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Half-diallel Analysis of *Fusarium* Head Blight Resistance in Bread Wheat (*Triticum aestivum* L.)

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TO CHARACTERIZE FHB resistance, a set of 48 advanced inbred lines (AILs) along with two Egyptian cultivars (Sakha-93 and Giza-168) were evaluated for their resistance to the FHB during 2015/2016 and 2016/2017 under both greenhouse and field conditions. We identified some resistant AILs to the FHB including 37, 35 and 22 based on percentages of diseased spikelets under both greenhouse and field conditions and free phenolic compounds along with grain yield (GY) under the field condition. While most of the AILs were susceptible to the FHB. Three resistant AILs, three susceptible AILs and an Egyptian susceptible cultivar were crossed in a half–diallel mating system. The parents and the non–reciprocal F_1 crosses were evaluated for their response to the FHB under infected conditions in both greenhouse and field conditions. Both general combining ability (GCA) and specific combining ability (SCA) were significant for all studied traits. Both additive and non–additive describes for resistance to the FHB; however, different calculations supported that additive gene action is the preponderant constituent. The moderately high estimates of narrow–sense heritability values implied that further improvement of the FHB resistance could be accomplished through selection. We found that AILs 22, 35 and 37 were good combiners and successfully conveyed their resistant genes to their offspring based on the SCA. These resistant AILs could be integrated in wheat breeding programs using bi-parental or multi-parental populations to develop new resistant varieties to FHB. In addition, they can be exploited to improve existing cultivars using backcrossing approach.

Keywords: General combining ability, Specific combining ability, Narrow-sense heritability, Free phenolic compounds, Grain yield

Introduction

The *Fusarium* head blight (FHB) is a fungal disease of cereal crops that affects kernel development. The FHB is caused by the *Fusarium graminearum, F. culmorum* and *F. avenaceum* (Osborne & Stein, 2007). Among them, *F. graminearum* was reported as an economically devastating disease (Windels, 2000). In Egypt, *F. graminearum* was determined as the main FHB pathogen (Mahmoud, 2016). The FHB causes significant losses in grain yield and grain quality (McMullen et al., 2012). The pathogens not only reduce the yield of wheat, but also influence the quality of wheat by the production of mycotoxins that affect livestock feed, the baking and milling quality of wheat (*Triticum aestivum* L.). The mycotoxins produced by the *F. graminearum* may pose a serious threat to human and domestic animal health (Desjardins, 2006; Desjardins et al., 2008). FHB was found to be prevalent in many counties after the anthesis stage of wheat (Kuo et al., 2014). Symptoms of FHB occur shortly after flowering. Diseased spikelets exhibit premature bleaching as the pathogen grows and spreads within the head. Warm and humid conditions are essential for spores to germinate and to infect wheat spikes (Parry et al., 1995). Previous studies indicate that no accession has yet been found to be completely immune to FHB (Gocho, 1985; Liu & Wang, 1991), although the resistance to FHB varies

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not only among wheat cultivars but also among some of their wild relatives (Mujeeb–Kazi et al., 1983; Ban, 1997). The FHB resistance in a diverse range of wheat genotypes is partially conditioned by the pore–forming toxin–like (PFT) gene. The profiling of FHB resistance and the PFT locus in this large collection of wheat germplasm may prove helpful for incorporating FHB resistance into wheat breeding programs (He et al., 2018).

Phenolic compounds are secondary natural metabolites, which are produced in plants and play an important role in resistance to pathogens (Lattanzio et al., 2006; Lattanzio, 2013). Phenolic compounds can be synthesized during normal growth and development of tissues or induced as a response to either biotic or biotic stress (Lattanzio et al., 2006; Lattanzio, 2013). The rapid accumulation of phenolic compounds causes isolation of the pathogen and prevent it from spreading to the remaining tissue in the infected sites (Fernandez & Heath, 1998). Toxic effects of phenolic compounds against *Fusarium* spp. have been reported (Siranidou et al., 2002). The presence of adequate amounts of phenolic compounds either prior or post infections play a substantial role in fungi diseases' resistance in plants (Goodman et al., 1986). It is paramount for plant breeders to understand the FHB resistance mechanisms in wheat as this helps them to select the beneficial and vital traits for the resistance against FHB (Siranidou et al., 2002). In general, phenolic compounds are highly synthesized in plants after infection with any pathogens (Matern et al., 1995). The content of free phenolic compounds such as flavonoids and phenylopropanoids was higher in the resistant wheat cultivars pre and post–inoculation, which emphasizes the significant role of free phenol compounds in the resistance of FHB in wheat (Siranidou et al. 2002).

One of the most important sources of management systems for the control of FHB is the development and use of resistant cereal cultivars. The diallel analysis allows studying the inheritance of different traits by partitioning the genetic variance into general combining ability (GCA) and specific combining ability (SCA) (Griffing, 1956). The estimation of them aids in identifying superior genotypes, which could be exploited to improve and develop cultivars (Malla et al., 2009). In addition, diallel analysis can be used in inference the type of gene action of the FHB and the preponderance of each constituent of gene action (Oettler et al., 2004; Soltanloo et al., 2010). Bai et al. (2000) stated that additive gene effect of resistance to the FHB is the predominant gene effect; although both constituents of gene effects are governing the inheritance of FHB. The objectives of this study were to 1) assess the resistance of FHB in some exotic germplasm and 2) estimate general and specific combining ability of the FHB resistance.

Materials and Methods

This study was accomplished based on two parts including preliminary evaluation for two years of exotic advanced inbred lines (AILs) and local wheat cultivars for their resistance to the FHB and in a half–diallel study using selected resistant and susceptible genotypes.

Preliminary evaluation

Plant materials and growing conditions

A set of 48 advanced inbred lines (AILs) obtained from CIMMYT (Table 1) along with two Egyptian wheat cultivars (Sakha–93 and Giza–168) were assessed for their resistance to the FHB caused by *F. graminearum* in both field and greenhouse conditions at Plant Pathology Department, Faculty of Agriculture, Assiut University for 2015/2016 and 2016/2017. For the field experiments, genotypes were sown in two sets (as control and inoculated) during the two growing seasons. Each set of experiment was sown in a randomized complete block design using four replications. Each of the 48 AILs along with Sakha–93 and Giza–168 was represented with one row in each replication. The row is 3 m long with 35 cm between rows. For the greenhouse experiment (control and inoculated), plant materials were sown in an RCBD with four replications (pots; diameter= 20cm; sterilized soil) using 10 seeds for each pot.

Source of the pathogen

The utilized isolates of *Fusarium graminearum* were previously isolated from infected wheat kernels obtained from fields in Assiut governorate (Mahmoud, 2016). Isolates were selected based on their known virulences. The infection was conducted by a mixture of these isolates. Isolates were identified as the *F. graminearum* on the basis of growth rate, pigmentation of colonies on potato dextrose agar (PDA), spore morphology on Spezieller Nahrstoffarmer agar (SNA) as well as morphology and size of microconidia and macroconidia according to Nelson et al. (1983) and Summerell et al. (2003).

TABLE 1. The pedigree of the 48 CIMMYT's advanced inbred lines along with Sakha-93 and Giza-168.

No	Pedigree	Origin
1	KACHU #1	CIMMYT, Mexico
2	PRL/2*PASTOR	
3	MUNAL #1	
4	BECARD #1/5/KIRITATI/4/2*SERI.1B*2/3/KAUZ*2/BOW//KAUZ	
5	BECARD/CHYAK	
6	TAITA	
7	KACHU//KIRITATI/2*TRCH	
8	KACHU/CHONTE	
9	KIRITATI//HUW234+LR34/PRINIA/3/BAJ #1	
10	MUTUS//ND643/2*WBLL1	
11	ND643/2*WBLL1/4/WHEAR/KUKUNA/3/C80.1/3*BATAVIA//2*WBLL1	
12	ND643/2*WBLL1//KACHU	
13	SUP152/QUAIU #2	
14	MUU/FRNCLN	
15	SAAR//INQALAB 91*2/KUKUNA/3/KIRITATI/2*TRCH	
16	SERI.1B*2/3/KAUZ*2/BOW//KAUZ/5/CNO79//PF70354/MUS/3/PASTOR/4/BAV92/6/ ND643/2*WBLL1	
17	BAJ #1/KISKADEE #1	
18	CHEWINK #1/MUTUS	
19	SERI.1B*2/3/KAUZ*2/BOW//KAUZ/4/2*MUNAL	
20	ATTILA*2/PBW65//FRNCLN/3/FRANCOLIN #1	
21	QUAIU #1/2*SUP152	
22	MUNAL*2/WESTONIA	
23	MUTUS*2/HARIL #1	
24	FRNCLN/3/ND643//2*PRL/2*PASTOR/4/FRANCOLIN #1	
25	FRNCLN/3/KIRITATI//HUW234+LR34/PRINIA/4/FRANCOLIN #1	
26	WBLL1*2/BRAMBLING*2//BAVIS	
27	CHYAK1*2/3/HUW234+LR34/PRINIA//PFAU/WEAVER	
28	SWSR22T.B./2*BLOUK #1//WBLL1*2/KURUKU	
29	QUAIU #1/BECARD	
30	WBLL1*2/BRAMBLING/5/BABAX/LR42//BABAX*2/4/SNI/TRAP#1/3/KAUZ*2/TRAP// KAUZ	
31	WHEAR/SOKOLL/4/PRINIA/PASTOR//HUITES/3/MILAN/OTUS//ATTILA/3*BCN	CIMMYT, Mexico
32	WHEAR//2*PRL/2*PASTOR/3/QUAIU #1	
33	WHEAR/VIVITSI//WHEAR/3/BECARD	
34	TRCH*2//ND643/2*WBLL1	
35	BLOUK #1/DANPHE #1//BECARD	
36	BLOUK#1/4/WHEAR/KUKUNA/3/C80.1/3*BATAVIA//2*WBLL1/5/MUNAL #1	
37	BABAX/LR42//BABAX*2/3/PAVON 7S3, +LR47/4/ND643/2*WBLL1/5/BABAX/LR42// BABAX*2/3/PAVON 7S3, +LR47	
38	QUAIU #1/5/KIRITATI/4/2*SERI.1B*2/3/KAUZ*2/BOW//KAUZ/6/BECARD	
39	CHIBIA//PRLII/CM65531/3/FISCAL/4/DANPHE #1/5/CHIBIA//PRLII/CM65531/3/SKAUZ/BAV92	
40	CROSBILL #1/DANPHE/7/CNDO/R143//ENTE/MEXI_2/3/AEGILOPS SQUARROSA (TAUS)/4/ WEAVER/5/2*KAUZ/6/PRL/2*PASTOR	
41	KACHU*2/CHONTE	
42	MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTAD F2004	
43	ND643/2*WBLL1//2*KACHU	
44	WAXWING*2/TUKURU//2*FRNCLN	
45	FRANCOLIN #1*2//ND643/2*WBLL1	
46	BECARD//KIRITATI/2*TRCH/3/BECARD	
47	WHEAR//2*PRL/2*PASTOR/3/KIRITATI/2*TRCH/4/WHEAR//2*PRL/2*PASTOR	
48	VEE/MJI//2*TUI/3/PASTOR/4/BERKUT/5/MUU	
Sakha–93	Sakha 92/TR 810328	Egypt
Giza–168	MIL/BUC/seriCM93046-8M-OY-OM-2Y-OB	

Infection test for the FHB resistance

The *F. graminearum* conidial inoculums were prepared with Mung Bean Agar Medium (MBA) (Bai & Shaner, 1996). The *F. graminearum,* used to inoculate wheat plants, was cultured at 25±1°C for14 days. Conidia suspension was harvested and adjusted to 5 x 10^5 conidia ml^{-1}. Three drops (0.01%) of Tween–20 was added to ensure uniform conidia dispersion. Wheat spikes were inoculated at 50% flowering (Zadoks et al., 1974 [GS65]) by spraying with a hand sprayer, exposing all spikelets to the inoculum. Inoculations were repeated three times for 10 days. A control experiment was treated similarly with distilled water only. After inoculation, the spikes were incubated under polythene bags for 48hr to ensure high relative humidity for optimal infection.

Disease assessment (number of infected spikelets per head)

The FHB was assessed as a percentage of heads showing disease symptoms, on ten average–sized spikes per replicate. The number of infected spikelets/head was recorded at two dates (14 and 28 days after inoculation) and adjusted to the total number of spikelets/heads. The relative number of infected spikelets of the two assessment dates was averaged (Cumagun & Miedaner, 2003; Mahmoud, 2016). No symptoms of the FHB were shown for the control experiment under the greenhouse condition for the two growing seasons. Therefore, the control experiment of the greenhouse condition was excluded from the statistical analysis of the current study.

Measurement of the free phenolic compounds (µg/g of dry weight)

The free phenolic compounds (µg/g of dry weight) were extracted from different parts such as glumes, lemmas and paleas under field conditions for the control and inoculated experiments for the two growing seasons after three days of inoculation. The Free phenolic compounds were extracted as per Kofalvi & Nassuth (1995). Briefly, a mix of glumes, lemmas and paleas (100mg of dry weight) were kept in 4 ml of 50% methanol for 90min at 80ºC. Consequently, the samples were centrifuged for 10min at 3000×g. The resultant supernatants were then utilized for a Folin–Ciocalteau assay as the following: to 100µl of the supernatant were added to 900µl of distilled water, 50 µl Folin–Ciocalteau mixture and 500 µl of 20% sodium bicarbonate (Kofalvi & Nassuth, 1995). Then this mixture was incubated at room temperature (26ºC) for 20min. A wavelength of 725nm was used to measure the absorbance of the samples. Finally, total phenolic content was determined using a standard curve for *p*–coumaric (Kofalvi & Nassuth, 1995).

Grain yield (g)

At harvest, the grain yield (GY; g/genotype) was recorded under field condition for the two types of experiments as control and inoculated similar to Jiang et al. (2007).

Statistical analysis

Both separated and combined analyses were carried out using GLM procedure in SAS v9.0 (The SAS Institute Inc., Cary, NC, USA, 2003) statistical software. All obtained variances were homogeneous based on Bartlett's test ($P \leq 0.05$). Pearson's coefficient of correlation was accomplished to investigate the relationship among the aforementioned traits using the CORR procedure in SAS v.9 statistical software, also (The SAS Institute Inc., Cary, NC, USA, 2003).

The half–diallel analysis

Plant material

Based on the preliminary evaluation, a set of seven parents included three resistant AILs (22, 35 and 37), three susceptible AILs (1, 6 and 13) and a susceptible Egyptian cultivar (Giza–168) were crossed in a half–diallel design during 2017/2018. The parents along with their 21 non–reciprocal F_1 crosses were evaluated for their response to the FHB under infection conditions of greenhouse and field during the growing season of 2018/2019. The 7 parents and their 21 non–reciprocal F_1 crosses were grown in a randomized complete block design with three replicates under both greenhouse and field conditions.

Traits studied

Percentages of diseased spikelets were recorded under greenhouse and field infected conditions. Free phenolic compounds (µg/g of dry weight) were measured and the grain yield was measured under infected field condition at the end of the growing season as indicated in the preliminary evaluation.

Statistical analysis

The diallel analysis was performed according to Griffing's Method 2 (Griffing, 1956), where

parents and one set of F_1 crosses (no reciprocal) were included in the analysis in method 2, model 1. The data were analyzed using AGDR–R version 4 (Rodríguez et al., 2015). The general linear model for Griffing's Method 2, model 1 is:

$$X_{ijk} = \mu + g_i + g_j + s_j + (\frac{1}{b})\sum_k e_{ijk}$$

(i=j=1….. number of parents (p); k=1… number of replications (b))

where X_{ijk} is the observed trait of *i* and *j* parents in the *k* replication), μ= The average of the population, g_i is the GCA effect for the i^{th} parent, g_j is GCA effect for the j^{th} parent, s_{ij} is the SCA effect for the cross between i^{th} and j^{th} parents and e_{ijk} is the experimental error.

Narrow sense heritability was calculated from the expected variance components of GCA and SCA effects from the analysis of variance based on the following equation:

$$h_n = \frac{\sigma_A^2}{\sigma_A^2 + \sigma_D^2 + \frac{\sigma_E^2}{2k}}$$

where, σ_A^2 is the additive variance, σ_D^2 is the dominance variance, σ_E^2 is the error variance, and *k* is a number of replications.

Gene action was predicted according to combining ability ratio (Baker, 1978). The GCA alone can be utilized to expect the performance of parents if the combining ability ration (CAR) close to unity. The CAR can be calculated based on the following equation:

$$CAR = \frac{2\sigma_{GCA}^2}{2\sigma_{GCA}^2 + \sigma_{SCA}^2}$$

where $2\sigma_{GCA}^2$ is the GCA variance and σ_{SCA}^2 is the SCA variance.

Results

Means of studied traits

Our results showed that most of the plant materials inoculated with *F. graminearum* displayed positive disease responses to FHB infection along with free phenolic compounds and grain yield separated by years (Table 2) and combined over the two years (Table 3). Under greenhouse condition, the plant materials were significantly varied in their response to FHB; the percentages of disease severity were ranged from 19.81%, for the most resistant AILs, to 87.75% for the most susceptible AILs. Fourteen AILs (39, 41, 37, 38, 42, 5, 27, 35, 4, 45, 29, 24, 49 and 40) showed resistant reactions to infection by *F. graminearum* and produced the highest percentages of resistance during two growing seasons. The average of the diseased spikelets were 19.81%, 22.12%, 22.37%, 24.75%, 24.93%, 25.37%, 26.50%, 27.37%, 27.87%, 28.25%, 28.62%, 29.31%, 29.56% and 29.62% respectively. Furthermore, obtained results showed that AILs 44, 10, 3, 117, 8, 7, 11, 15 and 2 along with Sakha-93 and Giza-168 were susceptible to the FHB, the average of the diseased spikelets were 50.25%, 52.00%, 54.00%, 58.56%, 82.18%, 83.56%, 85.25%, 85.68%, 87.75%, 54.62% and 59.62%, respectively. While, AILs 46, 32, 13, 36, 50, 34, 30, 18, 22, 26, 14, 31, 47, 21 and 25 were moderate resistance, the average of the diseased spikelets ranged from 30.62% to 38.81%. Other tested lines were moderately susceptible, they showed an average of the diseased spikelets ranged from 40.31% to 48.18%.

Over the two growing seasons, 10 AILs showed the highest resistance to FHB based on the percentage of diseased spikelets under greenhouse condition (less than 30%), percentage of diseased spikelets under the field condition (less than 30%), the free phenolic compounds under the field infection (above 485µg/g) and the grain yield under the field infection (more than 200g). These AILs included 37, 35, 22, 38, 36, 43, 25, 27, 3 and 4. These lines are potentially resistant to the FHB and can be used in the breeding program as promising parental lines to develop resistant verities to the FHB. On the other hand, the most susceptible AILs to the FHB based on percentage of diseased spikelets under greenhouse condition (more than 50%), percentage of diseased spikelets under the field condition (more than 23%), the free phenolic compounds under the field infection (less than 380 µg/g) and the grain yield under the field infection (less than 160g). These AILs were 1, 13, 6, 10, 7, 15 along with the Egyptian check cultivars Giza–168 and Sakha–93.

TABLE 2. Means of studied traits.

Gen	2015/2016							2016/2017						
	Control				Inoculation			Control				Inoculation		
	PDSF	FPC	GY	PDSG	PDSF	FPC	GY	PDSF	FPC	GY	PDSG	PDSF	FPC	GY
1	14.00	204.50	371.63	89.75	64.25	206.25	52.25	13.75	176.50	395.13	85.75	57.50	191.75	51.05
2	4.50	393.50	555.20	54.50	26.75	407.00	249.13	5.25	355.75	533.83	53.50	19.75	378.00	254.05
3	6.50	596.00	299.65	32.50	15.50	616.25	229.00	7.50	597.25	320.68	23.25	10.00	620.50	254.25
4	12.50	568.25	875.03	26.25	17.00	582.50	585.63	12.00	551.25	857.13	24.50	10.00	568.25	603.83
5	15.00	465.25	491.58	45.75	20.50	478.50	241.25	14.75	487.25	464.18	35.50	13.50	502.75	249.28
6	14.25	145.00	421.83	86.50	59.75	162.75	62.63	15.75	178.50	401.70	80.63	53.25	189.50	44.83
7	11.50	160.25	433.50	82.25	56.00	183.25	118.98	12.25	159.00	413.45	82.13	49.75	171.75	47.68
8	8.25	457.50	313.38	47.50	21.75	471.50	138.80	11.50	446.25	297.35	45.50	15.25	469.50	147.20
9	4.75	377.50	666.93	54.25	28.00	390.75	311.08	5.50	350.00	621.63	49.75	21.00	369.00	249.68
10	11.25	175.00	555.53	84.00	59.50	187.75	61.68	12.25	182.50	518.90	86.50	52.50	195.75	99.13
11	5.75	527.75	664.20	37.25	12.50	547.25	257.83	6.50	567.50	631.55	27.00	9.25	571.50	382.75
12	5.00	486.75	495.93	39.25	14.25	518.00	279.10	5.75	468.50	436.13	32.50	8.25	487.50	259.03
13	8.75	165.75	500.38	86.75	62.00	169.25	53.73	9.75	158.00	473.13	84.63	55.00	175.25	43.75
14	2.25	468.25	317.05	44.25	19.75	477.75	159.30	3.25	437.50	300.90	36.38	12.75	459.50	178.25
15	1.25	268.75	407.25	65.00	38.50	275.75	163.65	2.50	268.75	374.43	52.13	31.50	287.50	146.35
16	5.00	458.25	331.10	40.00	15.25	472.50	201.40	6.00	487.25	309.25	28.25	11.25	493.00	203.45
17	1.25	466.00	365.93	51.00	24.75	473.75	159.35	2.50	437.50	334.05	39.13	17.75	458.25	143.50
18	3.50	442.75	483.08	51.50	25.75	456.00	238.00	4.25	446.00	444.75	44.88	18.75	467.50	220.10
19	4.75	516.75	502.88	39.75	17.25	522.25	302.75	5.50	488.75	494.48	37.13	12.00	508.00	288.00
20	3.75	447.75	353.23	40.25	17.00	479.00	215.53	4.75	469.00	342.95	28.00	10.00	492.50	246.10
21	6.50	457.75	324.35	45.50	19.75	459.75	220.15	7.50	465.50	329.55	35.75	12.75	553.50	191.58
22	7.00	428.50	337.08	33.00	14.50	549.00	208.33	8.25	547.75	350.90	25.63	7.50	568.50	237.55
23	6.00	500.75	414.25	41.50	15.75	513.00	189.18	7.00	467.75	427.38	36.13	9.50	486.75	207.50
24	2.25	466.00	567.25	37.00	12.25	487.25	387.25	3.25	489.75	515.58	33.00	7.50	510.00	308.80
25	2.50	499.25	345.98	26.00	15.75	515.00	237.75	3.25	487.50	330.68	27.00	8.75	488.50	224.33
26	3.25	453.25	572.50	41.50	15.75	476.75	242.00	4.25	450.50	587.83	47.75	8.75	469.25	286.55
27	3.00	469.00	317.25	32.00	15.75	484.25	267.75	4.00	472.75	300.50	25.25	8.75	487.25	227.18
28	3.00	576.25	275.38	34.00	14.00	584.50	154.25	3.75	579.50	282.98	34.13	8.25	599.50	181.48

TABLE 2. Cont.

Gen	2015/2016							2016/2017						
	Control				Inoculation			Control				Inoculation		
	PDSF	FPC	GY	PDSG	PDSF	FPC	GY	PDSF	FPC	GY	PDSG	PDSF	FPC	GY
29	3.00	492.50	376.85	41.25	15.50	493.00	176.25	4.00	468.50	363.58	30.88	8.50	485.00	228.25
30	2.75	558.50	615.00	33.00	13.00	571.75	373.75	3.75	547.75	589.93	29.88	8.75	566.50	418.00
31	5.25	444.25	379.95	46.75	21.00	460.25	186.50	6.00	424.00	363.83	41.13	14.00	448.25	178.25
32	3.75	493.50	529.60	37.75	14.00	508.75	201.95	4.75	522.50	541.03	28.00	7.00	531.00	377.75
33	3.00	557.75	180.13	32.50	13.75	578.75	46.65	4.00	530.00	205.40	22.25	6.75	560.00	155.15
34	6.50	579.50	480.48	37.50	13.25	602.25	340.23	7.50	576.75	495.45	27.00	7.50	588.00	329.88
35	3.75	562.50	456.75	23.50	13.25	579.75	336.85	4.75	589.00	465.55	21.25	7.00	612.25	359.90
36	3.25	576.00	261.65	26.00	15.00	593.25	191.80	4.25	568.50	283.43	23.50	8.00	587.50	214.28
37	3.00	588.00	577.05	22.00	13.00	615.25	322.00	4.00	574.25	556.43	17.63	6.00	590.50	387.70
38	5.25	579.25	455.85	34.50	14.50	581.25	337.53	6.00	585.00	484.03	24.75	7.50	588.25	362.63
39	6.50	558.00	248.15	24.50	13.25	575.00	142.03	7.50	535.25	286.95	19.75	7.50	558.00	188.05
40	6.25	582.50	190.80	27.75	13.00	594.50	139.75	7.75	589.00	203.10	22.13	8.00	600.25	166.78
41	3.25	455.50	379.48	44.50	18.75	476.25	177.40	4.25	469.75	395.68	41.50	11.75	482.50	165.15
42	1.75	462.00	438.68	44.75	19.00	477.50	208.73	3.00	468.50	428.63	55.75	13.25	486.00	188.28
43	2.25	589.00	429.03	30.75	15.00	611.50	301.28	3.25	588.50	461.85	25.75	8.00	605.00	323.45
44	3.75	601.25	364.40	30.63	15.75	602.50	173.10	5.00	602.25	353.70	30.75	8.75	608.75	234.83
45	5.50	588.00	219.38	34.50	12.25	612.50	174.15	6.50	582.00	214.93	37.63	8.25	588.25	141.43
46	5.25	568.75	270.45	36.50	13.25	588.25	128.88	6.50	560.25	274.85	47.25	8.50	573.50	144.00
47	2.25	466.50	139.03	26.50	11.25	488.25	98.30	3.50	507.75	153.08	32.63	6.25	512.25	90.03
48	2.00	487.25	265.98	34.75	13.00	489.75	134.55	3.00	500.00	293.10	30.63	6.00	508.75	168.00
Sakha–93	3.75	338.00	261.68	56.75	31.00	355.50	127.93	5.00	370.00	293.83	52.50	24.00	389.50	115.78
Giza–168	2.50	319.75	388.18	63.25	36.75	330.50	129.95	3.50	369.00	371.20	56.00	29.75	386.75	147.00
Mean	5.24	461.81	409.36	43.57	21.96	478.68	208.75	6.21	464.05	403.41	39.20	15.64	481.55	221.23
Revised $LSD_{0.05}$	2.66	9.03	16.41	4.12	4.09	16.10	26.43	2.48	8.53	13.29	4.10	3.90	9.31	14.71

PDSF= Percentage of diseased spikelets under field condition.
FPC= Free phenolic compounds (µg/g of dry weight).
GY= Grain yield (g).
PDSG= Percentage of diseased spikelets under greenhouse condition.

TABLE 3. Means of studied traits combined over the two growing seasons (2015/2016 and 2016/2017).

Gen	Control			Inoculation			
	PDSF	FPC	GY	PDSG	PDSF	FPC	GY
1	13.88	190.50	383.38	87.75	60.88	199.00	51.65
2	4.88	374.63	544.51	54.00	23.25	392.50	251.59
3	7.00	596.63	310.16	27.88	12.75	618.38	241.63
4	12.25	559.75	866.08	25.38	13.50	575.38	594.73
5	14.88	476.25	477.88	40.63	17.00	490.63	245.26
6	15.00	161.75	411.76	83.56	56.50	176.13	53.73
7	11.88	159.63	423.48	82.19	52.88	177.50	83.33
8	9.88	451.88	305.36	46.50	18.50	470.50	143.00
9	5.13	363.75	644.28	52.00	24.50	379.88	280.38
10	11.75	178.75	537.21	85.25	56.00	191.75	80.40
11	6.13	547.63	647.88	32.13	10.88	559.38	320.29
12	5.38	477.63	466.03	35.88	11.25	502.75	269.06
13	9.25	161.88	486.75	85.69	58.50	172.25	48.74
14	2.75	452.88	308.98	40.31	16.25	468.63	168.78
15	1.88	268.75	390.84	58.56	35.00	281.63	155.00
16	5.50	472.75	320.18	34.13	13.25	482.75	202.43
17	1.88	451.75	349.99	45.06	21.25	466.00	151.43
18	3.88	444.38	463.91	48.19	22.25	461.75	229.05
19	5.13	502.75	498.68	38.44	14.63	515.13	295.38
20	4.25	458.38	348.09	34.13	13.50	485.75	230.81
21	7.00	461.63	326.95	40.63	16.25	506.63	205.86
22	7.63	488.13	343.99	29.31	11.00	558.75	222.94
23	6.50	484.25	420.81	38.81	12.63	499.88	198.34
24	2.75	477.88	541.41	35.00	9.88	498.63	348.03
25	2.88	493.38	338.33	26.50	12.25	501.75	231.04
26	3.75	451.88	580.16	44.63	12.25	473.00	264.28
27	3.50	470.88	308.88	28.63	12.25	485.75	247.46
28	3.38	577.88	279.18	34.06	11.13	592.00	167.86
29	3.50	480.50	370.21	36.06	12.00	489.00	202.25
30	3.25	553.13	602.46	31.44	10.88	569.13	395.88
31	5.63	434.13	371.89	43.94	17.50	454.25	182.38
32	4.25	508.00	535.31	32.88	10.50	519.88	289.85
33	3.50	543.88	192.76	27.38	10.25	569.38	100.90
34	7.00	578.13	487.96	32.25	10.38	595.13	335.05
35	4.25	575.75	461.15	22.38	10.13	596.00	348.38
36	3.75	572.25	272.54	24.75	11.50	590.38	203.04
37	3.50	581.13	566.74	19.81	9.50	602.88	354.85
38	5.63	582.13	469.94	29.63	11.00	584.75	350.08
39	7.00	546.63	267.55	22.13	10.38	566.50	165.04
40	7.00	585.75	196.95	24.94	10.50	597.38	153.26
41	3.75	462.63	387.58	43.00	15.25	479.38	171.28
42	2.38	465.25	433.65	50.25	16.13	481.75	198.50

TABLE 3. Cont.

Gen	Control			Inoculation			
	PDSF	FPC	GY	PDSG	PDSF	FPC	GY
43	2.75	588.75	445.44	28.25	11.50	608.25	312.36
44	4.38	601.75	359.05	30.69	12.25	605.63	203.96
45	6.00	585.00	217.15	36.06	10.25	600.38	157.79
46	5.88	564.50	272.65	41.88	10.88	580.88	136.44
47	2.88	487.13	146.05	29.56	8.75	500.25	94.16
48	2.50	493.63	279.54	32.69	9.50	499.25	151.28
Sakha–93	4.38	354.00	277.75	54.63	27.50	372.50	121.85
Giza–168	3.00	344.38	379.69	59.63	33.25	358.63	138.48
Mean	5.72	462.93	406.38	41.39	18.80	480.11	214.99
Rvised $LSD_{0.05}$	1.81	6.19	10.52	2.89	2.82	9.26	15.06

PDSF= Percentage of diseased spikelets under field condition.
FPC= Free phenolic compounds (µg/g of dry weight).
GY= Grain yield (g).
PDSG= Percentage of diseased spikelets under greenhouse condition.

Analysis of variance (ANOVA)

Genotypes showed significant differences (P< 0.001) for all studied traits either in separate ANOVA for growing seasons 2017/2018 or combined ANOVA over the two growing seasons (Tables 4, 5). Similarly, in the combined ANOVA, years × genotypes showed significant differences (P<0.001) except for the percentage of diseased spikelets under the controlled field condition (PDSFC).

Pearson's correlation coefficient

The relationships among studied traits were assessed using the Pearson's correlation coefficients (Table 6). There was a moderate negative significant correlation between the PDSFC on one hand and both free phenolic compounds under controlled the field condition (FPCC) and free phenolic compounds under the infected field condition (FPCI) on the other hand. However, moderate positive significant correlations were noticed between the PDSFC on one hand and both percentage of diseased spikelets under the infected greenhouse condition (PDSGI) and percentage of diseased spikelets under infected field condition (PDSFI) on the other hand. The FPCC showed close to perfect positive correlation with the FPCI, while the FPCC showed a very strong negative relationship with both the PDSGI and the PDSFI. The relationship between the grain yield under the controlled field condition (GYC) and grain yield under the infected field condition (GYI) was positive significantly moderately high. The relationship between the PDSGI and PDSFI was very strong and positive. Nevertheless, the associations between the PDSFI on one hand and both the FPCI and GYI, on the other hand, were negative and ranged from moderate to very strong, respectively. Finally, Both the FPCI and GYI showed a moderate positive association.

Diallel analysis

The analysis of variance of Griffing's method 2 is displayed in Table 7. Both the GCA and SCA constituents were significant (P< 0.001) for all traits indicating that both additive and non–additive gene actions were important for these traits. However, the additive gene action was the predominant as the ratio of GCA to SCA was significant (P< 0.001). Narrow–sense heritability ranged from 0.69 for FPC to 0.79 for PDSG. The combining ability ratio (CAR) ranged from 0.69 to 0.80 for FPC and PDSG, respectively.

Parental genotypes GCA effects (Table 8) showed that parents 37, 35 and 22 were the best combiners for FHB resistance based on all traits. The negative GCA effects in case of the PDSG and PDSF contribute to the resistance to FHB because low the values of PDSC or PDSF are associated with the high resistance to FHB. On the other hand, the positive GCA effects for the remaining traits participate in the resistance to FHB. Therefore, the most susceptible parents were 13, 6 and 1, while Giza–168 showed moderate resistance to FHB.

TABLE 4. Analysis of variance for studied traits in two seasons 2015/2016 and 2016/2017 for the 48 advanced inbred lines along the two Egyptian cultivars.

2015/2016								
Source	DF	Control			Inoculation			
		MS						
		PDSF	FPC	GY	PDSG	PDSF	FPC	GY
Rep	3	70.13	496.3	613.77	107.46	92.53	90.62	846.67
Gen	49	47.16***	60597.22***	80398.01***	1192.92***	812.00***	62381.23***	40934.44***
Error	147	3.63	41.742	137.974	8.69	8.58	132.78	357.8
2016/2017								
Source	DF	Control			Inoculation			
		MS						
		PDSF	FPC	GY	PDSG	PDSF	FPC	GY
Rep	3	285.57	680.03	141.12	24.71	55.02	339.14	240.9
Gen	49	43.95***	60139.40***	68664.27***	1307.10***	782.19***	60198.25***	46509.77***
Error	147	3.16	37.3	90.43	8.61	7.8	44.35	110.87

***Significant at the 0.001 probability level.
DF= Degrees of freedom, MS= Mean squares.
PDSF= Percentage of diseased spikelets under field condition.
FPC= Free phenolic compounds (µg/g of dry weight).
GY= Grain yield (g)
PDSG= Percentage of diseased spikelets under greenhouse condition.

TABLE 5. Analysis of variance for studied traits combined over the two growing seasons for the 48 advanced inbred lines along the two Egyptian cultivars.

Source	DF	MS						
		PDSFC	FPCC	GYC	PDSGI	PDSFI	FPCI	GYI
Year	1	94.09	501.76	3536.09*	1909.69**	4000.56***	823.69	15600.01**
Rep (Year)	6	177.85	588.17	377.45	66.09	73.78	214.88	543.78
Gen	49	90.61***	119240.83***	147908.13***	2438.45***	1592.16***	121476.50***	83393.06***
Gen×Year	49	0.49	1495.79***	1154.15***	61.57***	2.03***	1102.98***	4051.15***
Error	294	3.39	39.52	114.2	8.6496	8.1908	88.564	234.335

*,**,***Significant at the 0.05, 0.01 and 0.001 probability levels, respectively.
DF= Degrees of freedom, MS= Mean squares.
PDSFC= Percentage of diseased spikelets under field condition in control experiment.
FPCC= Free phenolic compounds (µg/g dry weight) under control condition.
GYC= Grain yield (g) under control condition.
PDSGI= Percentage of diseased spikelets under greenhouse in inoculated condition.
PDSFI= Percentage of diseased spikelets under field condition in inoculated experiment.
FPCI= Free phenolic compounds (µg/g dry weight) under inoculated condition.
GYI= Grain yield (g) under inoculated condition.

TABLE 6. Pearson's correlation coefficients among all traits for the 48 advanced inbred lines along the two Egyptian cultivars across two growing seasons.

	PDSFC	FPCC	GYC	PDSGI	PDSFI	FPCI
FPCC	–0.45***					
GYC	0.21	–0.11				
PDSGI	0.51***	–0.94***	0.12			
PDSFI	0.58***	–0.94***	0.12	0.95***		
FPCI	–0.44**	0.99***	–0.11	–0.95***	–0.94***	
GYI	–0.16	0.56***	0.69***	–0.58***	–0.55***	0.56***

***Significant at the 0.001 probability level.
PDSFC= Percentage of diseased spikelets under field condition in control experiment.
FPCC= Free phenolic compounds (µg/g dry weight) under control condition.
GYC= Grain yield (g) under control condition.
PDSGI= Percentage of diseased spikelets under greenhouse in inoculated condition.
PDSFI= Percentage of diseased spikelets under field condition in inoculated experiment.
FPCI= Free phenolic compounds (µg/g dry weight) under inoculated condition.
GYI= Grain yield (g) under inoculated condition.

TABLE 7. Mean squares for analysis of variance of Griffing's Method 2 for studied traits of the seven parents along with their 21 F_1 crosses.

Source	DF	MS			
		PDSG	PDSF	FPC	GY
Rep	2	29.23	5.58	10.78	23.50
Gen	27	1999.50***	1255.91***	94759.13***	42686.08***
GCA	6	7507.72***	4332.57***	315716.39***	152594.88***
SCA	21	425.72***	376.86***	31628.48***	11283.57***
Error	54	4.73	3.09	14.69	39.37
GCA/SCA		17.64***	11.50***	9.98***	13.52***
h_n		0.79	0.72	0.69	0.75
CAR		0.80	0.72	0.69	0.75

***Significant at the 0.001 probability level.
DF= Degrees of freedom, MS= Mean squares.
GCA= General combining ability, SCA= Specific combining ability, GCA/SCA= Mean square GCA/ mean square SCA, h_n= Narrow–sense heritability and CAR= Combining ability ratio calculated as GCA variance/SCA variance.
PDSG= Percentage of diseased spikelets under greenhouse condition.
PDSF= Percentage of diseased spikelets under field condition.
FPC= Free phenolic compounds (µg/g of dry weight).
GY= Grain yield (g) under field condition.

TABLE 8. Estimates of general combining ability (GCA) effects of Griffing's Method 2 for studied traits of the seven parents along with their 21 F_1 crosses.

Parent	GCA effect			
	PDSG	PDSF	FPC	GY
1	11.24***(3)	8.15***(3)	–58.22***(5)	–40.77***(4)
6	11.74***(2)	8.96***(2)	–71.71***(6)	–46.12***(5)
13	20.26***(1)	15.67***(1)	–145.96***(7)	–77.06***(7)
22	–11.38***(5)	–9.63***(5)	87.51***(3)	23.81***(3)
35	–17.70***(6)	–13.62***(6)	108.94***(2)	83.73***(2)
37	–22.09***(7)	–15.87***(7)	133.64***(1)	114.85***(1)
Giza–168	7.93***(4)	6.35***(4)	–54.19***(4)	–58.43***(6)
SE	0.39	0.31	0.68	1.12

***Significant at the 0.001 probability level, SE= Standard error.
PDSG= Percentage of diseased spikelets under greenhouse condition.
PDSF= Percentage of diseased spikelets under field condition.
FPC= Free phenolic compounds (µg/g of dry weight).
GY= Grain yield (g) under field condition.
(The rank of GCA effects are shown between brackets).

The SCA estimates of cross combinations are presented in Table 9. The best cross combinations for the PDSG were 1×37, 6×35, 6×22 and 13×37. For the PDSF, the best cross combinations were 13×37, 6×22, 1×22 and 1×37. The best cross combinations for the FPC were 13×37, 6×35, 6×22 and 1×35. Finally, the best cross combinations for the GY were 13×37, 1×37, 6×35 and 1×35.

Discussion

In this study, the evaluation of FHB resistance was performed during two growing seasons to ensure constant and the adequate FHB resistance in the investigated plant materials. In the present study, the FHB severities of the exotic 48 AILs along with two Egyptian cultivars were evaluated under greenhouse conditions, where humidity and temperature were controlled to favor FHB development. Previous studies indicate that infection of FHB usually occurs at flowering or shortly after, through the extruded or retained anthers. Warm and humid conditions are essential for spores to germinate and to infect wheat spikes (Parry et al., 1995). The disease severity of the exotic 48 AILs along with two Egyptian cultivars was significantly varied and the average percentages were ranged from 19.81%, for the most resistant AILs, to 87.75% for the most susceptible AILs.

The very strong negative correlation ($r > -0.90$, P value= 0.001) between free phenolic compounds and percentage of diseased spikelets under both greenhouse and field infection emphasizes that free phenolic compounds play an important role in the mechanisms of wheat resistance to FHB pathogen. Therefore, the more the free phenolic compounds are expressed in the wheat tissues, the less the percentage of diseased spikelets are shown. It has been reported that phenolic metabolisms in plants are boosted as a response to both biotic and abiotic stresses (Lattanzio, 2013). The amount of reduction in phenolic compounds was higher in the susceptible wheat cultivar to FHB compared to resistant ones after a few days of infection (Siranidou et al., 2002). Furthermore, due to the fact the GY is a polygenic trait that is highly affected by environmental factors, we found that the relationship between both grain yield and free phenolic compounds under field infection was moderately positive ($r \approx 0.6$, P value= 0.001). This implies that free phenolic compounds might be used in selection for the resistance to FHB. There was a negative moderate relationship ($r \approx -0.60$, P value= 0.001) between percentages of diseased spikelets under both infected greenhouse and field on one hand and the GY under field infection on the other hand. This magnitude of this relationship was less than the aforementioned relationship between amount free phenolic compounds and (%) diseased spikelets because of the nature of the GY trait as a quantitative trait compared to the free phenolic compounds or the (%) of diseased spikelets.

TABLE 9. Estimates of specific combining ability (SCA) effects of Griffing's Method 2 for studied traits of the 21 F_1 crosses.

Male	Female	PDSG	PDSF	FPC	GY
1	1	15.20***(2)	11.92***(2)	–97.09***(25)	–46.16***(23)
6	1	9.63***(5)	8.91***(6)	–92.73***(24)	–44.91***(22)
13	1	4.52***(11)	3.87***(13)	–15.02***(14)	–8.43*(17)
22	1	–11.85***(23)	–14.80***(26)	113.58***(6)	–7.31*(16)
35	1	–12.59***(24)	–13.61***(23)	123.41***(4)	69.44***(5)
37	1	–23.20***(28)	–14.73***(25)	117.39***(5)	82.32***(2)
Giza–168	1	3.10*(12)	6.51***(9)	–52.45***(21)	1.20ns(13)
6	6	10.40***(4)	7.34***(7)	–88.88***(23)	–34.24***(21)
13	6	1.25ns(15)	–2.60**(19)	–6.20**(13)	–4.69ns(15)
22	6	–15.95***(26)	–14.84***(27)	131.20***(3)	37.03***(7)
35	6	–16.43***(27)	–13.82***(24)	143.47***(2)	82.11***(3)
37	6	–0.14 ns(18)	–2.50*(18)	20.08***(11)	11.66**(11)
Giza–168	6	0.84 ns(16)	10.17***(3)	–18.06***(17)	–12.72***(18)
13	13	–7.37***(21)	–6.61***(21)	58.35***(7)	24.79***(9)
22	13	20.17***(1)	19.69***(1)	–153.42***(27)	–63.35***(26)
35	13	7.99***(6)	8.98***(5)	–166.15***(28)	–110.27***(28)
37	13	–15.25***(25)	–16.11***(28)	180.79***(1)	111.61***(1)
Giza–168	13	–3.94**(20)	–0.60ns(16)	43.29***(9)	25.56***(8)
22	22	–0.63 ns(19)	–0.64 ns(17)	–16.79***(15)	0.84ns(14)
35	22	0.16 ns(17)	2.61**(15)	–17.65***(16)	37.52***(6)
37	22	2.02 ns(13)	3.16**(14)	–34.21***(19)	17.74***(10)
Giza–168	22	6.72***(9)	5.47***(11)	–5.92**(12)	–23.31***(20)
35	35	6.15***(10)	6.03***(10)	–31.19***(18)	2.80 ns(12)
37	35	7.11***(8)	6.78***(8)	–43.45***(20)	–22.85***(19)
Giza–168	35	1.45 ns(14)	–3.01**(20)	22.75***(10)	–61.57***(25)
37	37	10.86***(3)	9.26***(4)	–70.97***(22)	–56.73***(24)
Giza–168	37	7.74***(7)	4.87***(12)	–98.64***(26)	–87.02***(27)
Giza–168	168	–7.95***(22)	–11.71***(22)	54.52***(8)	78.93***(4)

*,**,***Significant at the 0.05, 0.01 and 0.001 probability levels, respectively.
ns Not significant.
PDSG= Percentage of diseased spikelets under greenhouse condition.
PDSF= Percentage of diseased spikelets under field condition.
FPC= Free phenolic compounds (µg/g of dry weight).
GY= Grain yield (g) under field condition.
(The rank of the SCA effects are shown between brackets).

Diallel analysis

In the current study, both constituents of combining ability according to Griffing's method 2 showed significant differences, in addition, additive gene action was more important than non–additive gene action. Golparvar (2014) reported similar results about the existence of additive gene effects for some traits in wheat. However, Dağüstü (2008) highlighted the importance of non–additive gene effects under stress conditions. Malla et al. (2009) found that the significance of GCA mean squares emphasized that parental genotypes were different in their contribution to the FHB resistance; moreover, they elucidated that the significance of the SCA mean squares underlined the prominence of non–additive gene action explicit in the performance of the cross combinations. The findings of the current study revealed that narrow–sense heritability showed moderately high estimates for all traits, which further emphasizes the importance of additive gene action for studied traits. Singh et al. (1995) detected moderate to high estimates of narrow–sense heritability (0.7 to 0.9) in their study on FHB resistance in spring wheat. Furthermore, Malla et al. (2009) found moderate estimates of narrow–sense heritability (0.40 to 0.64) under the greenhouse and field conditions for the FHB resistance in their diallel analysis using both spring and winter wheat parental genotypes indicating that further improvements of the FBH resistance are expected from the selection using their parental genotypes. The combining ability ratio for studied traits in the current study was quite similar to the findings of Malla et al. (2009) who found values of combining ability ratio ranged from 0.7 to 0.9 under greenhouse and field conditions, which further highlighted the magnitude of additive gene constituent for the FHB resistance in wheat. In addition, Mardi et al. (2014) supported the predominance of additive gene action in governing the resistance to FHB based on the ratio of GCA variance to SCA variance, which indicates that parental genotypes determined the response of their offspring to FHB. In addition, the significance ratio of GCA mean squares to SCA mean squares further emphasized the importance of additive gene action in improving the FBH in wheat as indicated by Golparvar (2014). The resistant parents were displayed in the best cross combinations according to the SCA effects for all traits. This indicates that the resistance to FHB was transmitted to all progenies (Snijders, 1990; Oettler et al., 2004).

Conclusion

Some exotic wheat AILs may possess the resistant genes to the FHB in wheat. In the current study, we identified potential resistant wheat AILs to the FHB, which may be exploited in a wheat breeding program in Egypt to develop resistant varieties to the FHB. Furthermore, we highlighted the importance of free phenolic compounds in the mechanisms of resistance to the FHB in wheat. This is due to its very strong correlation with the percentage of diseases spike sets under both greenhouse and field conditions pre and post–infection. We may use these promising AILs 37, 35, 22, 38, 36, 43, 25, 27, 3 and 4 genotypes in the wheat disease breeding programs to produce resistant and adapted varieties to Egyptian conditions. Both additive and non–additive constituents of gene action describe the resistance to the FHB; nevertheless, the additive constituent is the most important constituent of resistance to the FHB. Parents 22, 35 and 37 were the best combiners according to the GCA effects for all traits, in addition, they existed in the best cross combinations based on the SCA effects. These resistant AILs successfully transmitted their resistance to the FHB to their progenies. Using these resistant AILs in bi-parental and multi-parental crosses will allow plant breeders to benefit from the existence of both additive and non-additive components of gene action. The outcome of these crosses may lead to develop new resistant varieties to FHB. In addition, these resistant AILs could be used to improve the resistance to FHB in susceptible existing cultivars via backcrossing approaches.

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تحليل الهجن نصف الدائرية للمقاومة لمرض لفحة السنابل الفيوزارمي في قمح الخبز

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يُعد مرض لفحة السنابل الفيوزارمي المتسبب عن *Fusarium graminearum* Schwabe واحداً من أكثر أمراض القمح تدميرا في جميع أنحاء العالم. لتوصيف مقاومة مرض لفحة السنابل الفيوزارمي، تم تقييم 48 سلالة متقدمة وصنفين من القمح لمعرفة مقاومتها لمرض لفحة السنابل الفيوزارمي خلال موسمين متتاليين تحت ظروف الصوبة والحقل. حددنا بعض السلالات المتقدمة المقاومة لمرض لفحة السنابل الفيوزارمي، والتى تشمل السلالات 37 و 35 و 22 بناءً على النسب المئوية للسنيبلات المصابة تحت ظروف الصوبة والحقل، والمركبات الفينولية الحرة إلى جانب محصول الحبوب تحت ظروف الحقل. في حين أن معظم السلالات المتقدمة كانت حساسة لمرض لفحة السنابل الفيوزارمي، بما في ذلك السلالة 1 و 13 و 6. تم التهجين بين ثلاث سلالات مقاومة وثلاث سلالات حساسة لمرض لفحة السنابل الفيوزارمي بالإضافة إلى صنف مصري حساس باستخدام طريقة الهجن نصف الدائرية. تم تقييم الآباء والجيل الأول الغير عكسي لاستجابتها لمرض لفحة السنابل الفيوزارمي. أظهرت كل من القدرة العامة على الإئتلاف، القدرة الخاصة على الائتلاف اختلافات معنوية ($P<0.001$) لجميع الصفات المدروسة. كان هناك تأثير مضيف وغير مضيف لصفة المقاومة لمرض لفحة السنابل الفيوزارمي، ومع ذلك، فإن العمليات الحسابية المختلفة دعمت أن الفعل الإضافي الجيني هو العنصر الأساسي الغالب. تشير التقديرات المرتفعة المعتدلة لقيم درجة التوريث الخاصة أنه يمكن تحقيق مزيد من التحسين في مقاومة مرض لفحة السنابل الفيوزارمي من خلال الإنتخاب. لقد وجدنا أن السلالات 22 و 35 و 37 كانت لها قدرة عامة على الائتلاف جيدة ونجحت في نقل جيناتها المقاومة إلى نسلها بناءً على القدرة الخاصة على الائتلاف. يمكن ادخال هذه السلالات المقاومة في برامج تربية القمح باستخدام التهجينات ثنائية أو متعددة الآباء لاستنباط أصناف جديدة مقاومة لمرض لفحة السنابل الفيوزارمي. بالإضافة إلى أنه يمكن استغلالها أيضا في تحسين الأصناف الموجودة من خلال طرق التهجيين الرجعي.