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GENETIC SYSTEM CONTROLLING CADMIUM STRESS TOLERANCE AND SOME RELATED CHARACTERS IN BREAD WHEAT

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ABSTRACT

Six populations of three bread wheat (*Triticum aestivum* L.) crosses namely 1) Giza 168 x Sids 6, 2) ACSAD 925 x Gemmeiza 10 and 3) ACSAD 935 x Line 1 were grown during 2009/2010, 2010/2011 and 2011/2012 at the Experimental Farm, Fac. Agric., Zagazig Univ., Egypt. The six populations were evaluated in two adjacent experiments, one with 30 ppm cadmium (Cd), and the other without, to assess some breeding parameters for Cd stress tolerance, flag leaf area, leaf chlorophyll content, proline content, and grain yield/plant. Results indicated that, F_1 exceeded the better parent for low Cd concentration in all crosses; flag leaf area and grain yield/plant in most studied crosses under both conditions. Positive and significant heterobeltiosis was detected for proline content in 3rd cross under control and leaf chlorophyll content in 1st and 2nd crosses under Cd stress. The lowest amount of Cd has been accumulated by Giza 168 and Sids 6 and their BC_1 and Gemmeiza 10 and their BC_1, which were bellow or equal the critical concentration, 0.2 mg/ kg suggested by CAC (2010). Cd sensitivity index revealed that F_2 population in 1st cross; Gemmeiza 10 and their BC_2 in 2nd cross as well as ACSAD 935 and Line 1 and their F_1, F_2, BC_1 and BC_2 in 3rd cross expressed as tolerant to Cd stress**.** Genetic system and gene expression differed greatly from the control to Cd stress treatment in most cases. Where, scaling tests (A, B and C) provide evidence for the suitability of a simple additive - dominance genetic model for explaining the genetic system controlling flag leaf area in 1st cross; proline content in 3rd cross; Cd concentration in 2nd and 3rd crosses and leaf chlorophyll content in the three crosses under control, as well as leaf chlorophyll content in 2nd cross; proline content in 3rd cross and Cd concentration in 1st and 2nd crosses under Cd stress. Otherwise, the complex genetic model was responsible for the inheritance of proline content in 1st and 2 nd crosses and grain yield/plant in all crosses under both conditions, and flag leaf area in all crosses; leaf chlorophyll content in 1st and 3rd crosses and Cd concentration in 3rd one under Cd stress. Additive gene effect (d) was significant for leaf chlorophyll content in all crosses; Cd concentration in 2nd and 3rd crosses; flag leaf area in 1st cross and proline content in 3rd one under the control, and Cd concentration in 1st and 2nd crosses under Cd stress condition. Both additive (d), dominance (h) and their interaction types, additive × additive (i) and dominance × dominance (l) were involved in the genetics of flag leaf area and grain yield/plant in 2nd and 3rd crosses under control as well as flag leaf area in 2nd and 3rd crosses under Cd stress condition. Additive (d), dominance (h), additive x additive (i), additive x dominance (j) and dominance x dominance (l) were highly significant for proline content in 1st and 2nd crosses and grain yield/plant in all crosses under Cd stress. Additive (D) and dominance (H) genetic variances were significant for flag leaf area, leaf chlorophyll content and Cd concentration in all crosses under both conditions, and proline content under Cd stress one, with the predominant of additive component, resulting in $(H/D)^{1/2} < 1$. Dominance genetic variance played a major role in controlling grain yield/plant in all crosses, with $(H/D)^{1/2}$ ›1 under both conditions. Heritability in narrow sense was high (> 50%) for flag leaf area, leaf chlorophyll content, proline content and Cd concentration in most cases and ranged from low to moderate for grain yield/plant under both conditions. Expected response from selection was high for praline content and Cd concentration, while it varied from low to moderate for the remaining characters under both conditions.

Key words: Wheat, cadmium, tolerance, heterobeltiosis, genetic system, heritability, response, selection.

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INTRODUCTION

Cadmium (Cd) is a nonessential heavy metal that is highly toxic to living cells at very low concentrations. Cd is a risk factor in cereal crops due to its high toxicity and accumulation in the body, particularly to liver and kidneys, with associated osteoporosis and cancer (Tanhuanpää *et al*., 2007). So, it is highly toxic to plants, animals and human. Cadmium is a heavy metal present in soils from natural and anthropogenic sources. Much of the Cd taken up by plants is retained in the root, but a portion is translocated to the aerial parts of the plant and into the seed. The main source of contamination of soil and crops with Cd is industrial effluents. Many reports have shown that the use of Cd containing fertilizers increased Cd uptake by plants (Anderson and Simon, 1991 and Chaudri *et al*., 2001). Atmospheric deposition of Cd onto the leaf surfaces of cereals can be important because cereal based foods are consumed in large amounts, representing 54% of the food (*i.e.* dry matter) consumed worldwide (Graham and Welsh, 1996). The emission of toxic substances and ions destroy or damage cell structures, leading to metabolic disturbances, enzyme inhibition and modifications in photosynthesis and plant biomass distribution (Das *et al*., 1997 and Starck, 1998), it causes damage the structure of chloroplasts, chlorophyll fluorescence responses and chlorophyll nutrient concentration as well as growth changes of the whole plant (Ouzounidou *et al*., 1997).

Cereal grains represent a large portion of our diet and are therefore a major contributor to Cd intake (Wagner, 1993). The concentration of Cd in food crops are subject to regulation by national and international agencies. Chaudri *et al*. (2001), in wheat genotype Soissons have found that Cd content in the grain was greater than the EU limit (0.24 mg / kg dry wt). The limit for Cd in wheat (*Triticum* spp) is currently 0.2 mg kg^{-1} (CAC, 2010). In this respect, Li *et al*. (1997) found that grain Cd concentration ranged from 0.11 to 0.34 mg Cd /kg DW for 30 durum wheat lines. This variability indicates that breeding for low grain Cd in durum wheat should be feasible. Also, significant differences were found between the mean values of Cd concentration varied from 0.465 ppm in *Triticum aestivum* ssp *vulgare* var. *nigracolor* to 3.035 ppm in variety Timgalen, originating from Australia (Kraljevic-Balalic *et al*., 2008). Differences between wheat lines and cultivars in their ability to accumulate Cd have also been shown by Oliver *et al*. (1995), Stolt (2002) and Clarke *et al*. (2002).

Plants tolerate heavy metals through sequestration with cysteine rich peptides, proline, chlorophyll content and other physiological and biochemical characters (Lagriffoul *et al.*, 1998; Mahgoub *et al*., 1998 and Awaad *et al*., 2010). In continuous, Awaad *et al*. (2010) indicated that wheat genotypes ACSAD 903, Sakha 94, ACSAD 939, Prl(S)/ Pew(S), Tow(S)/Pew(S) and Gemmeiza 5 were classified according to lead sensitivity index as tolerant to lead stress with high values of proline content, leaf chlorophyll content, flag leaf area and yield attributes in most cases. Whereas, ACSAD 925 was ranked in the first order in sensitivity to lead. Heritability estimates in broad sense were high under normal and moderate under lead stress conditions for proline content, leaf chlorophyll content and flag leaf area, however it was low for grain yield/fad., under both conditions.

In respect to gene action, Penner *et al.* (1995) identified a single gene governing low Cd uptake in Western Canadian durum wheat by using RAPD markers. Genetic analysis of grain Cd concentration was determined in the F_2 and in $F_{2:3}$ families of one cross and in $F_{2:3}$ and $F_{3:4}$ families of two crosses by Clarke *et al*. (1997) and showed that low grain Cd concentration was largely controlled by a single dominant gene (*Cdu1*), with high heritability estimates (>70%). Apparent transgressive segregation in all three crosses suggest the presence of other minor genes directly or indirectly affecting Cd concentration. Grain Cd concentration showed different degrees of dominance *i.e.* over dominance, complete dominance and partial dominance in 77 F_2 plants and 50 $F_{2:3}$ families from the cross between Fanfarron/DT 369. Also, over dominance and desirable heterobelteiosis for flag leaf area, leaf chlorophyll content and grain yield/plant were registered by Awaad (2002a and 2002b).

Knox *et al*. (2009) identified Cd uptake gene *Cdu1* in segregants from the cross between a Kyle*2/ Biodur (low Cd uptake) and Kofa (high Cd uptake) mapped by using microsatellite

markers. The Cd concentration segregated bimodally, allowing *Cdu1* to be mapped qualitatively as well as quantitatively with quantitative trait locus analysis. The *Cdu1* gene mapped to the long arm of chromosome 5B. Whereas, Ishikawa *et al*. (2010) detected two QTLs with additive effects for grain Cd concentrations on chromosomes 2 and 7 and designated tentatively as *qGCd2* and *qGCd7*, respectively, they registered high broad-sense heritability values for metal concentrations in grains and straw.

The objective of this research was to determine the genetic variability, heterobeltiosis, genetic system, gene effects, heritability and response to selection for Cd tolerance, flag leaf area, leaf chlorophyll content, proline content, and grain yield/plant in three cross populations using six parameters genetic model.

MATERIALS AND METHODS

Crossing Technique and Experimental Layout

The present investigation was conducted during the three winter growing seasons 2009/ 2010, 2010/ 2011 and 2011/2012 at the Experimental Farm, Faculty of Agriculture, Zagazig Univ., Zagazig, Egypt, to study the genetic system controlling Cd tolerance. Six diverse parental bread wheat genotypes *i.e.* Giza 168, Sids 6, ACSAD 925, Gemmeiza 10, ACSAD 935 and Line 1 (Table 1) were selected as parental materials to build six population of three wheat crosses *i.e.* Giza 168 x Sids 6, 2) ACSAD 925 x Gemmeiza 10 and 3) ACSAD 935 x Line 1.

In the first season of 2009/2010, the six parental wheat genotypes were sown and pair crosses were performed to obtain F_1 cross grains. In the second season 2010/2011, three F_1 cross grains were sown to produce F_1 plants. Each of the F_1 plants were crossed back to their respective parent to obtain first (F_1 x P_1) and second (F_1 x P_2) backcrosses. In the meantime, pair crosses were made to produce more F_1 grains, also the F_1 plants were selfed to produce F_2 grains. In the third season 2011/2012, the obtained grains of six populations (P_1, P_2, F_1, F_2, BC_1 and BC_2) for each of the three crosses were evaluated using a randomized complete block design with three replications in two parallel experiments. The first experiment was treated under controlled conditions carefully at beginning heading stage by spray heavy metal Cd solution. Cadmium sulfate $CdSO_4 \cdot 8/3H_2O$ was used as source of cadmium in the present study. The concentration was 30 ppm Cd ion per liter of water (200 liters/fad.). Mane *et al*. (2010) treated wheat plants with increasing concentrations of cadmium chloride i.e. 25, 50 and 75 ppm. Singh (2004) showed that selection for mineral toxicity can be carried out in a field having mineral toxicity problem. The second experiment included the same populations which used as control with pure water spraying. Wheat grains were sown on 21st November. Row length was 2.5 m, row to row and plant to plant spaces were 20 and 10 cm, respectively. The normal agricultural practices for wheat production were performed. Data were recorded on individual guarded plants for the six populations in every replicate. Flag leaf area was measured at the time of full emergence of main spike, also flag leaf

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

Name	Pedigree	Origin
Giza 168	MIL/BUC//Seri: CM 93046-8M-OY-OM-2Y-OB.	Egypt
Sids 6	Maya (S) Mou (S)//CMH 74A 592/3/ Sakha 8 *25 D 1002-4sd-3sd-1sd-0sd.	Egypt
ACSAD 925	GEN/3/Gov/AZ//MUS"S"/4/Sannine/Ald"S" ACS-W-9174-10 IZ-5 IZ-0 IZ.	Syria
Gemmeiza 10	MAYA74"S"/0N//1160-147/3/BB/GLL/4/CHAT "S"/CROW"S"	Egypt
ACSAD 935	ACSAD 529//Yr/Sprw"S" ACS-W/8023- 1IZ-2I Z-0IZ	Syria
Line 1	N.S.732/Pim/Veery(S) sd 735- 4sd-1sd 0sd/3/ CM 87688 – 02910P m-5Y-OH-Osy-1M-0Y	Egypt

chlorophyll content was estimated using SPAD-502 apparatus (Castelli *et al*., 1996) and leaf proline content was assessment according to Bates *et al*. (1973) and grain yield/plant was estimated. For cadmium analysis, dried grain samples were weighed and digested at 160 C° in 0.5 ml of concentrated glass - distilled HNO_3. A 1:1 mixture of HNO_3: $HClO_4$ (0.25 ml) was added to the acid digestion residue and the digestion was continued at 200 C° to dryness. The dry residue was dissolved in 1 ml of 8 n HNO_3, then diluted 10:1 with d1 H_2O and analyzed for Cd via inductively coupled argon plasma emission spectrometry (Model ICAP 61E; Thermo-Jarrell Ash, Waltham, MA, USA). Standard of appropriate concentration of Cd was concurrently analyzed for quality control (Hart *et al.*, 2005).

Cadmium sensitivity Index (CdSI) was used to characterize the relative stress tolerance of all genotypes included in the study using a generalized formula suggested by Fischer and Maurer (1978) as follows:

Cadmium Sensitivity Index (CdSI)={1-(Y_s/Y_p)}/ SI

Where, Ys and Yp are the grain yield of a genotype in stress and control conditions, respectively. SI is stress intensity, where:

$SI = 1 - \overline{Y}s/\overline{Y}p$, $\overline{Y}s$ and $\overline{Y}p$ are the mean grain yield of all genotypes under stress and control conditions, respectively.

Biometrical Assessment

A regular analysis of variance was firstly performed for the studied characters of the three wheat cross populations. Better parent heterosis or heterobeltiosis was calculated by using formula outlined by Bitzer *et al*. (1982) as follows:

$$\text{Heterobeltiosis } (HB_{\%}) = \frac{\overline{F}_1 - \overline{BP}}{\overline{BP}} \times 100$$

S.E for heterobeltiosis $\overline{F}_1 - \overline{BP} = (\overline{V}F_1 + \overline{V}BP)^{1/2}$

Testing the genetic model

The A, B and C scaling test as outlined by Mather and Jinks (1982) were applied to test the presence of non-allelic interactions as follows;

$A = 2\overline{B}C_1 - \overline{P}_1 - F_1, B = 2\overline{B}C_2 - \overline{P}_2 - \overline{F}_1$ and $C = 4\overline{F}_2 - 2\overline{F}_1 - \overline{P}_1 - \overline{P}_2$

Joint scaling test proposed by Cavalli (1952) as indicated by "χ^2" was applied for testing the goodness of fit of the adequacy genetic model controlling the studied characters. Due to unknown biased effect of non-allelic interaction, the simple genetic model {m, d and h} was applied when epistasis was absent. Whereas, in the presence of non-allelic interaction, the analysis was proceeded to compute the interaction types involved using the six-parameters genetic model according to Jinks and Jones (1958). The significance of the genetic components were tested using the "t" test, where:

$$\pm t = \frac{\text{Effect}}{\sqrt{\text{variance of effect}}}$$

Components of Genetic Variance, Heritability and Expected Response from Selection

The components of the genetic variance for each character in the studied crosses were partitioned into additive (D), dominance (H) genetic variances and environmental (E) one using Mather and Jinks (1982) formulae as follows:

$E = (1/3)(VP_1 + VP_2 + VF_1)$

$D = 4\,VF_2 - 2(VBC_1 + VBC_2)$

$H = 4(VF_2 - 1/2\,VD - E)$

Genetic components of variance were used further to compute average degree of dominance $(H/D)^{1/2}$ and heritability in narrow sense (h^2ns).

$$h^2ns = \frac{1/2D}{1/2D + 1/4H + E}$$

Expected response from selection (R) was also computed using Falconer (1989) formula as follows: (R) = I.hns.σ D

Where:

I: The selection differential at 10% selection intensity.

hns: Square root of narrow sense heritability.

σD: Square root of additive genetic variance.

RESULTS AND DISCUSSION

Mean Performance and Heterobeltiosis

The results given in Tables 2 and 3 indicated significant differences between parental wheat genotypes and their populations for the studied characters, suggesting the presence of high degree

Table 2. Generation means, standard errors and heterobeltiosis ($HB_{\%}$) for flag leaf area and leaf chlorophyll content in the six populations of three bread wheat crosses under control and Cd stress conditions

Characters / Cross populations	Flag leaf area (cm^2)			Leaf chlorophyll content (SPAD)		
	1	2	3	1	2	3
		Control			Control	
P_1	44.620±7.752	37.800±0.269	40.356±0.516	47.50±0.713	46.50±0.641	54.29±0.706
P_2	40.176±0.797	52.272±0.378	51.840±0.451	49.60±0.612	48.10±0.426	58.53±0.508
F_1	47.800±0.301	49.600±0.549	53.800±0.518	48.90±0.834	49.50±0.066	53.70±0.389
F_2	46.500±1.853	40.166±1.753	50.900±2.231	51.30±1.448	48.00±3.097	53.03±1.177
BC_1	45.400±1.520	39.700±1.952	40.160±2.104	50.00±1.193	48.60±1.363	54.88±0.880
BC_2	43.710±2.995	50.250±1.013	50.400±1.312	51.30±1.606	47.50±2.556	56.40±1.128
$HB_{\%}$	7.127**	-5.112**	3.781*	-1.411	2.911*	-8.252**
		Cd stress			Cd stress	
P_1	38.480±0.217	32.400±0.326	34.556±0.759	34.80±0.834	41.70±0.396	48.10±0.360
P_2	34.560±0.226	44.640±0.422	48.852±0.440	38.30±0.682	43.30±0.564	52.19±0.497
F_1	45.420±0.070	42.500±0.174	49.800±0.307	44.40±1.232	44.30±0.447	50.40±0.500
F_2	42.500±1.449	34.100±1.902	46.500±2.068	44.14±1.418	43.40±1.152	51.30±1.003
BC_1	41.700±0.755	39.124±1.928	39.600±1.262	43.60±1.379	45.40±0.956	53.52±0.889
BC_2	43.100±0.864	45.230±0.803	45.000±0.725	48.40±1.787	43.40±1.098	55.83±0.634
$HB_{\%}$	18.136**	-4.794*	1.941	15.927**	2.309*	-3.429

*, ** Significant and highly significant at 0.05 and 0.01 probability levels, respectively.

Table 3. Generation means, standard errors and heterobeltiosis ($HB_{\%}$) for proline content, Cd concentration and grain yield / plant in the six populations of three bread wheat crosses under control and Cd stress conditions

Characters / Cross populations	Proline content (µmoles/g.f.w.)			Cd concentration (mg Cd/kg DW)			Grain yield/plant (g.)		
	1	2	3	1	2	3	1	2	3
		Control			Control			Control	
P_1	1.170±0.223	3.210±0.250	3.170±0.225	0.196±0.008	0.283±0.012	0.203±0.014	8.23±0.245	6.35±0.306	11.55±0.278
P_2	0.670±0.038	3.500±0392	1.640±0.264	0.163±0.005	0.207±0.012	0.330±0.020	6.04±0.230	7.74±0287	5.30±0.208
F_1	1.330±0.110	3.200±0.204	2.680±0.223	0.200±0.011	0.235±0.015	0.307±0.020	9.07±0.310	8.90±0.229	9.77±0.262
F_2	1.720±0.332	2.890±0.447	2.230±0.432	0.237±0.041	0.230±0.047	0.253±0.048	7.96±0.431	8.85±0.421	8.75±0.64
BC_1	2.020±0.301	2.510±0.387	2.750±0.397	0.180±0.028	0.190±0.034	0.213±0.021	9.59±0.362	7.11±0.440	9.13±0.343
BC_2	1.060±0.281	5.500±0.296	1.650±0.420	0.270±0.032	0.250±0.032	0.285±0.38	6.28±0.399	8.73±0.420	6.97±0.361
$HB_{\%}$	13.675**	-8.571**	-15.457**	22.699**	13.527**	51.231**	10.207*	14.988**	-15.411**
		Cd stress			Cd stress			Cd stress	
P_1	2.080±0.016	4.770±0.094	4.480±0.003	0.710±0.020	0.897±0.012	0.800±0.011	5.00±0.264	4.54±0.282	10.34±0.284
P_2	1.620±0.044	5.590±0.095	3.480±0.029	0.603±0.014	0.610±0.026	0.893±0.008	4.22±0.221	6.77±0.412	4.42±0.214
F_1	2.060±0.050	5.101±0.182	3.760±0.082	0.660±0.016	0.780±0.041	0.926±0.024	6.67±0.256	7.25±0.354	7.17±0.339
F_2	1.900±0.196	3.300±0.419	3.180±0.224	0.680±0.060	0.650±0.124	0.805±0.067	6.88±0.404	7.34±0.557	7.08±0.449
BC_1	2.570±0.081	5.460±0.289	4.470±0.077	0.730±0.026	0.835±0.048	0.767±0.029	6.64±0.332	4.28±0.394	7.62±0.447
BC_2	1.890±0.074	6.400±0.365	3.440±0.108	0.570±0.032	0.780±0.108	0.942±0.049	4.79±0.291	7.97±0.347	6.02±0.410
$HB_{\%}$	-0.962	-8.766**	-16.071**	9.453**	27.868**	15.750**	33.4**	7.090*	-30.658**

*, ** Significant and highly significant at 0.05 and 0.01 probability levels, respectively.
Cd concentration: Cadmium concentration

of genetic variability valid for further biometrical analysis. Data of mean performance and heterobeltiosis ($HB_{\%}$) showed that, under control condition, the F_1 exceeded the better parent for flag leaf area in 1st and 3rd crosses; leaf chlorophyll content in 2nd cross; proline content in 3rd cross as well as Cd concentration and grain yield/plant in 1st, 2nd and 3rd crosses, showing heterotic effects and accumulation of favorable alleles for such characters. On the other hand, under Cd stress condition, positive and significant heterobeltiosis was detected for flag leaf area in 1st and 3rd crosses; leaf chlorophyll content and grain yield/plant in 1st and 2nd crosses as well as Cd concentration in the three crosses. In this respect, positive and significant heterobeltiosis was detected for flag leaf area, leaf chlorophyll content and grain yield/plant by Awaad (2002a and 2002b) and for Cd concentration by Clarke *et al.* (1997).

It is interest to note that, under control condition, the lower amounts of Cd content has been registered by the parental wheat varieties Giza 168 and Sids 6 and their BC_1 with values of 0.196 and 0.163 and 0.180 mg/kg DW, respectively as well as the parent Gemmeiza 10 and their BC_1 with values of 0.207 and 0.190 mg/kg DW, respectively, rather than the remaining populations, these amounts of Cd in the previous genotypes were bellow or equal the critical limit 0.2 mg/kg DW suggested by national and international agencies (CAC, 2010).

Whereas under Cd stress condition, Cd concentration ranged from 0.570 in BC_2 of the 1st cross to 0.942 mg/ kg DW in BC_2 of the 3rd cross, also the parent Sids 6 and their BC_2 accumulated lower concentrations of Cd with values of 0.603 and 0.570 mg/kg DW, respectively compared with the other populations. In this respect, the genotypes with lowest Cd concentrations in the grains, could be chosen as parents in the hybridization for breeding new lines with low Cd concentration. Substantial variation in Cd concentration was found among and within wheat species (Li *et al*., 1997, Cakmak *et al.,* 2000 and Clarke *et al.,* 2002), apparently, genotypic variation in grain Cd content has been recorded in both common (Oliver *et al.,* 1995) and durum wheat (Penner *et al.,* 1995). Generally, the values of flag leaf area, leaf chlorophyll content and grain yield/plant were reduced as a results of Cd effect, whereas, proline content was found to be greatly increased from the control to Cd stress conditions as a mechanism defense of wheat genotypes to tolerate Cd pollution stress. In this respect, the emission of toxic substances and ions destroy or damage cell structures, leading to metabolic disturbances, enzyme inhibition and modifications in photosynthesis, also damage the structure of chloroplasts, chlorophyll fluorescence and chlorophyll nutrient concentration and plant biomass distribution (Das *et al*., 1997, Ouzounidou *et al*.1997 and Starck, 1998). Thus, wheat growth was decreased linearly with increase in concentrations of cadmium chloride from 25, 50 to 75 ppm (Mane *et al*., 2010). In pot trials, application of 6 - 12 ppm Cd reduced grain yield of wheat cv. Tano by 10%. At 48 ppm Cd, wheat grain yield was only 6% of the control (Hofer and Schutz, 1980).

Cadmium Sensitivity Index

Data of cadmium sensitivity index "CdSI" (Table 4) show that, F_2 populations in 1st cross; parent (P_2) Gemmeiza 10 and their BC_2 in 2nd cross as well as parent (P_1) ACSAD 935 and Line 1 and their F_1, F_2, BC_1 and BC_2 in 3rd cross exhibited lower values of CdSI (<1) which indicated high degree of tolerance to Cd stress. Whereas, the other parental wheat genotypes (P_1) Giza 168, (P_2) Sids 6 and their populations F_1, BC_1 and BC_2 in 1st cross; (P_1) ACSAD 925 and their populations F_1, F_2, and BC_1 in 2nd cross gave high values of CdSI (>1) indicated high degree of sensitivity to Cd stress. In this regard, Awaad *at al*. (2010) classified wheat genotypes Sakha 94, ASCAD 903, ASCAD 939 and Gemmeiza 5 as tolerant to lead stress as they exhibited lead sensitivity index of grain yield/fad. less than unity. Whereas, ACSAD 925 was ranked in the first order in sensitivity to lead stress followed by Sids 6 and TSI (S) /Pew(S).

Adequacy Genetic Model and Gene Effects

Scaling tests (A, B and C) are presented in Tables 5 and 6, under control condition, the results provide evidence for the suitability of a simple additive - dominance genetic model to explain the genetic mechanism controlling flag leaf area in 1st cross; proline content in 3rd cross; Cd concentrations in 2nd and 3rd crosses as well as leaf chlorophyll content in 1st, 2nd and 3rd crosses.

Table 4. Cadmium sensitivity index of wheat grain yield/plant for six populations in three bread wheat crosses

Cross populations	1	2	3
P_1	2.295	2.087	0.380
P_2	1.762	0.914	0.603
F_1	1.547	1.353	0.967
F_2	0.793	1.245	0.694
BC_1	1.798	2.186	0.601
BC_2	1.387	0.635	0.495

Table 5. Scaling tests (A, B and C) and adequacy genetic model for flag leaf area and leaf chlorophyll content in three bread wheat crosses growing under control and Cd stress conditions

Character	Flag leaf area			Leaf chlorophyll content		
Cross populations	**1**	**2**	**3**	**1**	**2**	**3**
Scaling test		Control			Control	
A	-1.620	-8.000*	-13.836**	3.600	1.200	1.770
B	-0.556	-1.372	-4.840	4.100	-2.600	0.570
C	5.604	-28.608**	3.804	10.300	-1.600	8.100
χ^2	N.S.	**	*	N.S.	N.S.	N.S.
Adequacy genetic model						
m	50.178**	40.166**	50.900**	51.150**	47.100**	45.970**
d	2.222**	-10.550**	-10.246**	-1.050*	-0.800*	-2.120**
h	-12.334	23.800**	-14.778*	2.850	1.200	20.510
i		19.236*	-22.480**			
j		3.314	-4.498			
l		9.864*	41.156**			
Scaling test		Cd stress			Cd stress	
A	-0.500	3.348	-5.156*	8.000*	-0.800	8.540**
B	6.220**	3.320*	-8.652**	12.500**	1.600	9.110**
C	6.120*	-25.640**	2.992	14.660*	0.200	4.110
χ^2	**	**	**	**	NS	**
Adequacy genetic model						
m	42.500**	34.100**	46.500**	44.140**	42.700**	51.300**
d	-1.400	-6.106**	-5.400**	-4.000*	-0.900*	-2.330*
h	8.500**	36.288**	-8.704*	13.690*	3.3	13.795**
i	-0.400	32.308**	-16.800*	5.840*		13.540**
j	-3.360**	0.014	1.748	-2.250		-0.285
l	-5.320	-38.976**	30.608**	-26.34**		-31.190**

m = mean, d = additive effect, h = dominance effect, i = additive x additive genic type interaction, j = additive x dominance genic type interaction and l = dominance x dominance genic type interaction.
*, ** Significant and highly significant at 0.05 and 0.01 probability levels, respectively.
N.S.: Not significant.

Table 6. Scaling tests (A, B and C) and adequacy genetic model for proline content, Cd concentration and grain yield/plant in three bread wheat crosses growing under control and Cd stress conditions

Character	Proline content			Cd concentration			Grain yield/plant		
Cross populations	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Scaling test		**Control**			**Control**			**Control**	
A	1.540*	-1.390	-0.350	-0.036	-0.038	-0.084	1.880	-1.030	-3.060**
B	0.120	4.300**	-1.020	0.137**	-0.038	-0.067	-2.550**	0.820	-1.130
C	2.380	-1.550	-1.250	0.189	-0.040	-0.135	-0.570	3.510**	-1.390
χ^2	**	**	N.S.	*	N.S.	N.S.	**	**	**
Adequacy genetic model									
m	1.720**	2.890**	2.525	0.237**	0.281**	0.283	7.960**	8.850**	8.750**
d	1.960*	-2.990**	0.765**	-0.090*	0.038**	-0.064**	3.310**	-1.620**	2.160**
h	-0.310	4.305*	-1.335	-0.027	-0.158	-0.143	1.835	-1.865*	-1.455*
i	-0.720	4.460*		-0.043			-0.100	-3.720	-2.800
j	0.710*	-2.845**		-0.106*			2.215**	-0.925	-0.965
l	-0.940	7.370**		-0.093			0.770	3.930*	6.990**
Scaling test		Cd stress			Cd stress			Cd stress	
A	1.000**	1.049	0.7000	0.090	-0.007	0.192**	1.610**	-1.830*	-2.270*
B	-0.360	2.109**	-0.360	-0.123	0.170	0.065	-4.310**	1.920*	0.450
C	1.020	-7.362**	-2.760	0.107	-0.467	-0.325	4.960**	3.550	-0.780
χ^2	**	**	N.S.	N.S.	N.S.	*	**	**	**
Adequacy genetic model									
m	1.900**	3.301**	0.880*	0.796**	0.124*	0.805**	6.880**	7.340**	7.080**
d	0.680**	-0.940*	0.500**	0.054*	0.143**	-0.175**	1.850**	-2.990**	1.600**
h	2.590**	10.441**	6.320**	-0.309	1.450	0.278	-2.600*	-1.865*	-1.250*
i	1.320*	10.520**				0.198	-4.660*	-3.460*	-1.040*
j	0.450**	-0.530*				-0.129*	1.460**	-1.875**	-1.360*
l	-2.420*	-13.678**				-0.071	4.360*	3.370*	2.860*

m = mean, d = additive effect, h = dominance effect, i = additive x additive genic type interaction, j = additive x dominance genic type interaction and l = dominance x dominance genic type interaction.
*, ** Significant and highly significant at 0.05 and 0.01 probability levels, respectively.
N.S.: Not significant.
Cd concentration: Cadmium concentration.

These information's could be used to facilitate breeding of cultivars with low grain Cd concentration. Similar observations were reported by Clarke *et al.* (1997) who found that a single dominant gene (*Cdu1*) for low grain Cd concentration appeared to be specific in durum wheat. Also, Salem *et al*. (2003) found that the simple additive – dominance genetic model was adequate to explain the inheritance of flag leaf area in the three crosses; leaf chlorophyll content in two crosses and proline content in one cross only out of five cross populations studied.

Otherwise, the complex genetic model was found to be adequate for explaining the inheritance of flag leaf area in 2nd and 3rd crosses; proline content in 1st and 2nd crosses; Cd concentration in 1st cross and grain yield/plant in 1st, 2nd and 3rd crosses. Similar results were registered for flag leaf area, leaf chlorophyll content and grain yield/plant by Awaad (2002b). Whereas, Knox *et al*. (2009) indicated that grain Cd concentration segregated bimodally, and *Cdu1* mapped qualitatively as well as quantitatively with quantitative trait locus analysis.

Additive gene effect (d) was significant and considered the main type controlling the inheritance of leaf chlorophyll content in all crosses; Cd concentration in 2nd and 3rd crosses, flag leaf area in 1st cross as well as proline contents in 3rd cross only. Meanwhile, additive (d), dominance (h), additive × additive (i) and dominance × dominance (l) interaction types were significant and important in the genetic system controlling flag leaf area and grain yield/plant in 2nd and 3rd crosses. Moreover, additive gene effect (d) and their digenic interaction type additive x dominance (j) were significant and involved in the inheritance of proline content, Cd concentration and grain yield/plant in 1st cross. The negative signs of additive effects has been detected for Cd concentration, indicating that decreasing alleles for Cd amount were more frequent. Furthermore, additive (d), dominance (h) and their digenic interaction types additive x additive (i), additive x dominance (j) and dominance x dominance (l) were involved in the genetics of proline content in 2nd cross only. Similar findings were recorded by many investigators such as Mahgoub *et al*. (1998) for total chlorophyll and proline content and Awaad (2002b) for flag leaf area, leaf chlorophyll content and grain yield/plant.

Whereas, under Cd stress treatment, the simple additive - dominance genetic model was adequate for explaining the inheritance of leaf chlorophyll content in 2nd cross; proline content in 3rd cross and Cd concentration in 1st and 2nd crosses. In this connection, Mahgoub *et al.* (1998**)** showed that the level of total chlorophyll, carotenoids and proline can serve as a simple, reliable and early indicator of environmental pollution by heavy metals in higher plants. Penner *et al*. (1995) identified a single gene governing low Cd uptake in Western Canadian durum wheat lines. Salem *et al*. (2003) found that the simple additive - dominant genetic model was adequate for explaining the inheritance of leaf chlorophyll content in Sakha 69 x Shi#4414/Gow 's'//Seri 82 and Shi#4414/ Gow 's'//Seri 82 x Bocro-4 crosses; proline content in Gemmeiza 5 x Giza 168. Otherwise, the adequacy genetic model (Tables 5 and 6) indicated that, the simple additive - dominance genetic model was not adequate to explain the inheritance of flag leaf area and grain yield /plant in all crosses; leaf chlorophyll content in 1st and 3rd crosses. These results reveal the presence of epistasis and the complex genetic model was adequate to explain the genetics of the above-mentioned characters in the corresponding crosses. Similar findings were reported by Awaad (2002b) for morpho-physiological and grain yield/plant characters. Whereas, Verbruggen and LeDuc (2013) stated that Cd accumulation in grain can be regulated by multiple genes with combined effect on uptake, translocation and sequestration.

It has been observed that, additive (d) gene effect was significant and expressed the main type controlling the inheritance of leaf chlorophyll content in 2nd cross and Cd concentration in 1st and 2nd crosses. Hereby phenotypic selection would be effective for improving both characters.

Both additive (d) and dominance (h) gene effects were involved in the genetics of proline content in 3rd cross. Hereby pedigree method would be effective for improving Cd tolerance.

Grain Cd concentration showed different degrees of dominance *i.e.* over dominance, complete dominance and partial dominance in 77 F_2 plants and 50 F_3 families from the cross between Fanfarron/DT 369 (Clarke *et al*., 1997). However, additive (d), dominance (h) and their digenic interaction types additive x additive (i) and dominance x dominance (l) were significant for flag leaf area in 2nd and 3rd crosses. Whereas, additive (d), dominance (h) and their digenic interaction types additive x additive (i), additive x dominance (j) and dominance x dominance (l) appeared to be highly significant and responsible in the inheritance of proline content in 1st and 2nd crosses and grain yield/plant in the three crosses. Dominance (h) and the digenic interaction type additive x dominance (i) were highly significant for flag leaf area in 1st cross, whereas additive (d) gene effect and its digenic interaction type additive x dominance (j) were significant for Cd concentration in 3rd cross. Additive, dominance and different types of their interactions were involved in the genetics of flag leaf area, proline content and leaf chlorophyll content (Awaad, 2002b and Salem *et al*., 2003) as well as for Cd concentration (Shu Tu, 2000).

It is worthy to note that, under control condition the genetic system controlling flag leaf area and leaf chlorophyll content in 1st cross and leaf chlorophyll content in 3rd cross, inherited under simple additive - dominance genetic model, with the prevailed type of additive (d) gene effect, whereas under Cd stress treatment, these crosses showed another behavior and inherited under complex genetic model with the prevailed type of epistasis, this may be due to the effect of Cd stress on the gene expression.

It is worthy to note that, dominance (h) and its digenic interaction type dominance x dominance (l) were significant and has different signs for grain yield/plant in 2nd and 3rd crosses under control condition; flag leaf area in 1st and 3rd crosses; proline content in 1st and 2nd crosses and grain yield/plant in the three crosses under Cd stress. This result indicate that interaction is predominantly of duplicate type. Dominance (h) and its digenic interaction type dominance x dominance (l) were significant and has similar signs for proline content in the 2nd cross under control condition, suggesting that interaction is predominantly of complementary type.

Components of Genetic Variance, Heritability and Expected Response from Selection

Results given in Tables 7 and 8 clearly indicate that both additive (D) and dominance (H) genetic variances were significant for flag leaf area, leaf chlorophyll content and Cd concentration in all crosses under control and Cd stress conditions, as well as proline content under Cd stress condition, with the predominant of additive component, resulting in $(H/D)^{1/2}$ ratio was less than unity. These results suggest the effectiveness of phenotypic selection for improving the foregoing characters.

Dominance genetic variance was the prevailed type controlling the inheritance of grain yield/plant in all crosses, resulting in $(H/D)^{1/2}$ was more than unity under both conditions. The previous results indicating the importance of over dominance in the genetic mechanism controlling the abovementioned characters in the corresponding crosses, therefore hybrid breeding method could be used for improving these characters. In this connection, ShuTu (2000) registered significant additive and over dominance gene action for four morphological characters related to Cd tolerance in rice *i.e.* shoot dry weight, root dry weight, shoot length, with moderate to high narrow-sense heritability.

Environmental variance under control condition was found to be significant for grain yield/ plant in all the studied crosses; flag leaf area in 3rd cross and leaf chlorophyll content in 1st and 2nd crosses. Whereas under Cd stress, it was significant for flag leaf area in 1st and 3rd crosses; leaf chlorophyll content in 1st cross; proline content in 2nd cross and grain yield/plant in all the studied crosses. Environmental variance was found to be significant for grain Cd concentration in the 42 families of the cross Kyle/Nile (Clarke *et al*., 1997).

Table 7. Components of variance (D, H and E), heritability in narrow sense (h^2ns%) and expected response from selection (R%) for flag leaf area and leaf chlorophyll conten in three bread wheat crosses under control and Cd stress conditions

Cross	Parameter						Parameter					
	D	H	E	$\sqrt{H/D}$	h^2ns%	R%F_2	D	H	E	$\sqrt{H/D}$	h^2ns%	R%F_2
	Flag leaf area						Leaf chlorophyll content					
	Control						Control					
1	6.086**	4.619*	0.207	0.871	69.08	7.761	72.740**	32.008*	3.115*	0.660	76.00	2.548
2	65.776**	24.408*	0.874	0.609	82.50	32.278	133.053**	22.531*	1.370*	0.412	90.00	5.230
3	51.832**	29.580*	1.547*	0.755	74.30	21.458	4.958*	2.344	0.963	0.680	61.00	5.772
	Cd stress						Cd stress					
1	-17.040	50.440**	2.913*	1.720	35.40	10.171	133.878**	122.311**	4.898*	0.96	65.00	37.195
2	34.313**	14.686*	0.526	0.654	80.30	27.092	122.208**	56.878*	0.459	0.68	81.00	39.797
3	94.175**	74.568**	1.507*	0.889	70.03	30.738	3.828	4.500*	1.123	1.08	45.00	4.502

*, ** significant and highly significant at 0.05 and 0.01 probability levels, respectively.

Table 8. Components of variance (D, H and E), heritability in narrow sense (h^2ns%) and expected response from selection (R%) for proline content, Cd concentration and grain yield/plant in three bread wheat crosses under control and Cd stress conditions

Cross	Parameter						Parameter						Parameter					
	D	H	E	$\sqrt{H/D}$	h^2ns%	R%F_2	D	H	E	$\sqrt{H/D}$	h^2ns%	R%F_2	D	H	E	$\sqrt{H/D}$	h^2ns%	R%F_2
	Proline content						Cd concentration						Grain yield/plant					
	Control						Control						Control					
1	0.855**	0.065	0.110	0.27	77.00	83.025	0.0161*	0.0059	0.0003	0.61	82.00	85.326	2.440	3.656**	0.969**	1.23	38.96	21.550
2	0.780**	0.212	0.077	0.52	75.00	46.579	0.0150*	0.0042	0.0004	0.53	83.52	85.649	1.062	2.144**	0.861*	1.42	27.55	10.757
3	1.022**	0.200	0.187	0.44	68.30	65.939	0.2239**	0.0097	0.0008	0.43	77.60	91.490	3.486*	3.841**	0.930**	1.05	47.90	8.219
	Cd stress						Cd stress						Cd stress					
1	0.877**	0.828**	0.006	0.97	67.00	61.046	0.0476*	0.0408*	0.0009	0.93	68.00	46.225	1.530	4.352**	0.723*	1.68	29.69	17.240
2	0.700**	0.064	0.234*	0.30	58.00	33.983	0.0214*	0.0087	0.0006	0.64	79.30	35.273	0.606	2.264**	0.833*	1.93	17.80	7.876
3	0.687*	0.617*	0.012	0.94	67.30	37.633	0.0030	0.0091	0.0002	1.74	37.50	7.333	3.189*	4.705**	0.824*	1.21	44.30	29.547

*, ** significant and highly significant at 0.05 and 0.01 probability levels, respectively.

Cd concentration: Cadmium concentration.

Heritability estimates in narrow sense (h^2ns%) under control condition was high (>50%) for flag leaf area, leaf chlorophyll content, proline content and Cd concentration in all the studied crosses. Meanwhile, under Cd stress condition, heritability was high (>50%) for flag leaf area in 2nd and 3rd crosses as well as leaf chlorophyll content and Cd concentration in 3rd one. These results allow considerable progress from selection. In this concern, the simple inheritance and high heritability of grain Cd concentration will facilitate the breeding of low Cd concentration wheat cultivars (Clarke *et al*., 1997 and 2002). Furthermore, heritability in narrow sense ranged from low to moderate for grain yield/plant under both control and Cd stress conditions, where yield is quantitively and greatly affected by environmental changes. Also, low to moderate h^2ns% estimates were registered in the remaining crosses for the various characters under both conditions. Similar results were recorded for morpho-physiological characters and grain yield/plant by Awaad (2002a and b), Awaad *et al.,* (2010) and Salem *et al*. (2003) as well as for Cd concentration by Clarck *et al*. (1997).

Expected response from selection (R) was high for proline content, Cd concentration, whereas it varied from low to moderate in the remaining characters under both control and Cd stress conditions. It is interest to note that heritability in narrow sense (h^2ns%) and expected response from selection (R) estimates tended to decrease from the control to Cd stress condition, this attributed to the low genetic variance as a result of Cd effect on the gene expression. In this respect, substantial progress could be achieved through selection for low Cd concentration (Mahgoub *et al.,* 1998 and Clarck *et al*. 2002).

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النظام الوراثى المتحكم فى تحمل إجهاد الكادميوم وبعض الصفات المرتبطة فى قمح الخبز

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٢- قسم بحوث القمح - مركز البحوث الزراعية - الجيزة - مصر
٣- قسم الأصول الوراثية النباتية - مركز بحوث الصحراء- المطرية - القاهرة - مصر

أجريت هذه الدراسة خلال الموسم الشتوى لأعوام ٢٠٠٩/٢٠١٠، ٢٠١٠/٢٠١١ و٢٠١١/ ٢٠١٢ بالمزرعة التجريبية - كلية الزراعة - جامعة الزقازيق باستخدام تحليل العشائر الستة لثلاثة هجن من قمح الخبز هى ١) جيزة ١٦٨ x سدس ٦ ،٢) أكساد ٩٢٥ x جميزة ١٠ و ٣) أكساد ٩٣٥ x سلالة ١ في تصميم قطاعات كاملة العشوائية فى تجربتين، الاولى خضعت للمعاملة بالكادميوم والثانية كمعاملة كنترول. واستهدفت الدراسة تقدير بعض مؤشرات التربية المرتبطة بتحمل إجهاد الكادميوم وبعض الصفات المرتبطة وهي مساحة ورقة العلم، محتوى كلوروفيل الورقة، محتوى البرولين ومحصول حبوب/النبات. وقد أظهرت نتائج متوسط السلوك وقوة الهجين تفوق الجيل الاول على متوسط الاب الاحسن فى تركيز الكادميوم المنخفض فى الهجن الثلاثة، مساحة ورقة العلم ومحصول حبوب/النبات في معظم الهجن تحت ظروف الكنترول وإجهاد الكادميوم. هذا وقد سُجلت قوة هجين موجبة ومعنوية لمحتوى البرولين فى الهجين الثالث تحت ظروف الكنترول ومحتوى كلوروفيل الورقة فى الهجين الاول والثانى تحت ظروف إجهاد الكادميوم. وقد سجلت الآباء جيزة ١٦٨ وسدس ٦ والجيل الرجعى الاول (BC_1) لها أقل معدل تراكم للكادميوم، وكذلك الاب جميزة ١٠ والجيل الرجعى الاول (BC_1) له مقارنة بباقى العشائر، حيث كانت أقل أو مساوية للتركيز الحرج (٠,٢مجم / كجم مادة جافة) والمحدد بواسطة الهيئات الدولية والعالمية (CAC, 2010). وقد صنف دليل الحساسية لإجهاد الكادميوم عشيرة الجيل الثانى F_2 فى الهجين الاول، والصنف جميزة ١٠ والجيل الرجعى الثانى BC_2 فى الهجين الثانى، وكذلك الاب أكساد ٩٣٥ والسلاله ١ وعشائرهما من الجيل الاول F_1 والثانى F_2 والجيل الرجعى الاولBC_1 والجيل الرجعي الثانى BC_2 فى الهجين الثالث كتراكيب عالية التحمل لإجهاد الكادميوم. وقد إختلف النظام الوراثي والتعبير الجينى من ظروف الكنترول الى معاملة إجهاد الكادميوم للصفات المدروسة فى معظم الحالات. فقد أظهرت نتائج إختبار المقياس (A, B and C)، تحت ظروف الكنترول، ملاءمة الموديل الوراثى البسيط "المضيف- السيادى" فى تفسير ميكانيكية وراثة مساحة ورقة العلم فى الهجين الاول، محتوى البرولين فى الهجين الثالث، تركيز الكادميوم فى الهجين الثانى والثالث ومحتوى كلوروفيل الورقة فى جميع الهجن تحت الدراسة. بينما تحت ظروف إجهاد الكادميوم، كان الموديل الوراثى البسيط هو الملائم لتفسير وراثة محتوى كلوروفيل الورقة فى الهجين الثانى، محتوى البرولين فى الهجين الثالث وتركيز الكادميوم فى الهجين الاول والثانى. وعلي الجانب الآخر، كان الموديل الوراثى المعقد هو الملائم لتفسير وراثة محتوى البرولين فى الهجين الأول والثاني ومحصول حبوب/النبات فى جميع الهجن، تحت ظرفي التجريب، ومساحة ورقة العلم فى جميع الهجن ومحتوى كلوروفيل الورقة فى الهجين الاول والثالث وتركيز الكادميوم فى الهجين الثالث، تحت ظروف إجهاد الكادميوم. لعب الفعل الجينى المضيف دوراً معنوياً فى وراثة محتوى كلوروفيل الورقة فى جميع الهجن، تركيز الكادميوم فى الهجين الثانى والثالث، مساحة ورقة العلم فى الهجين الاول ومحتوى البرولين فى الهجين الثالث، تحت ظروف الكنترول، وتركيز الكادميوم فى الهجين الاول والثاني، تحت ظروف إجهاد الكادميوم. كان الفعل الجينى المضيف والسيادى والتفاعل مضيف X مضيف وسيادى X سيادى هو المتحكم فى وراثة مساحة ورقة العلم ومحصول حبوب/النبات فى الهجين الثانى والثالث تحت ظروف الكنترول، بينما كان الفعل الجينى المضيف والسيادى والتفاعل مضيف X مضيف وسيادى X سيادى معنوياً وذوأهميه فى وراثة مساحة ورقة العلم فى الهجين الثانى والثالث تحت ظروف إجهاد الكادميوم. ولعب الفعل الجينى المضيف والسيادى والتفاعل مضيف X مضيف، مضيف X سيادى وسيادى X سيادى دوراً هاماً في وراثة محتوى البرولين فى الهجين الاول والثاني ومحصول حبوب/النبات فى جميع الهجن تحت الدراسة، تحت ظروف إجهاد الكادميوم. أظهر كلاً من التباين الوراثى المضيف والسيادي دوراً معنوياً في وراثة صفات مساحة ورقة العلم، محتوى كلوروفيل الورقة وتركيز الكادميوم فى جميع الهجن تحت ظروف الكنترول وإجهاد الكادميوم، ومحتوي البرولين تحت ظروف إجهاد الكادميوم مع سيادة المكون المضيف في وراثة تلك الصفات، ومن ثم كان متوسط درجة السيادة $(H/D)^{1/2}$ أقل من الوحدة. وعلى الجانب الآخر، كان التباين الوراثي السيادي هو المتحكم في وراثة محصول حبوب/النبات فى جميع الهجن، بمتوسط درجة سيادة أكبر من الوحدة. وكانت تقديرات معامل التوريث فى المعنى الخاص عالية (> 50%) لمساحة ورقة العلم، محتوى كلوروفيل الورقة، محتوى البرولين وتركيز الكادميوم فى معظم الحالات، بينما تراوحت من منخفضة الى متوسطة لمحصول حبوب/النبات في جميع الهجن، وكانت الاستجابة المتوقعة من الانتخاب عالية لمحتوى البرولين وتركيز الكادميوم، بينما إختلفت من منخفضة الى متوسطة لباقى الصفات تحت ظرفى التجريب.

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