/*Yr57*) in number of kernels per spike and from 104.4% (Misr 1/*Yr57*) to 1445% (Gemmeiza 11/*Yr15*) in spike kernels weight.

Table 8. Mean and change percentage of plant height number of kernels per spike and spike kernels weight of commercial bread wheat cultivar`s parent and F_2 strip rust resistant plants selected from 18 studied crosses.

Cross	Plant height (cm)			No. of kernels/spike			Spike kernels weight (g)		
	Commercial cultivar	Selected F_2 plants mean	Change %	Commercial cultivar	Selected F_2 plants mean	Change %	Commercial cultivar	Selected F_2 plants mean	Change %
Misr 1 /*Yr8*	107±1.22	113±1.10	5.6	43.4±2.80	64±2.75	47.5	1.14±0.13	2.59±0.11	127.2
Misr 1 /*Yr15*	107±1.22	117±1.30	9.4	43.4±2.80	64±2.18	47.5	1.14±0.13	2.59±0.09	127.2
Misr 1 /*Yr27*	107±1.22	111±1.29	3.7	43.4±2.80	55±1.89	26.7	1.14±0.13	2.35±0.10	106.1
Misr 1 /*Yr57*	107±1.22	108±2.55	0.9	43.4±2.80	59±3.01	35.9	1.14±0.13	2.33±0.15	104.4
Average	107	112	4.9	43.4	60.5	39.4	1.1	2.5	116.2
Misr 2 /*Yr8*	102±1.22	114±1.15	11.8	35.8±3.18	61±2.48	70.4	1.0±0.09	2.63±0.11	163.0
Misr 2 /*Yr15*	102±1.22	124±1.14	21.6	35.8±3.18	69±2.85	92.7	1.0±0.09	2.63±0.13	163.0
Misr 2 /*Yr27*	102±1.22	121±1.20	18.6	35.8±3.18	69±1.69	92.7	1.0±0.09	2.83±0.09	183.0
Misr 2 /*Yr57*	102±1.22	111±4.68	8.8	35.8±3.18	71±4.86	98.3	1.0±0.09	2.86±0.17	186.0
Average	102	118	15.2	35.8	67.5	88.5	1.0	2.7	173.8
Gemmeiza 11 /*Yr8*	103±1.22	119±1.29	15.5	15.3±1.37	64±2.85	318.3	0.2±0.04	3.03±0.14	1415.0
Gemmeiza 11 /*Yr15*	103±1.22	123±1.33	19.4	15.3±1.37	62±3.31	305.2	0.2±0.04	3.09±0.13	1445.0
Gemmeiza 11 /*Yr27*	103±1.22	116±0.99	12.6	15.3±1.37	66±2.28	331.4	0.2±0.04	2.95±0.11	1375.0
Gemmeiza 11 /*Yr34*	103±1.22	NA	NA	15.3±1.37	NA	NA	0.2±0.04	NA	NA
Gemmeiza 11 /*Yr57*	103±1.22	118±2.82	14.6	15.3±1.37	67±2.58	337.9	0.2±0.04	3.04±0.15	1420.0
Average	103	119	15.5	15.3	64.8	323.2	0.2	3	1413.8
Shandaweel 1 /*Yr8*	114±1.00	109±2.09	-4.4	66.8±2.03	61±3.70	-8.7	3.14±0.12	2.89±0.17	-8.0
Shandaweel 1 /*Yr15*	114±1.00	129±2.03	13.2	66.8±2.03	74±4.25	10.8	3.14±0.12	2.95±0.20	-6.1
Shandaweel 1 /*Yr27*	114±1.00	107±5.82	-6.1	66.8±2.03	63±1.52	-5.7	3.14±0.12	2.71±0.10	-13.7
Shandaweel 1 /*Yr34*	114±1.00	106±0.97	-7.0	66.8±2.03	NA	NA	3.14±0.12	NA	NA
Shandaweel 1 /*Yr57*	114±1.00	110±2.19	-3.5	66.8±2.03	60±3.63	-10.2	3.14±0.12	2.29±0.18	-27.1
Average	114	113	-0.9	66.8	64.3	-3.4	3.1	2.7	-13.7

CONCLUSION

The efficiency of examined genes in the studied wheat genotypes was observed in the order of *Yr15 >Yr27 >Yr8 >Yr57 >Yr34*. The national wheat breeding program should incorporate and pyramid the Yr8, Yr15, Yr27, and Yr57 yellow rust resistance genes for genetic control of the disease. The promising F_2 plants from this study can be used to create genetic diversity and to obtain high yielding wheat germplasm carrying these effective genes.

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إدخال جينات مقاومة الصدأ الأصفر ***Yr8*** و ***Yr15*** و ***Yr27*** و ***Yr34*** و ***Yr57*** في بعض أصناف قمح الخبز المصرية القابلة للإصابة

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الملخص

استخدمت خمسة سلالات أحادية الجين للصدأ الأصفر كمانح لجينات المقاومة *Yr8* و *Yr15* و *Yr27* و *Yr34* و *Yr57* إلى أصناف قمح الخبز المصرية مصر 1، مصر 2 ، جميزة 11 وشندويل 1 من خلال التهجين في محطة البحوث الزراعية بسخا خلال مواسم 2020/2019 إلى 2022/2021. تم تقييم السلالات أحادية الجين في محطات سخا وكفر الحمام وسدس وتم تقييم الآباء والجيل الأول والثاني في محطة بحوث سخا. سجلت السلالات التي تحمل جينات مقاومة الصدأ الأصفر *Yr5* و Yr8 و *Yr10* و *Yr15* و *Yr27* و *Yr33* و *Yr37* و *Yr51* و *Yr57* و *YrKK* و *YrALD* مقاومة لسلالات الفطر السائدة في المواقع الثلاثة. سجلت جميع الهجن بين الأصناف والسلالات أحادية الجين *Yr8* و Yr15 و *Yr27* مقاومة بينما سجلت معظم الهجن التي تضمنت *Yr34* و *Yr57* حساسية للصدأ المخطط. تم الحصول على تقديرات عالية للتباين الوراثي وكفاءة التوريث بالمعنى الواسع لجميع الهجن مما يشير إلى أن الانتخاب لمقاومة الصدأ المخطط يمكن أجرائه في الأجيال الانعزالية المبكرة. تم تسجيل أكثر عدد من النباتات المقاومة في الجيل الثاني لهجن السلالة الأحادية الجين Yr*15* مع أي من أصناف القمح الأربعة الحساسة. من نتائج الدراسة يمكن ترتيب كفاءة الجينات كالتالي *Yr15 >Yr8 >Yr27 >Yr57* عند إضافتها لخلفية الأصناف مصر 1 ومصر 2 وبالترتيب Yr*15* *>Yr27 >Yr8 >Yr34* عند إضافتها لخلفية الأصناف جميزة 11 وشندويل1. يوصى بإدخال جينات مقاومة الصدأ الأصفر في البرنامج القومي لتربية القمح للتحكم الوراثي في الصدأ الأصفر. وسيتم استخدام نباتات F_2 المنتخبة من هذه الدراسة في برنامج تربية القمح للحصول على سلالات عالية الغلة تحمل هذه الجينات الفعالة.